University of Notre Dame
Methods of Experimental Physics
Lab Manual

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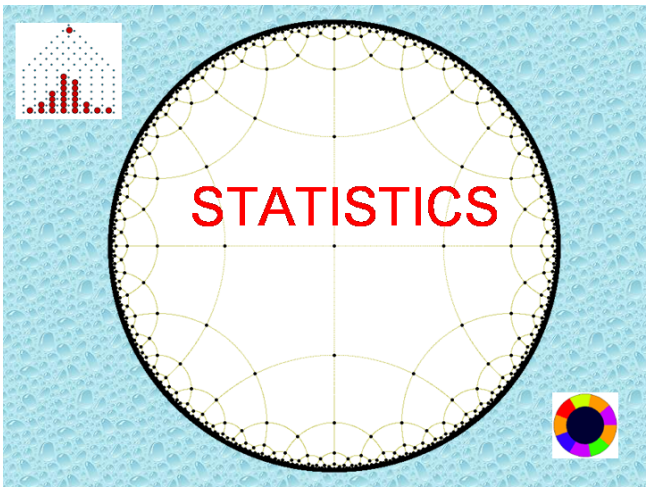
Contents

1 Statistics



Location: room Jordan 308

A. Short Description

Many effects in nature are subject to the laws of statistics, like tossing a coin or rolling a die. To estimate correctly the uncertainties and the physical relevance of a process dominated by statistics one needs to know the physical context. Radioactive decay is a statistical process in the time domain and at low numbers the so-called Poisson Statistics apply. Using two independent nuclear detectors one can produce randomly generated and uniformly distributed pulses with a time-to-amplitude converter. Measuring the pulse height of these pulses with a 16000 channel multi-channel-analyzer enables one to perform 16000 experiments at once in the time domain. Thus the Poisson distributions for $\frac{1}{2}$, 1, 2, 4, 8, 16, 32 and 64 events for example can be obtained with high precision. For numbers >20 the Poisson distribution incrementally becomes the more simple Gaussian distribution. The Statistics set-up uses the elements of the Nuclear Lifetime experiment, but both detectors run fully independently.

B. Necessary Knowledge

Physics :

- Basics statistical distributions for small numbers:
  A. Binomial;
  B. Poisson;
  C. Gaussian Distribution – Cases, which distribution applies for which case?
- Derive errors and uncertainties from the formulae
- Maximum likelihood method

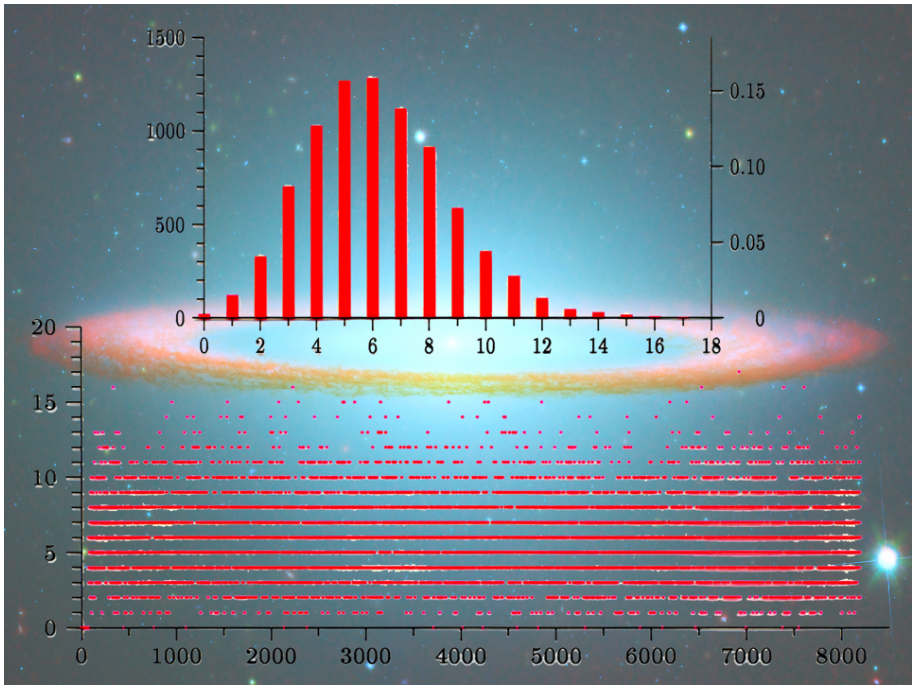


Figure 1: Concept scheme of the experiment with 8000 (or 16000) independent and simultaneous counters using a multichannel analyzer.

Measuring Technique :

- Use of a MCA to have simultaneous high number (8000 or 16000) of counters to obtain a perfect average of the measured distributions
- Noise sources, scintillation detectors, photomultipliers
- Constant fraction discriminators, time-to-pulse-height-converters (TAC)
- How is the uniform distribution produced?

Mathematics :

- Use Excel to get the statistical distributions, but be careful to chose only the selected 8000 or 16000 channels
- χ^2-test
- Optimizing of counting experiments
- Error propagation

References

[1]	**Fey, M. :** Zählstatistik und Fehlerfortpflanzung : Ein Praktikumsversuch Thesis of high school teachers, University of Stuttgart 1999	Original thesis on this teaching lab experiment
[2]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard work on detectors and related features
[3]	**Nicholson, P.W. :** Nuclear Electronics John Wiley & Sons, New York 1974	Standard work on nuclear electronics
[4]	**Leo, W.R. :** Techniques for Nuclear and Particle Physics Experiments Springer Verlag, Berlin 1987	Standard work on nuclear electronics
[5]	**Bevington, P.R. and D.K. Robinson:** Data reduction and error analysis for the physical sciences Mc Graw-Hill, New York 1992	Standard work on error analysis
[6]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics
[7]	**Melissinos, A. C. and Napolitano J.:** Experiments in Modern Physics Academic Press, Amsterdam etc. 2003	Textbook on Modern Physics Experiments
[8]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data

Some formulae

Binomial Distribution

The most general type of statistical model distribution for binary processes (i.e. yes or no; 1 or 0; boys or girls etc.). If n is the number of trials, and each trial has a success probability p, then the predicted probability of counting exactly x successes can be shown to follow this formula:

$$P(x) = \frac{n\,!}{(n-x)\,!\,x\,!} \quad P^x\ (1-p)^{n-x}$$

P(x) is the predicted probability distribution function, as given by the binomial distribution, and is defined only for integer values of n and x. (Find some examples in 7). This distribution is computationally cumbersome for radioactive decays and it needs only to be applied in rare cases where the observation time is comparable to the half-life of the sample. The success probability is constant.

Poisson Distribution

Many categories of binary processes can be characterized by a constant, small probability of success for each given individual trial. Included in these categories are most nuclear counting experiments, in which the number of nuclei in the sample is large and the observation time is short compared with the half-life of the radioactive species. In these situations the Binomial Distribution reduces to the Poisson form shown below:

$$P(x) = \frac{(p\,n)^x\, e^{-pn}}{x\,!}$$

Because pn = $\bar{x}$ holds for this distribution, as well as for the parent binomial distribution, one can obtain the Poisson form which depends now only on one parameter, $\bar{x}$, the product of the number of trials and the success probability p:

$$P(x) = \frac{(\bar{x})^x\, e^{-\bar{x}}}{x\,!}$$

The Poisson distribution is normalized to 1; the mean value is $\bar{x}$ (first moment) and the square of the standard deviation, (second moment), is also $\bar{x}$.

Gaussian Distribution

If the mean value of a Poisson distribution gets large, greater than 20, the distribution becomes more and more the form the symmetric Gaussian distribution,

$$P(x) = \frac{1}{\sqrt{2\,\pi\bar{x}}}\, exp\left(-\frac{(x\,-\,\bar{x})^2}{2\,\bar{x}}\right).$$

The Gaussian distribution has the same properties as the Poisson distribution, it is normalized to 1, it is characterized by a single parameter $\bar{x}$ = n p and the predicted variance, σ^2, is again equal to the mean value $\bar{x}$.

Experimental Tasks

- Set-up of the two NaI(Tl) detectors of the Nuclear Lifetime set-up, with faces in opposite directions, high voltage is negative -1800 Volts (for the new detectors).
- The pulses behind the main amplifier should not exceed 8 Volts in amplitude
- Both detectors run with separate sources, preferably the ^{137}Cs sources or the ^{133}Ba source, to get statistically uncorrelated pulses, like a source of noise.

- The timing pulses are derived from the zero crossing of the bipolar pulses after the Ortec # 460 DDL-amplifier and a subsequent TSCA # 455. This is the set-up of the Life-time experiment, for this experiment something simpler would also do it.

- The TAC produces a uniform distribution of all amplitudes because the time intervals between uncorrelated pulses are uniformly distributed. The amplitude range is from 0 – 8 Volts but there are little deviations at the TAC on both ends of the range, therefore we choose out of channels [0 – 8192] only the channels 100 – 8100 respectively channels 200 – 16200 [out of 0 – 16384] – enter this in the preset setup.

- With the distance source–detector one adjusts the single rates which should be about the same for both detectors. With both channels and a proper choice of the TAC range one can adjust a reasonable coincidence rate, about a few per second.

- By preselection of an exact number of 8000 counts for exact 16000 channels (channel 200 – 16200 for example) one selects an average number of $\frac{1}{2}$ count per channel, statistically distributed. The measuring time adjusts itself until the preselected counts are reached. Running 16000 channels means 16000 independent counting experiments at the same time to get the Poisson distribution with high accuracy. By preselection of 16000, 32000, 64000 etc. counts for that range of channels (200–16200) one selects 1, 2, 4 etc. counts per channel in the average.

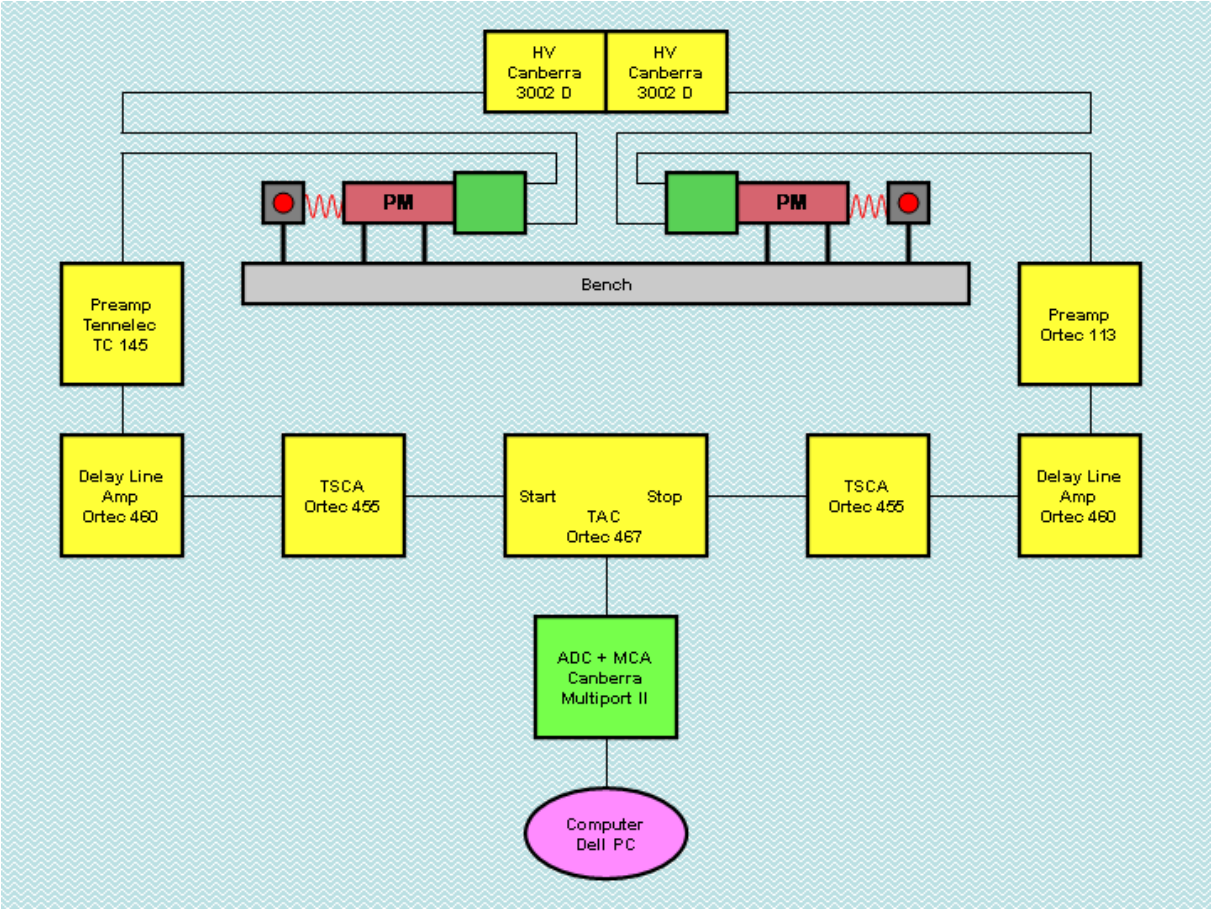
- With Excel one can determine how many channels show zero, one, two, three etc. events which gives the Poisson distribution after normalization to the number of counts corresponding to 100 % (or given in fractions of one).

- Determine the Poisson distributions for $\frac{1}{2}$, 1, 2, 4, 8, 10, 16, 20, 25, 32, 64 average counts and plot them in comparison with a) the Poisson formula and b) with comparison to the Gaussian distribution, use different colors in the plot.

- Alternative task : Measure distributions in the time domain verifying the scaler formula. Technical problem: one needs a very fast downscaler with selectable scaling factor.

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

Detector :	NaI(Tl) detectors $1\frac{1}{2}$" x $\frac{1}{2}$", photomultiplier: Electron Tubes (former EMI company) # 9814KB, assembly home-made, active voltage divider Electron Tubes # TB1106-01,
HV :	High voltage power supply for both detectors, Canberra # 3002D; negative HV = - 1800 V
pre-amps :	Ortec # 113 and unknown #, input capacitor setting
Amp :	Main Amplifier Ortec # 460, Double Delay Line Amp (DDL) for medium fast timing
TSCA :	Timing Single Channel Analyzer for energy selection and time signal derivation Ortec # 455

TAC :	Time-to-Amplitude-Converter Ortec # 467
MCA :	Multichannel Analyzer Canberra Multiport II (USB); software GENIE 2000, dongle
Computer :	Standard PC

Information on the radioactive sources

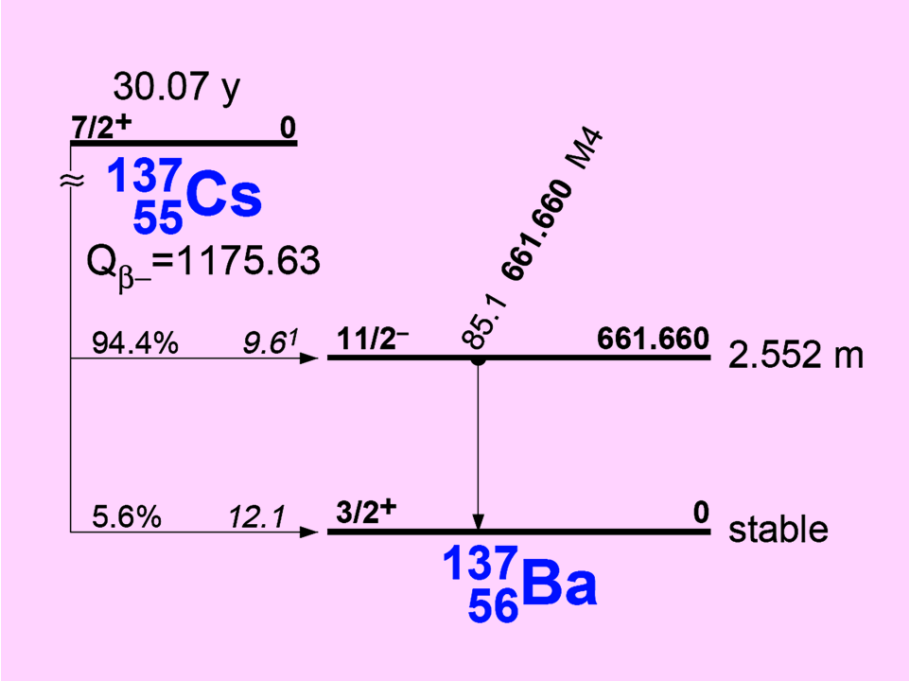


Figure 2: Decay scheme of ^{137}Cs from [8].

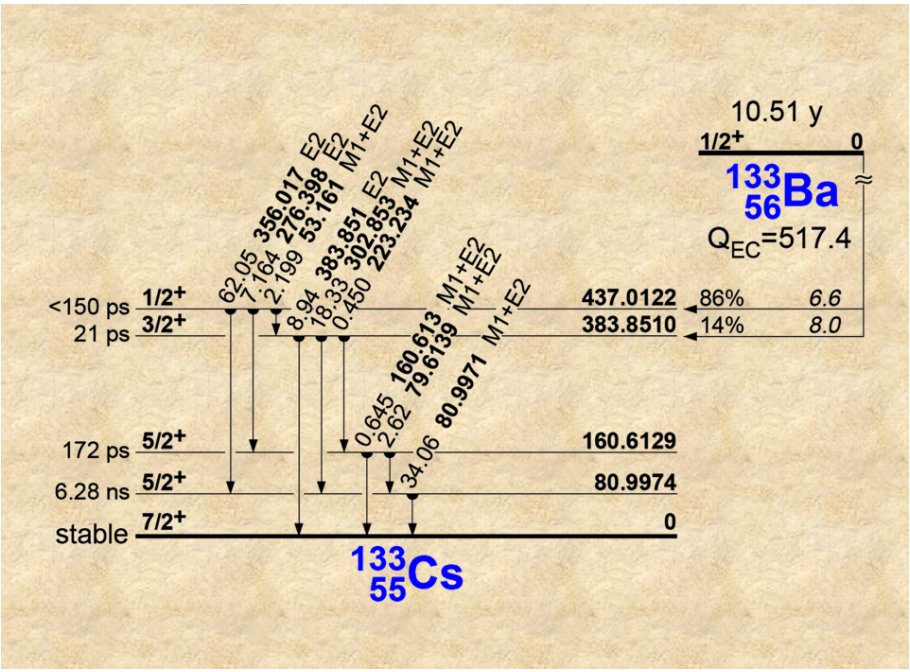


Figure 3: Decay scheme of ^{133}Ba from [8].

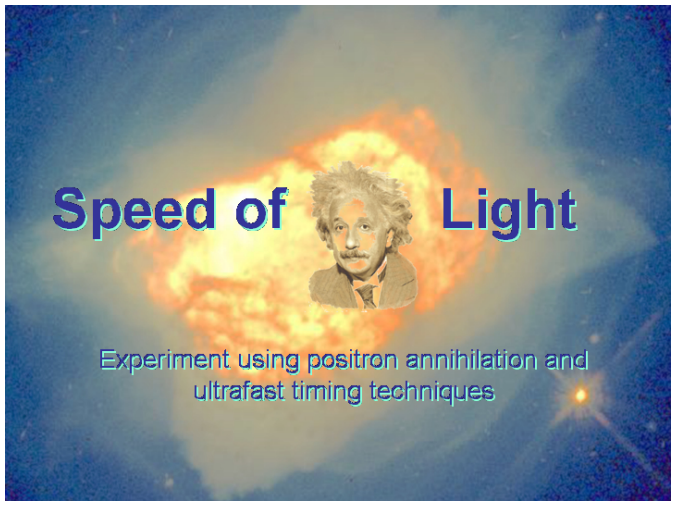
D. Discussion of Results

- Provide plots of all measured distributions correctly normalized. Discuss the accuracy. (Reminder use the middle channels 100–8100 resp. 200–16200)
- Compare measured 'Poisson' with calculated 'Poisson', and with calculated 'Gaussian'. Make plots of these comparisons using different colors.

E. Example Questions

- Describe the three main statistical distributions and describe their case of application.
- What is a "statistical error" and how is it calculated, what is the meaning? What other errors have to be considered in an experiment?
- Considering the time intervals between statistically arriving pulses, which time interval has the highest probability ? How can you explain it? Which kind of statistics applies?
- Why is the Poisson distribution asymmetric?
- Which process mainly defines the resolution of a nuclear detector? Give three examples for nuclear detectors with their typical resolution and the resolution defining number.

2 Speed of Light – Experiment using positron annihilation and ultrafast timing techniques



Location: room Jordan 308

A. Short Description

The speed of light c (latin *celeritas*) dominates most processes in the universe and has outstanding importance for the principle of relativity. It is the speed of anything having zero rest mass. It has practical applications in all communication-, telecommunication-, satellite- and space-systems, or positioning systems as for example GPS.
The speed of light in vacuum c_0 is nowadays fixed by definition (c_0 = 299 792 458 m/s) to replace the standard meter. In the present experiment the speed of light is measured to study fast timing methods at the extremes. In the present case the "light" has the very short wavelength of a γ quantum. One makes use of the simultaneous emission of two annihilation quanta from the positronium decay and their strong angular correlation (180 degrees). Two ultrafast plastic scintillation detectors (Pilot U, BC 418) face each other on an optical bench at a distance of about 2.7 meters. A positron source (sodium-22) in between emits the annihilation quanta. One is measuring the small time difference between the arrival of both quanta at the detectors for different positions of the source on the bench. The set-up is time calibrated using two different methods to obtain absolute values for the speed of light which can be determined with a precision of about 0.5 %.

B. Necessary Knowledge

Physics :

- Speed of light history, methods of measurement; see appendix;

Today fixed by definition (replaces meter-definition, a block of material, difficult to reproduce)

- Importance of the speed of light
- Goal of this experiment: Training of ultrafast timing methods
- Units and numbers, standards
- Physics of beta-decay, positron annihilation, theory and effects
- Positron sources

Measuring Technique :

- Fast γ-detectors : Pilot U (now BC 418 Saint Gobain), and BaF_2;
- Compare organic with anorganic scintillators
- Fast photomultipliers, characteristics
- Fast electronics: constant fraction discriminators and TAC's
- Signals and cables
- Fast-slow method (timing and energy)
- Make familiar with *differential* constant fraction discriminators, which is much more elegant
- Compare coincidences with regular source and with annihilation radiation source (strong angular correlation); efficiency considerations
- Multi channel analyzer (MCA),
- Time resolution

Mathematics : Method of least squares, linear fits, peak fitting

References

[1]	**Chow, L., S. Lukacs, and K. Hopkins :** Speed of light measurement using BaF_2 scintillation detectors Eur. J. Phys. **15** 49 (1994)	Original diploma
[2]	**Mohr, J.P., B.N. Taylor, and D. B. Newell :** CODATA Recommended Values of the Fundamental Physical Constants arXiv:0801.0028v1, physics.atom-ph, (2006); Rev. Mod. Phys. **80**, 633 (2008)	Most recent compilation of fundamental constants
[3]	**Cohen, E.R., and B. N. Taylor :** The Status of the Fundamental Constants-1992 Inst. Phys. Conf. Ser. No. 132, Section 9, pp. 969-977 (1992) 6th Int. Conf. on Nuclei Far From Stability and 9th Int. Conf. on Atomic Masses and Fundamental Constants, Bernkastel-Kues	Overview from 1992
[4]	**Cohen, E.R. :** Changes in the Fundamental Constants-Past and Future IEEE Trans. Instrumen. and Meas. 38(2), 167-171 (1989)	Review of changes of fundamental constants
[5]	**Taylor, B.N. :** Recommended Values of the Fundamental Physical Constants: A Status Report J. Res. Natl. Inst. Stand. Technol. 95, 497-523 (1990)	Review of 1990
[6]	**Maier, J. :** Aufbau und Erprobung von Praktikumsversuchen zur Positronenzerstrahlung Thesis of high school teachers, University of Stuttgart 1998	Original thesis on this teaching lab experiment
[7]	**Firestone, R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[8]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard work on detectors
[9]	**Schatz G. and A. Weidinger :** Nuclear Condensed Matter Physics, first edition John Wiley and Sons, Chichester 1996	Textbook

Experimental Tasks

- Set-up of detectors and electronics using oscilloscope; negative HV = - 2100 Volts
- Set-up of the MCA to 1024 or 2048 channels, keep same setting for both runs
- Use Co-60 source: Set the differential constant fractions to the major portion of the 1.17 and 1.33 MeV Compton spectrum (important)

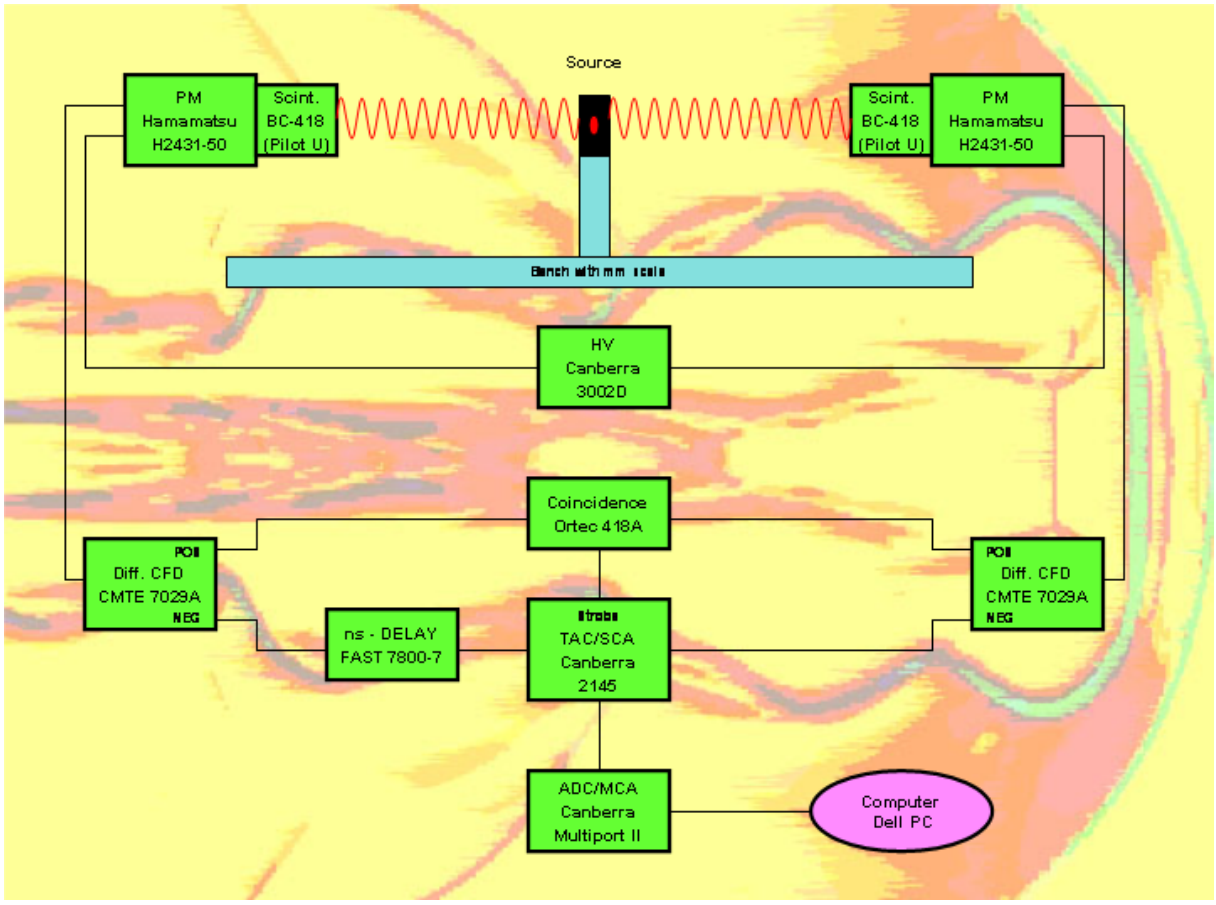
- Watch coincidence line using Co-60 source and about 30 cm distance source–detector, TAC range 50 ns is more linear, determine 'standard' resolution
- Set the differential constant fractions to the major portion of the 511 keV Compton spectrum (important)
- The additional coincidence and gating of the TAC is optional
- Measurement of speed of light: detector distance = max, source in the center, coincidence peak at middle channel (512 or 1024)
- Measure peak for variations of source positions every 20 cm's, one spectrum for all peaks Stop MCA and continue without erase
- Determine average value of channels/displacement (least square)
- Measure two time calibrations:
  1) using the Ortec time calibrator; this module is shared with some other experiments
  2) using calibrated delay lines
  One spectrum for all peaks. Don't change anything between the two runs (distance and time calib.) – even don't add or remove the scope, little impedance changes jeopardize precision
- Determine average channels/time interval
- Determine speed of light immediately
- Measure the energy spectrum of the $^{22}\mathrm{Na}$ source with appropriate settings, use Ortec # 435A amp in unipolar mode but obtaining bipolar signals, explain

WARNINGS

- Keep yourself at about 1m distance from source except when changing source position
- Don't exceed HV-setting

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

HV :	High voltage power supply for the detectors, Canberra # 3002D
BC-418 :	Pilot-U (BC-418) plastic scintillation detector; diameter 40 mm, thickness 25 mm (?)
PM :	Photomultiplier, Hamamatsu # H2431-50
COINZ :	Coincidence module, ORTEC # 418A (only optionally used)
Diff.CFD :	Differential constant fraction discriminator, CMTE # 7029A
DELAY :	nsec-Delay, FAST # 7800-7
TAC :	Time amplitude converter, Canberra # 2145
ADC/MCA :	MCA with Analog digital converter, Canberra Multiport II

Computer :	Computer Dell PC with Canberra Genie 2000 multichannel analyzer program, dongle
AMP :	Ampifier, ORTEC # 435A (used only for the energy spectrum)

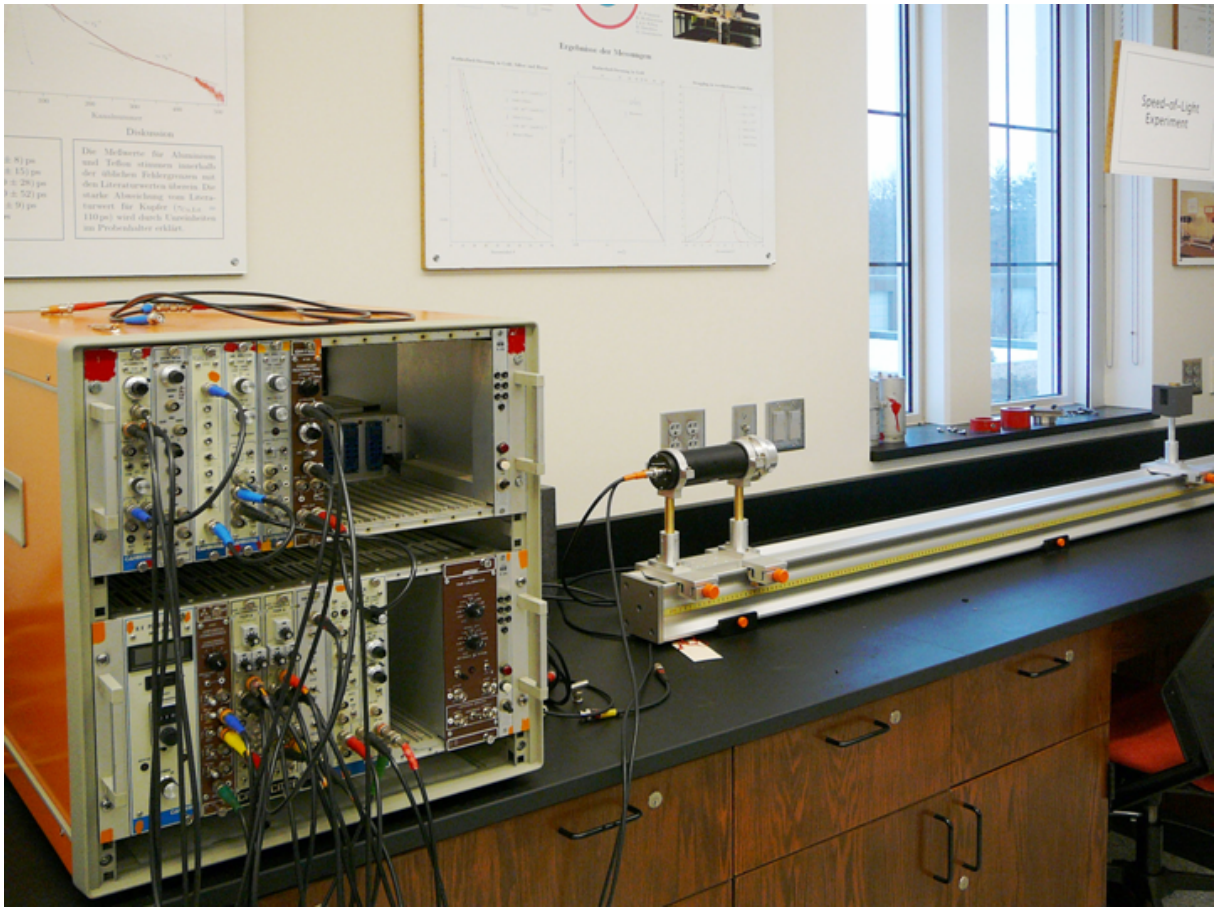


Figure 4: Set-up of the speed of light experiment with the electronic units and the left Pilot-U detector on the optical bench LINOS X 95.

Information on the used radioactive sources

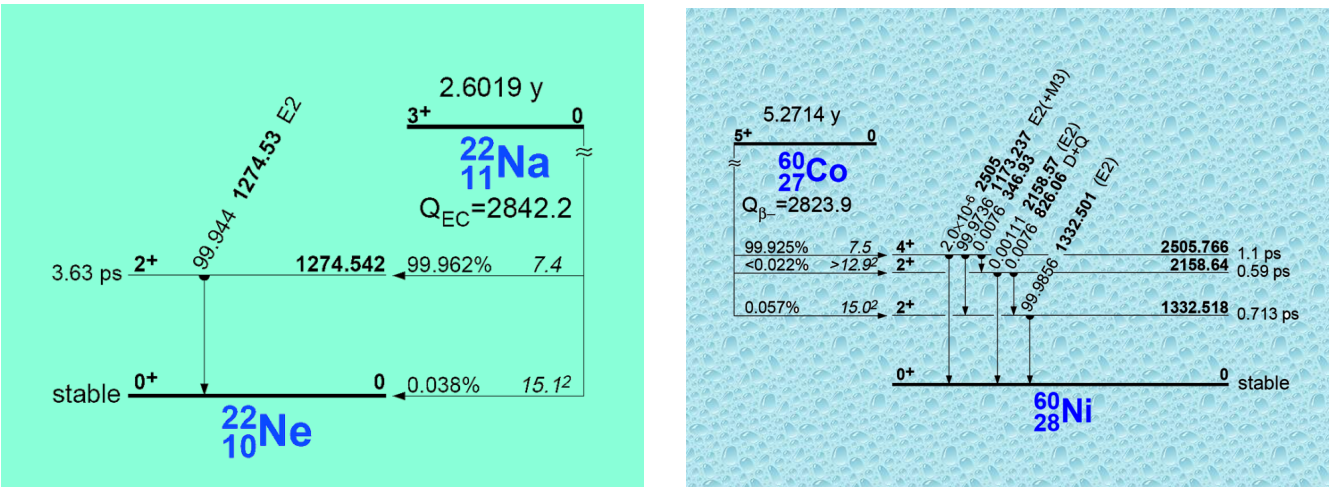


Figure 5: Decay scheme of ^{22}Na and ^{60}Co from [7].

D. Discussion of Results

1. Plot all time and energy spectra.
2. Provide a plot of the energy spectrum and explain it.
3. Provide a plot of the calibration curve.
4. Plot the centroid shift of the time spectra as function of distance.
5. Determine the 'standard' time resolution of the overall system (with plot).
6. Compute the speed of light.
7. Compute the errors associated with the experiment.

E. Example Questions

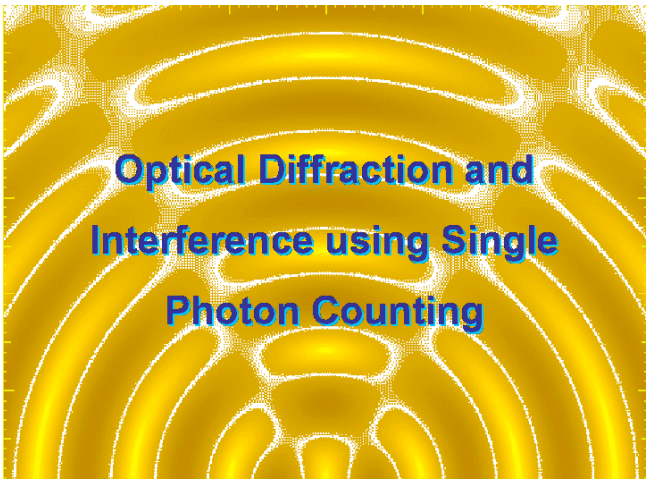
- Which methods to determine the speed of light do you know?
- Is the improvement of a speed of light experiment still required?
- What do we learn from a measurement using γ-rays?
- Is the use of annihilation radiation important or could the experiment also be performed using a cobalt-60 source?

- What is the detection efficiency of a coincidence experiment?
- Which relation is valid in this experiment for the efficiency?
- How can we get better time resolution?
- How is the time calibration performed?
- What makes a scintillator fast? What makes a photomultiplier fast?

Appendix: Some History about the Speed of Light

Year	Scientist	Method	Speed of Light in km/s	Remarks
about 1620	Galileo Galilei	time delay observing lanterns covered or uncovered by hand	at least several km/s	
1676 - 1678	Ole Rømer	time delays at astronomical observations (moons of Jupiter)	213,000	Proof for finite speed of light
1728	James Bradley	Aberration	301,000	Measurement of constancy of speed of light to 1%
about 1775	?	Venus-Transit 1769	etwa 285,000	First precise determination of AE
1834	Charles Wheatstone	Rotating Mirror Method for measurement of speed of electric current	402,336	El. current in conductor
1838	François Arago	Proposal of the Rotating Mirror Method	-	No measurement
1849	Armand H. L. Fizeau	Toothed wheel method	315,000	
1851	Léon Foucault	Rotating Mirror Method	$298{,}000 \pm 500$	
1875	Alfred Cornu	Rotating Mirror Method	299,990	
1879	Albert A. Michelson	Rotating Mirror Method	$299{,}910 \pm 50$	
1888	Heinrich Hertz	Frequency and wavelength measurement on standing radio waves	about 300,000	Proof that light is an electromagnetic wave
1907	Edward Bennett Rosa, Noah Dorsay	theoretical calculation according to Maxwell equations	$299{,}788 \pm 30$	
1926	Albert A. Michelson	Rotating Mirror Method	$299{,}796 \pm 4.$	
1947	Louis Essen, Albert Gordon-Smith	electric micro wave resonator	$299{,}792 \pm 3$	
1958	Keith Davy Froome	Interferometer	$299{,}792.5 \pm 0.1$	
1973	Boulder-Group at NBS	Laser measurement	$299{,}792.4574 \pm 0.001$	
1983	(Definition of the CGPM)	New Definition of the Meter	299,792.458 (exact)	No measurement
about 2005	Grayfox, Internet	chocolate bar - microwave method	298,900	Quick and simple method, accuracy 1%

3 Optical Diffraction and Interference using Single Photon Counting



Location: room Jordan 305

A. Short Description

In this experiment the wave and quantum properties of light can be studied and measured with high precision and within many aspects. The often complicated diffraction and interference patterns can be measured quantitatively and the results compared with theory. Effects of single-, double-, multiple slits, gratings, razor blade, disks and balls are measured in a wide dynamic range of up to 1 : 10 000 using single photon counting as the detection technique. A linear motion fine stepper motor allows scanning of the patterns within a precision of a few microns. A 50 μm optical fiber is used to transmit the light from the plane where the effects are displayed to the single photon detector, a fast and very sensitive photomultiplier. The effects can be stored, displayed and evaluated on a computer. The use of single photon counting takes into account the quantum nature of light.

B. Some history

C. Necessary Knowledge

Physics :

- Diffraction of light
- Huygens principle
- Fraunhofer and Fresnel diffraction
- Wave-particle dualism, Heisenberg uncertainty principle
- Interference patterns

- Diffraction and interference behind various objects: slits, double, multiple, grating, razor blade
- The so-called Poisson point

Measuring Technique :

- Basic optical set-ups
- Single photon counting technique
- Physics and technics of basic lasers
- Beam expander and spatial filter
- Technique of micro-stepper motors and linear motion stages
- Fast counting electronics and multiscaler technique
- Photomultipliers

Mathematics : Method of least squares, MATHEMATICA program, MAPLE program, MATHCAD program

References

[1]	**Melissinos, A. C. and Napolitano J.:** Experiments in Modern Physics Academic Press, Amsterdam etc. 2003	Textbook on Modern Physics Experiments
[2]	**Hecht, E. :** Optics Addison-Wesley Publ. Comp. Reading, Amsterdam Tokyo etc. 1987	Fundamental optics textbook

Experimental Tasks

- Get familiar with principal optical set-ups, aligning, adjusting
- Adhere to laser safety rules
- Start with the preparation of the light source and alignment for a single and a double slit, the light beam must be very parallel and "clean"
- The diffraction and interference pattern must be clearly visible on the paper screen.
- Align the slit vertically so that the end of the optical fiber (core) stays at the center of the pattern during the whole scan; the slit can also be rotated to achieve this
- Prepare the photon counter; HV = - 2000 Volts; threshold for pulses set at -50 mV (check values); software selectable

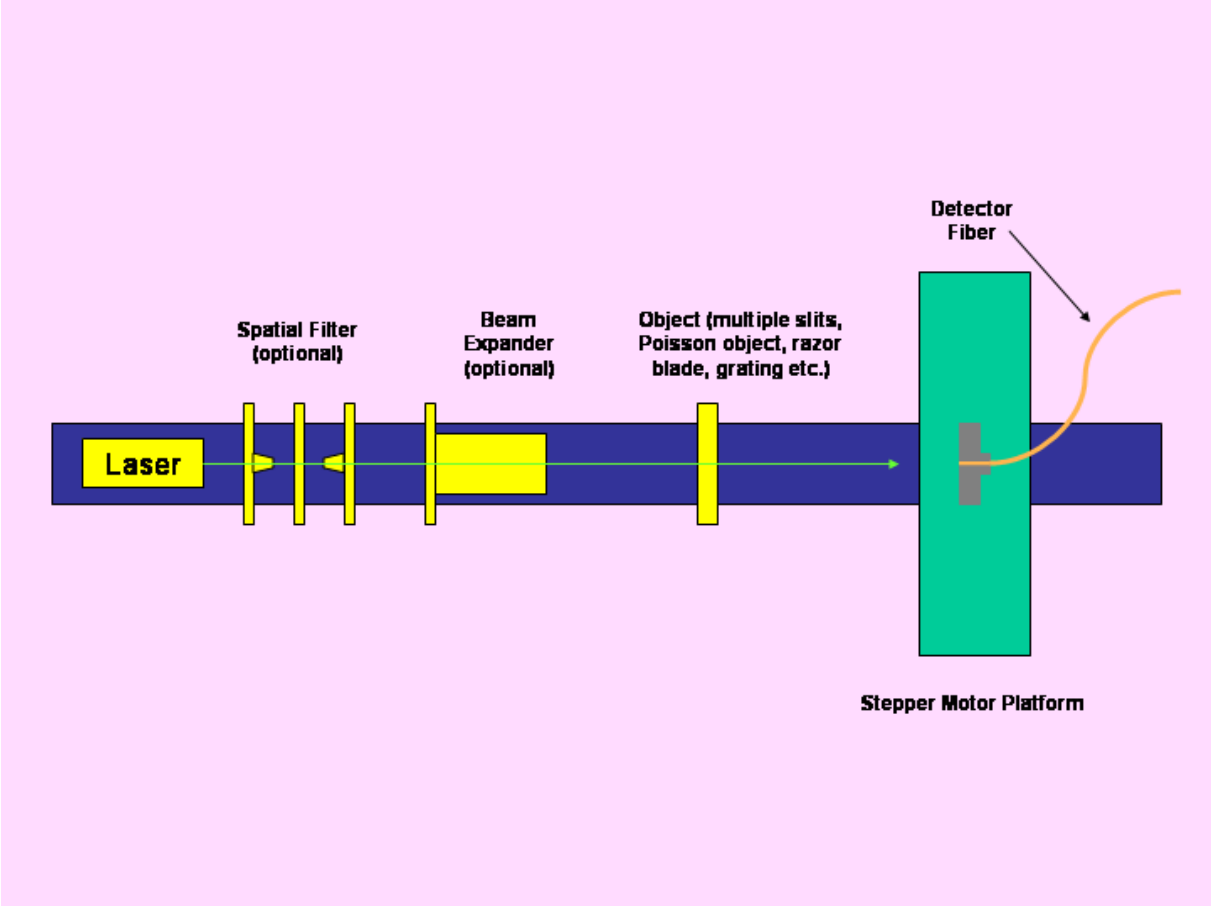
- Get familiar with the two programs for scanning (ORTEC multiscaler and LINOS stepper drive)
- Take several scans, duration about 10 – 30 min each
- Compare at least one pattern with theory quantitatively, the slit widths and distance are fit-parameters
- Produce diffraction patterns using the green and the red laser and compare both results
- Produce diffraction patterns of a razor blade and a round disk
- Get a clear scan of the so-called Poisson point alternatively the razor blade
- Proper graphical documentation of all scans and calculations

WARNINGS

- Wear laser safety glasses when laser is on
- Switch off lasers when experiment is finished
- Shut down high voltage of the photomultiplier

D. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

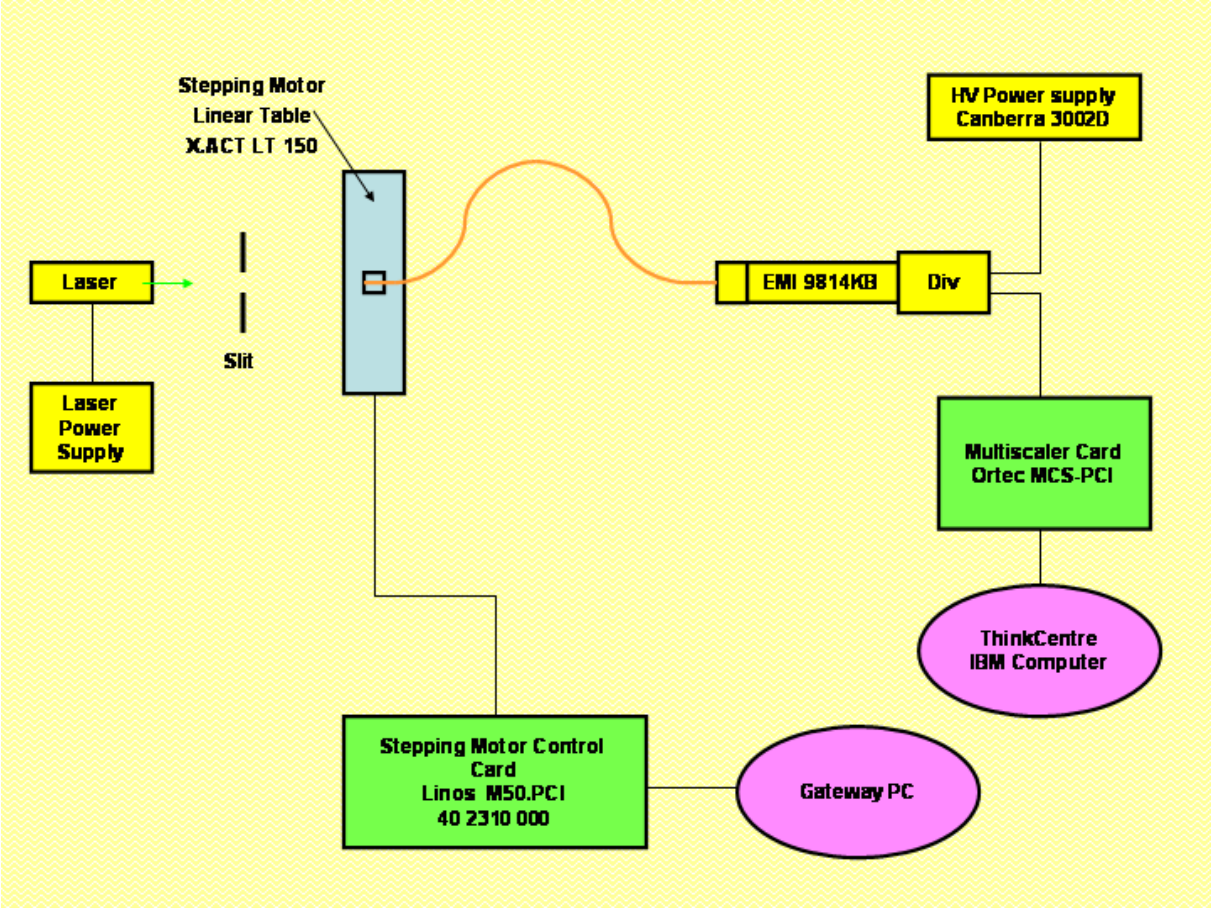
Laser :	3 Lasers available: 1) red diode laser with output 10mW; 2) green diode laser 10? mW with adjustable output power and 3) a green HeNe-Laser with 0.5mW output
Beam :	Preparation of light beam by means of a spatial filter (optional) or a beam expander (10x or 20x) or both of them
Object :	Various elements available: single slits, double slits, multiple slits, optical grating, razor blade, round disks, balls, different holes
HV :	High voltage power supply for the detectors, Canberra # 3002D

Detector : Single photon detector with a fast photomultiplier: Electron Tubes (former EMI Company) # 9814KB, assembly home-made with a light diffusor, active voltage divider Electron Tubes # TB1106-01, quick connector to optical fiber

Fiber : Optical fiber to transmit light from the field to the counter, 50 μm cross section with optical plugs

Stepper : Stepper motor driven linear table LINOS # XACT LT 150; max. path length 150mm, resolution 2μm, with program control and control board LINOS # 150.PCI in a standard PC, software

Multiscaler : Ortec multiscaler card with input discriminator Ortec # MCS.PCI in a standard PC, software



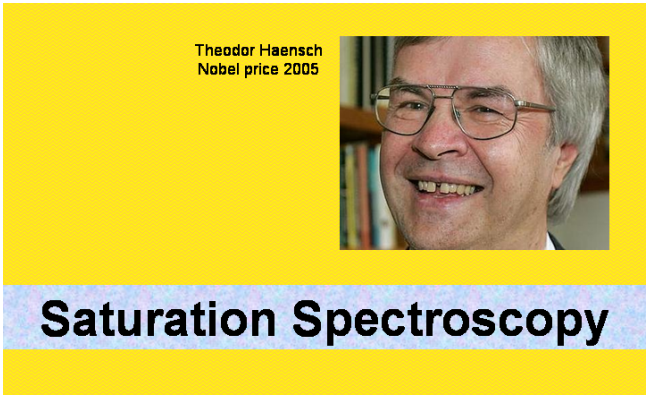
E. Discussion of Results

- Provide plots of all measurements with logarithmic intensity scale. Explain the observed patterns.
- Describe at least two patterns mathematically: a double slit pattern and the razor blade or the Poisson point pattern. Compare the graphs using different colors and use i.e. the 'MATHEMATICA' program.
- For the double slit the slit width and the distance of both slits can be used as parameters to obtain a better fit and to determine those two values from the experiment.

F. Example Questions

- What is Fraunhofer diffraction?
- What is Fresnel diffraction?
- How does interference take place?
- Is there a difference between diffraction and interference?
- How does particle/wave dualism come into play?
- Which typical patterns do we observe?
- What story is behind the "Poisson point"?
- Compare diffraction from a disk with that of a hole of the same diameter, which effects are expected, explain.
- Why do we apply single photon counting, several reasons?
- How does the beam expander work, what are the benefits?
- How does a spatial filter work?
- How does single photon counting technique work?
- Explain the multiscaler technique?
- Explain the function of a grating?

4 Saturation Spectroscopy



Location: room Jordan 305

A. Short Description

Saturation spectroscopy is a kind of high resolution spectroscopy free of Doppler broadening of lines, similar to the Mößbauer-effect. It became available with the development of tunable lasers. A monochromatic and tunable laser beam is absorbed in the vapor of a species in the region of a strong line from the ground to the excited state. If one monitors the transmitted light as a function of frequency, a Doppler broadened absorption spectrum will be observed. If one splits the laser beam into a strong and a weak one, coming from opposite directions one observes Doppler free absorption because only excited atoms with no velocity component in either direction can interact, the others don't match in frequency because of the opposite Doppler shift. The sharp absorption lines have nearly the natural line width and are sometimes called Lamb dip. When the level scheme shows narrow level splittings as from the hyperfine interaction the so-called crossover lines can occur which are explained below. Saturation spectroscopy can be easily observed in rubidium, cesium and sodium and it is used to lock lasers to a narrow frequency.
Lit.: K.B. Mac Adam, A Steinbach, and C. Wiemann, Am. J. Phys. 60, 1098 (1992)

B. Notes on the rubidium hfs spectrum

Natural rubidium has two isotopes ^{85}Rb with nuclear spin I = $\frac{5}{2}$ (abundance 72 %) and ^{87}Rb with I = $\frac{3}{2}$. It is an alkali metal (Z = 37) with one single valence electron (5s) above a closed krypton shell (n = 1,2,3 fully filled, $4s^2 4p^6$).
The nuclear spin causes splitting of the ground states ($^1S_{\frac{1}{2}}$) and excited states $^2P_{\frac{1}{2}}$ and $^2P_{\frac{3}{2}}$ which

is shown in the next diagram. The hyperfine splitting is characterized by quantum numbers F.
For ^{85}Rb the groundstate splits in two levels with F = 2 and 3 and 4 levels in the $^5P_{\frac{3}{2}}$ - state (F = 1.....4).
The so-called D2-line at 780.23 nm is split into 3 components because of the selection rule $\Delta F = 0, \pm 1$ for dipole transitions. In fact one observes 3 more lines the so-called cross-over-lines.
For ^{87}Rb the splittings are larger and better visible, the groundstate splits into a F = 1 and F = 2 level, the $^5P_{\frac{3}{2}}$ - state into 4 levels (F = 1.....4).
The regular Doppler broadening covers all hfs levels and one observes only *one* broad absorption line.
Switching on the pump beam one can observe all partners of the multiplet. Using two absorption beams, a probe beam with saturation and a reference beam with non-saturated Doppler broadened absorption on two detectors which are delivering currents with opposite sign one cancels out the regular absorption and slopes and gets as a difference signal the sharp dip lines.

Cross over lines

One can define for all atoms in the probe different velocity classes or bins according to the movement of the atoms. The Doppler shift of an atom with velocity $v_{|alpha}$ is then ν_α and the laser frequency is ν_L. An excited state of this velocity class has frequency ν_1

$$\nu_1 = \nu_L + \nu_\alpha$$

But for the probe beam the frequency for the same class of atoms is

$$\nu_2 = \nu_L - \nu_\alpha$$

If this frequency happens to correspond to another atomic transition ν_2 then the absorption will again be saturated.
The condition is:

$$\nu_2 = \nu_L - \nu_\alpha \qquad \rightarrow \qquad \nu_L = (\nu_1 + \nu_2)/2$$

One obtains frequencies exact in the middle from two multiplet levels, the "cross-over frequencies". For ^{87}Rb for example one obtains for F = 2 $\rightarrow$ F' six lines : ν_1, ν_{12}, ν_2, ν_{13}, ν_{23}, ν_3 and their frequencies can be determined in our experiment as well as for the other 3 transitions.

C. Necessary Knowledge

Physics :
- Physics of tunable lasers
- Absorption spectroscopy, Doppler broadening

- Rubidium absorption spectroscopy
- Doppler-free spectroscopy
- Lamb dip
- Hyperfine interaction
- Physics of atomic clocks

Measuring Technique :

- Elements of an optical absorption set-up
- Mirrors, beam splitters, filters, positioning and aligning elements (optomechanics)
- Photodiodes
- Fabry-Perot wavelength determination
- Temperature stabilization and compensation of laser diodes
- Lock-in signal technique
- Oscilloscope techniques

Mathematics : Method of least squares

References

[1]	**Haensch, T.W., M.D. Levenson and A.L. Schawlow:** Complete Hyperfine Structure of a Molecular Iodine Line Phys. Rev. Lett. **26**, 946 (1971)	Original article explaining the method on the example iodine
[2]	**Haensch, I.S. Shahin and A.L. Schawlow:** ..... Phys. Rev. Lett. **27**, 707 (1971)	Original article
[3]	**Pappas, P.G., M.M. Burns, D.D. Hinshelwood, M.S. Feld and D.E. Murnick:** Saturation spectroscopy with laser optical pumping in atomic barium Phys. Rev. **A 21**, 1955 (1980)	Theoretical treatment of optical pumping Lamb dips and cross over resonances
[4]	**Letokhov, V.S. :** Saturation Spectroscopy Topics in Applied Physics Vol. 13, ed. K. Shimoda, Springer Verlag, New York 1976	High Resolution Laser Spectroscopy
[5]	**Demtröder, W. :** Laser Spectroscopy Springer Verlag, New York, 3^{rd} ed., 2003	Textbook on Laser Spectroscopy
[6]	**Camparo, J.C.:** The Diode Laser in Atomic Physics Contemp. Phys. **26**, 443 (1985)	Basic review article on Diode Lasers
[7]	**Melissinos, A. C. and Napolitano J.:** Experiments in Modern Physics Academic Press, Amsterdam etc. 2003	Textbook on Modern Physics Experiments

[8] **THORLABS catalogue, Volume 18, 964 pages:** Thorlabs Inc., North Newton, NJ 07860, USA
www.thorlabs.com optical components of nearly any kind

Experimental Tasks

- Set-up of the optical path using alignment aids
- Adjust the power in the different beams

WARNINGS

- Wear laser safety glasses when laser is on

D. Information Regarding the Experimental Setup

Some hints for the set up:

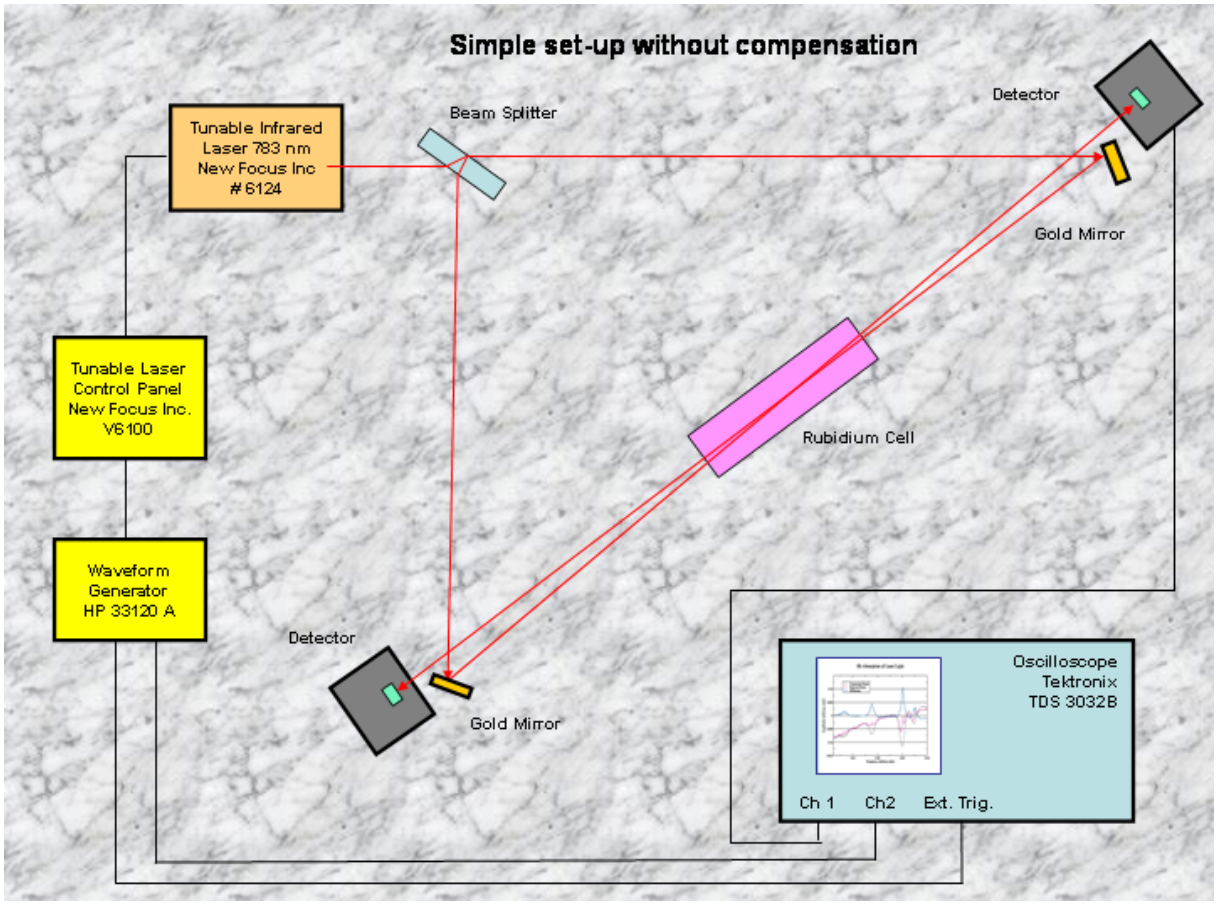
- The light paths should be set up according to the second scheme. The IR-light can only be seen by using the fluorescence card or an image intensifier. All beams should be horizontal in the same plane.
- To achieve the saturation effect well, a certain beam power has to be set in the different light paths by using adjustable grey filters, otherwise the lines are broadening.
- Some settings are important:
  The laser should be at 25 °C and needs several hours to stabilize. Laser beam output power should be about 20 mW (use the extra power meter !). The frequency of the laser can be fine-tuned with the Helipot at the left side (about 350 units) to bring it into the middle of the tuned region. The laser frequency is tuned by a triangular and symmetric ramp from the function generator. The repetition frequency should not be too high (stress for the laser mechanics), about 20-30 Hz is appropriate. The amplitude of the ramp defines the tuning range of the laser frequency; 220 mV is an appropriate value to cover two of the rubidium resonances and about 1400 mV to see all four rubidium absorption lines, but with reduced resolution. With about 120 mV one can observe one multiplet with high resolution. Store a single scan in the Tektronix scope to obtain a sharp track.
- The second thick beam splitter achieves 3 beams:
  1. the test beam which should produce the saturation effect (set to about 85 μW)
  2. the reference beam (set also to about 100 μW) which doesn'Št undergo saturation but

shows the same absorption, Doppler- and ramp effect. It is used to compensate the test beam. Without beam 3 the beams 1 and 2 should cancel out using the two detectors which are summed with opposite signs.
3. The beam which produces the saturation effect in beam 1 and it should have as much as possible overlap with beam 1 in the Rb vapor cell. Its power needs to be higher (about 1.5 mW before the mirror and 0.7 mW after the mirror).

- The first beam splitter splits the main laser beam in a beam for the saturation effect (power after the splitter 8.5 mW) and a beam for the wavelength measurement (power 11.5 mW) in a Fabry Perot interferometer unit. But the wavelength measurement disturbs the saturation effect because a part of the beam is reflected backwards and makes the main laser beam somewhat unstable. Therefore the wavelength determination has to be made separately. The distance between the interference peaks is exactly tuned to 8 GHz and is used to calibrate the frequency axis.

Schematic Drawing, Block Diagram

One can obtain the effect already with a rather simple set-up shown below, but with a curved base-line.

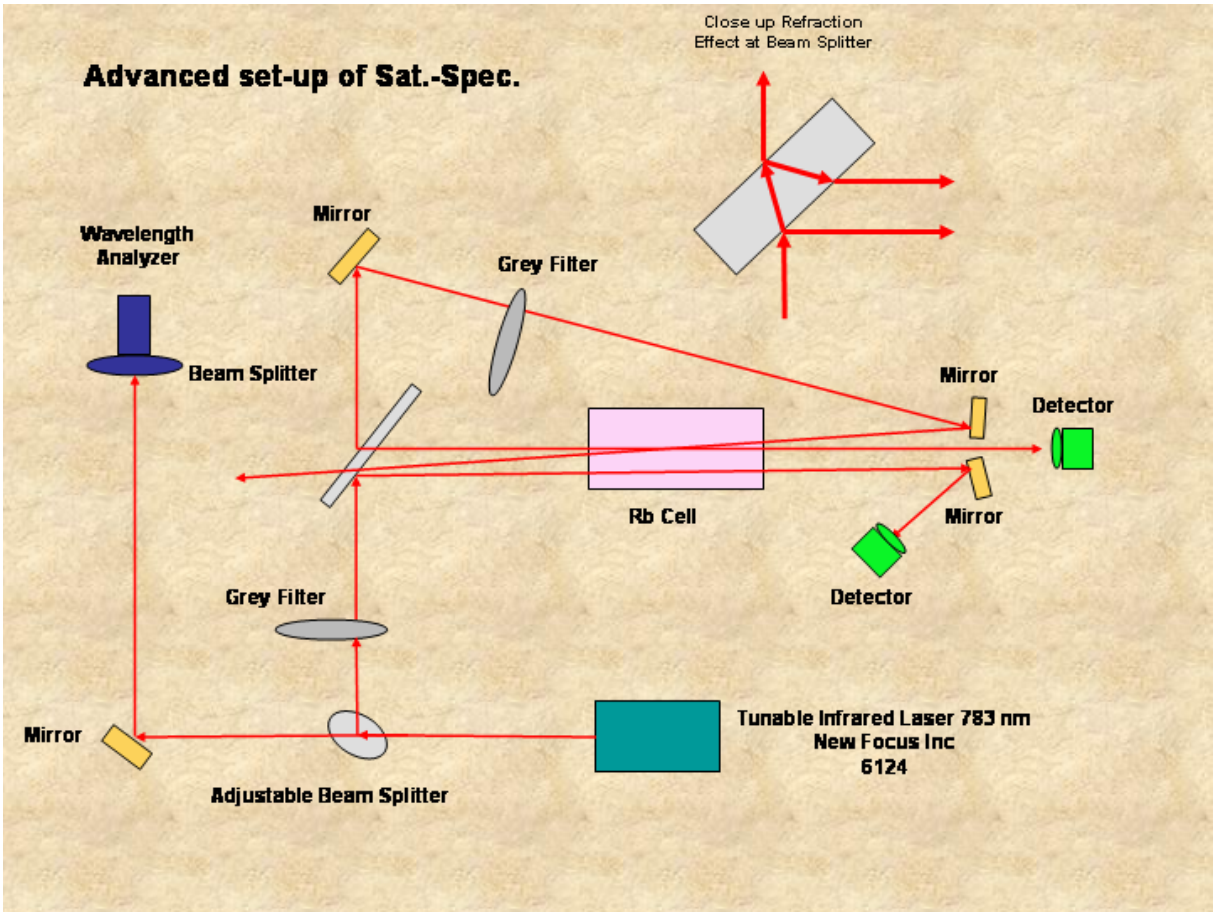


Legend:

Laser :	Tunable infrared laser 783 nm, New Focus Inc. Mod. 6124
Control :	Tunable laser control, New Focus Inc. Mod. V 6100, temperature and output power control for the laser, laser frequency remote control (ramp)
WaveGen :	Waveform Generator, Hewlett Packard Mod. HP 33120 A, provides the ramp for the frequency sweep of the laser
Oscill. :	Two beam digital oscilloscope, 300 MHz, Tektronix Mod. TDS 3032 B
Rb-cell :	Cylindrical glass cell filled with rubidium-vapor, length 75.0 mm, diameter 25.0 mm, pressure (20 °C) $> 10^{-7}$ mbar,

	windows Borofloat glass, flat, 3mm thick
Mirrors :	Gold coated mirrors on an optomechanical mount, 3 degrees of motion freedom, good for IR radiation
Splitter :	Simple beam splitters, thickness defines the separation of beams (see scheme)
Si-diodes :	IR sensitive photodiodes to measure light intensity, working with or without bias voltage

Advanced set-up for saturation spectroscopy with compensation of background to obtain clear net-spectra, free of background.

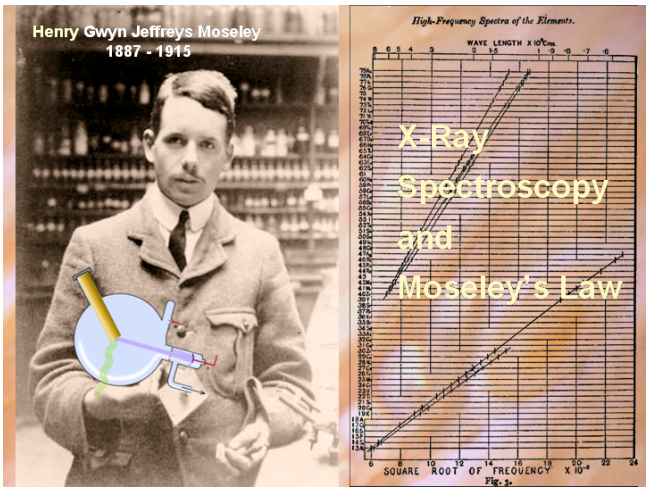


Legend:

Laser-etc. :	Laser+controller, Rb-cell, mirrors, waveform generator, silicon-diodes, oscilloscope are the same as in the simple set-up (see scheme of simple set-up)

Grey-filter :	Adjustable grey filters to set the necessary beam intensity
WaveAna :	Wavelength analyzer from Burleigh, Fabry-Perot principle, and wavelength analyzer controller, Burleigh

5 X-Ray-Spectroscopy and Moseley's Law



Location: room Jordan 305

A. Short Description

X-ray spectroscopy can be used to study inner shell phenomena of atoms, states of highly ionized atoms produced by accelerators or to determine material properties. There are two principal methods : Using a semiconductor detector or a Bragg-type spectrometer (see expt. Nr. 17). Semiconductor detectors are advantageous as they are simple, portable and yield sufficient resolution to distinguish adjacent elements. They have a good intrinsic efficiency, and an acceptable energy resolution in the range of a few percent, conversely the Bragg method yields much higher resolution, but very poor detection efficiency. In our experiment a high resolution silicon detector is used to measure the K-lines (or also L-lines) of several elements to verify Moseley's law. The excitation of inner shell vacancies is performed by using the 59.5 keV γ-line of a strong ^{241}Am source (best range $30 < Z < 65$), or by using a small special X-ray tube with a rhodium anode which has its maximum of emission near 10 keV. The second method is preferable for lower Z elements ($10 < Z < 30$). By observing the characteristic L - lines, one gets access to the elements with Z up to 92, but the L–spectra yield more lines, and are more complicated. Moseley's relation has a broad field of application in material analysis — see experiment Nr. 18.

Remarks

Henry Gwyn Jeffreys Moseley (November 23, 1887 – August 10, 1915) was an English physicist and a graduate of Trinity College Oxford. His main contributions to science were the quantitative justification of the previously empirical concept of atomic number, and Moseley's law.

This law advanced chemistry by immediately sorting the elements of the periodic table in a more logical order. Moseley could predict the existence of several then-unknown elements. Moseley's law also advanced basic physics by providing independent support for the Bohr model of the Rutherford/Antonius Van den Broek nuclear atom, containing positive nuclear charge equal to atomic number.

As Niels Bohr once said in 1962, "You see actually the Rutherford work [the nuclear atom] was not taken seriously. We cannot understand today, but it was not taken seriously at all. There was no mention of it any place. The great change came from Moseley."

Moseley fought at Gallipoli, Turkey, where he was killed in action by a sniper in 1915, shot through the head while in the act of telephoning an order. Many speculated that he should have won the Nobel Prize, but was unable to because it is only awarded to the living. It is speculated that because of Moseley's death in the war, the British and other world governments began a policy of no longer allowing their scientists to enlist for combat.

B. Moseley's Formulae

Moseley's formulae for K-alpha and L-alpha lines, in his original semi-Rydberg style notion (squaring both sides for clarity) :

$$f(K_\alpha) = (3.29 \times 10^{15}) \cdot \frac{3}{4} \cdot (Z - 1)^2 \qquad Hz$$

$$f(L_\alpha) = (3.29 \times 10^{15}) \cdot \frac{5}{36} \cdot (Z - 7.4)^2 \qquad Hz$$

the simple notation of Moseley's law being :

$$\sqrt{f} = k_1 \cdot (Z - k_2).$$

Here f is the frequency of the main or K-X-ray emission line, and k_1 and k_2 are constants that depend on the type of line, k_1 is given in units of the fundamental Rydberg frequency f_{Ry} = (3.29×10^{15}), $k_1 = \frac{3}{4} = 1 - \frac{1}{4}$ for the K-alpha-lines and $k_1 = \frac{5}{36}$ for the L-alpha lines.
The constant k_2 describes the screening of the nuclear charge and it was obtained empirically to be 1 for the K-alpha transitions, and 7.4 for the L-alpha transitions.

C. Necessary Knowledge

Physics :

- Basic atomic physics of inner shells, concepts and terms, characteristic numbers, Roentgen fluorescence yield, bind-

ing energy in the shell model of the atom, Auger electron emission

- Production of X-rays
- Bremsstrahlung; Synchrotron radiation
- Characteristic X-rays, selection rules, K- and L-series
- Absorption and scattering of X-rays
- Applications of characteristic X-ray spectroscopy
- Some quantitative considerations

Measuring Technique :

- Principles of X-ray detectors, especially silicon detectors
- Classical method of X-ray wavelength determination
- Function of the specific ^{241}Am source
- Function of an X-ray tube
- Required electronic units and function
- Multichannel-Analyzer

Mathematics : Method of least squares, line separation, background subtraction

References

[1]	**Moseley H. G. J. :** Phil. Mag. **26**, 1024 (1913) and Phil. Mag. **27**, 703 (1914)	Original papers
[2]	**Deslattes, R.D., E.G. Kessler Jr., P Indelicato, L. de Billy, E. Lindroth and J. Anton :** X-ray transition energies : new approach to a comprehensive evaluation Re. Mod. Phys. **75**, 35 (2003)	Most recent review article on all X-ray transitions of the elements
[3]	**Jelen, Christian :** Moseley's Gesetz und Röntgen Spektroskopie Thesis of high school teachers, University of Stuttgart 2000	Original thesis on this teaching lab experiment

[4]	**Bergmann-Schäfer:** Experimentalphysik, Bd. IV, Teil 1, S. 129 ff Walter De Gruyter, Berlin, 1975	Basics of x-ray Radiation
[5]	**Firestone, R. B. :** Table of Isotopes Vol. II John Wiley & Sons, New York, 1996	Current reference on nuclear data
[6]	**Mayer-Rimini:** Ion Beam Handbook for Material Analysis Ch. 5	

Experimental Tasks

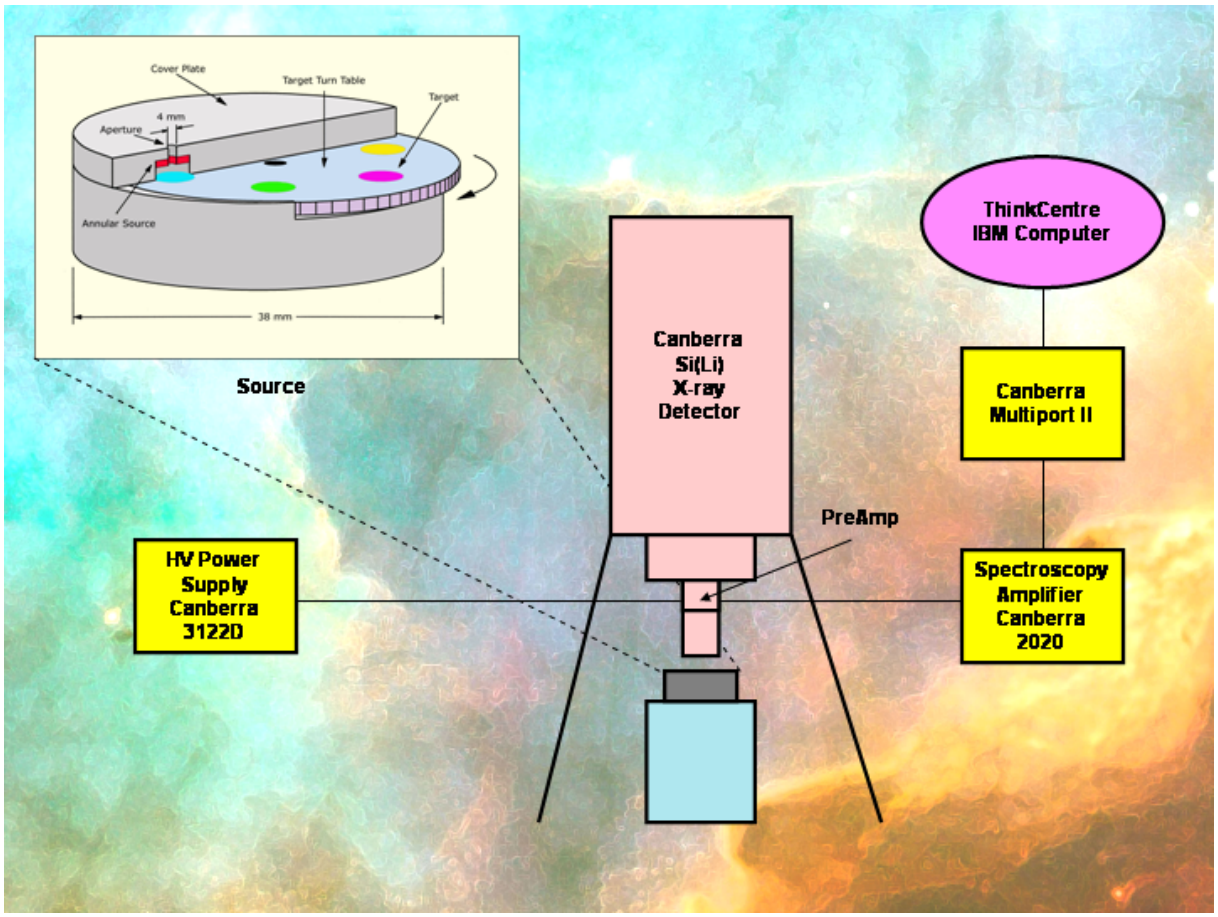
- Get the variable X-ray source from the TA
- Turn on first the NIM power, then turn on very slowly the high voltage bias of the detector (- 500 Volts) and watch the signals from the main amplifier. In case they are not regular stop and ask.
- Important: Check the main settings of the main amplifier to obtain good resolution. Time constant 2 - 3 μs should work best. Set amplification so that the 59.5 keV line of ^{241}Am has an amplitude of nearly 8 Volts.
- Set MCA to 2048 or 4096 channels (both channel select and conversion gain)
- Check pole zero cancellation very carefully with the oscilloscope
- Calibration of the detector using three lines Cu K_α, Ba K_α and 59.5 keV ^{241}Am line, you can also use the Cs-137 (36 keV X-ray), the Mn-54 (5.4 keV X-ray) and the Co-57 (14.4 keV γ-ray) source; measure the calibration spectrum with all lines at once, but keep the total count rate within reasonable limits (1 kHz)
- Determine detector resolution in keV for at least two lines (iron K_α and 122 keV line of ^{57}Co)
- Measure the K_α and K_β lines of the six elements of the variable source
- Verify Moseley's law with a graph and table (+ uncertainties)
- Determine 1 – 2 unknown samples (ask TA which ones)
- Alternative task: Measure several L-spectra for various elements and explain them
- In addition, you can determine more elements than six, which have appropriate K lines

WARNINGS

- Make sure that the detector was cold for 3 hours or more prior to HV application
- No HV without preamp power on! Internal FET can die!
- HV turn on and off very slowly. No abrupt switch off!
- Remove protection cap from detector before starting measuring
- Never touch the ultra thin Be window of the detector
- Watch count rates! Too high count rate can latch up preamp or deteriorate resolution
- Be careful with the ^{241}Am source, it is strong and under special regulations (transuranium element)
- No measurement of spectra during LN_2 filling

D. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

Detector :	Si(Li)–Semiconductor Detector Canberra EURISYS Mod. ESLX 30-150-ER No 0251 (year 2002) Crystal dimensions: useful surface 30 mm^2; external diameter 6.2 mm; length 5.5 mm; volume 0.15 cm^3; dead layer $\simeq$ 0.2 μm/Si; distance from cap 3 mm Energy resolution 150 eV at 5.9 keV
Bias :	Canberra bias voltage supply Canberra # 2122 D, neg. - 500 Volts
Preamp :	Preamplifier Canberra # PSC 854, "'reset" - type
SpecAmp :	Main spectroscopy amplifier CANBERRA # 2020, (important for "'reset" - type preamp)

MCA,ADC :	Canberra multiport II (ADC and MCA)
Computer :	Computer IBM think centre; CANBERRA MCA software Genie 2000 (dongle !)

The preamplifier works with a so-called optical feedback, which means that most of the time the feedback resistor is nearly infinite, but when the output signal reaches a certain amplitude, it is switched to a low value by a flash of a light emitting diode. The main amplifier has to deal with these strong negative switching signals and only a few have this property, the Canberra 2020 being one of them. The advantage is better resolution and higher count rates. The proper settings for pole zero cancellation and base line recovery are very important.

Gamma source for the excitation of characteristic X rays

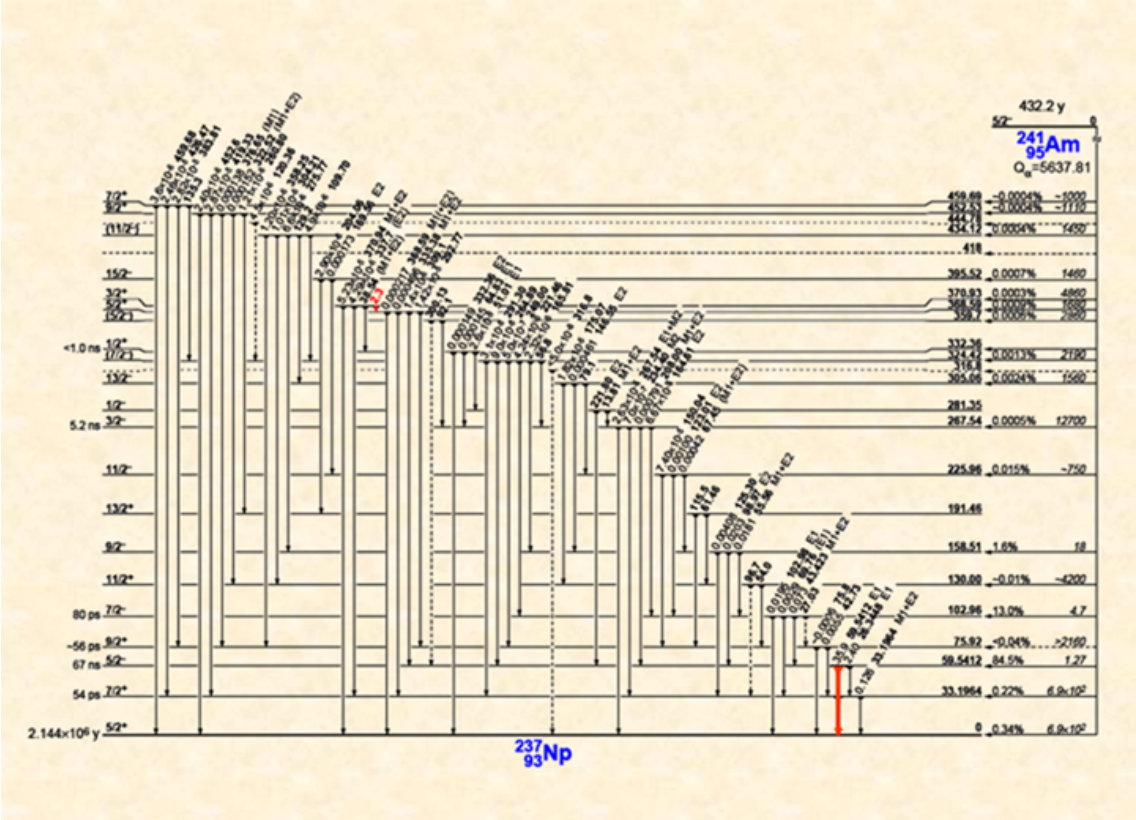


Figure 6: Decay scheme of ^{241}Am from [5].

In the block scheme the scheme of the so-called variable X-ray source is also given. The ^{241}Am source is encapsulated in ring form and radiates downwards onto samples of material. This americium-241 decay yields, besides α-particles, a strong 59.5 keV γ-transition which is used

for the excitation. The alphas cannot escape from the source which is shielded in the upwards direction by tungsten to prevent the direct beam of 59.5 keV radiation being 'seen' by the detector. The produced characteristic X-rays are emitted upwards through the opening of the ring and reach the detector. The source assembly includes a target revolver with six different samples covering the range 29 < Z < 65 (copper Cu, rubidium Rb, molybdenum Mo, silver Ag, barium Ba, terbium Tb). For other materials the source is disassembled carefully and set on top of material to be investigated.

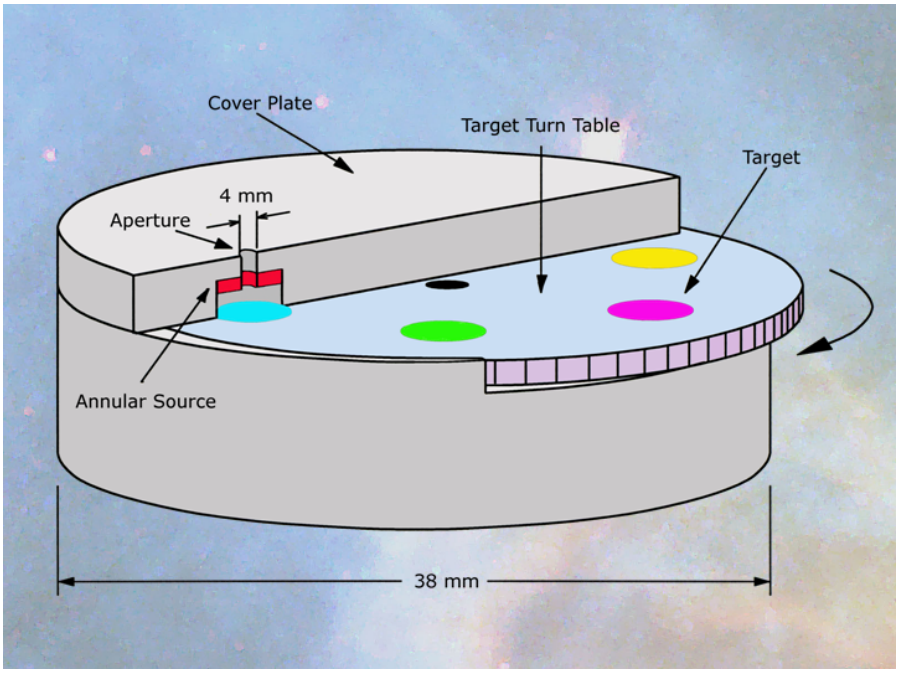


Figure 7: Variable X-ray source, an encapsulated ^{241}Am ring source radiating on six elementary targets (Cu, Rb, Mo, Ag, Ba, Tb) on a revolving disk to obtain characteristic X-rays for elements in the range 29 < Z < 65.

Calibration sources for energy calibration of the detector

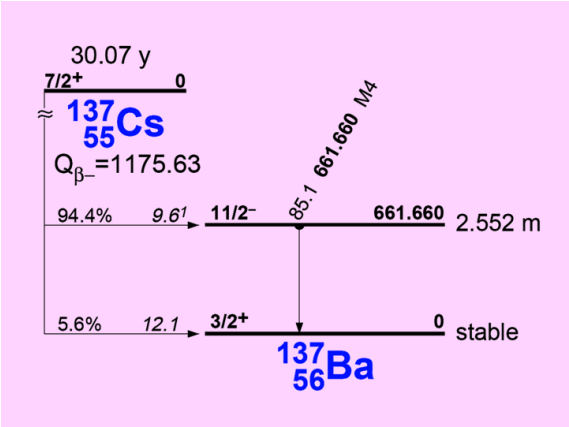
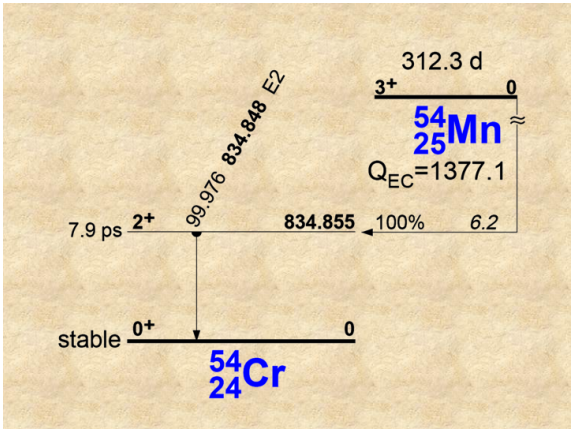


Figure 8: Decay scheme of ^{137}Cs from [5].



Decay scheme of ^{54}Mn from [5].

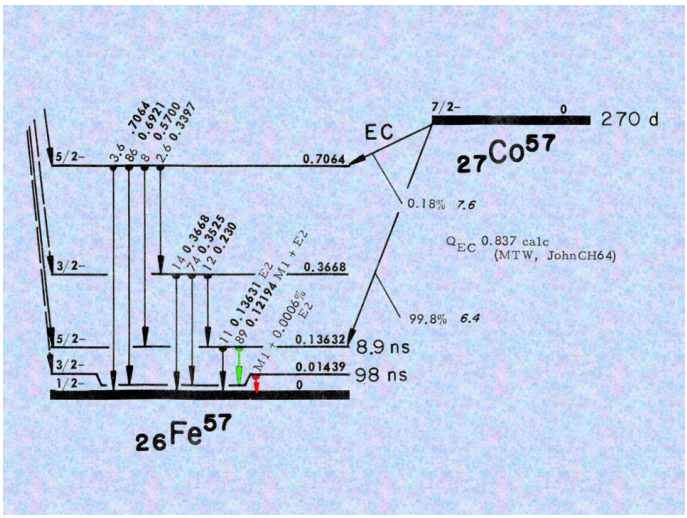


Figure 9: Decay scheme of ^{57}Co from [5].

The Cs-137 source delivers characteristic X rays of barium ($K_{\alpha_1} = 31.8$ keV, $K_{\beta_1} = 36.38$ keV), the Mn-54 source those of chromium ($K_{\alpha_1} = 5.4$ keV), and the Co-57 source those of iron ($K_{\alpha_1} = 6.4$ keV) in addition to the 14.4 keV Mößbauer-line.

X-ray tube for the excitation of characteristic X-rays

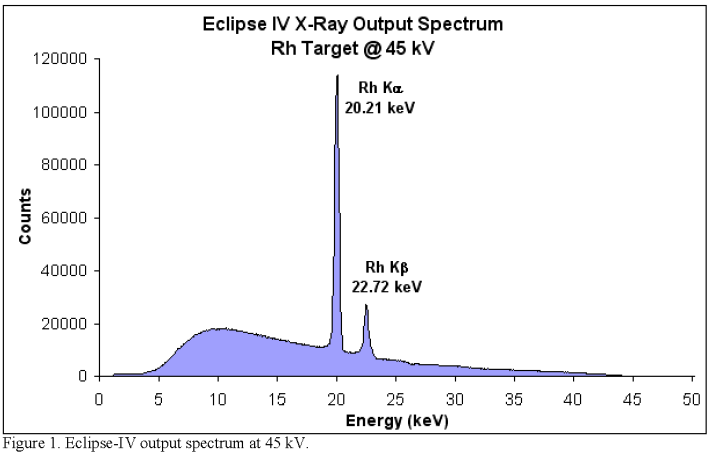


Figure 1. Eclipse-IV output spectrum at 45 kV.

Figure 10: X-ray tube Eclipse IV. Emission spectrum of an Eclipse IV tube.

The Eclipse IV X-ray tube from Oxford Instruments, resp. AmpTek is designed as a compact mobile X-ray source for material analysis. The maximum voltage applied is 45 kV, and it can be set in a range from 10 to 45 kV. The X-ray tube is pressurized under sulfur-hexafluoride to isolate the high voltage. The anode current can also be varied in the range $0 - 50\ \mu$A by varying the current through the tungsten cathode. The anode material is rhodium, the exit window is made from a beryllium foil and the tube is operating in transmission yielding the spectrum shown in Fig. 1b. Here the characteristic rhodium lines sit on a broad Bremsstrahlungs-spectrum ranging from about 4 to 40 keV. The radiation is emitted in a cone with an angle of 130 degrees, therefore a collimator is indispensable.

E. Data Tables on the Periodic System and X-ray transitions

Amptek Inc.
14 DeAngelo Drive
Bedford, MA 01730 USA
Tele: +1 781-275-2242 Fax: +1 781-275-3470
e-mail: sales@amptek.com
www.amptek.com

Amptek K and L Emission Line Lookup Chart

Key to Energy Values in keV

$K_{\alpha 1}$ $K_{\beta 1}$
Au
79
$L_{\alpha 1}$ $L_{\beta 1}$

XR-100CR / XR-100T-CdTe / GAMMA-8000 / X-123

X-Ray and Gamma Ray Detectors

Group IA	IIA	IIIB	IVB	VB	VIB	VIIB	Group VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
H 1																	He 2
0.052 Li 3	0.110 Be 4											0.185 B 5	0.282 C 6	0.392 N 7	0.526 O 8	0.677 F 9	0.851 Ne 10
1.04 1.07 Na 11	1.25 1.30 Mg 12											1.49 1.55 Al 13	1.74 1.83 Si 14	2.02 2.14 P 15	2.31 2.46 S 16	2.62 2.82 Cl 17	2.96 3.19 Ar 18
3.31 3.59 K 19	3.69 4.01 Ca 20 0.34	4.09 4.46 Sc 21 0.40	4.51 4.93 Ti 22 0.45 0.46	4.95 5.43 V 23 0.51 0.52	5.41 5.95 Cr 24 0.57 0.58	5.90 6.49 Mn 25 0.64 0.65	6.40 7.06 Fe 26 0.70 0.72	6.93 7.65 Co 27 0.78 0.79	7.48 8.26 Ni 28 0.85 0.87	8.05 8.90 Cu 29 0.93 0.95	8.64 9.57 Zn 30 1.01 1.03	9.25 10.26 Ga 31 1.10 1.12	9.89 10.98 Ge 32 1.19 1.21	10.54 11.73 As 33 1.28 1.32	11.22 12.50 Se 34 1.38 1.42	11.92 13.29 Br 35 1.48 1.53	12.65 14.11 Kr 36 1.59 1.64
13.39 14.96 Rb 37 1.69 1.75	14.16 15.83 Sr 38 1.81 1.87	14.96 16.74 Y 39 1.92 2.00	15.77 17.67 Zr 40 2.04 2.12	16.61 18.62 Nb 41 2.17 2.26	17.48 19.61 Mo 42 2.29 2.40	18.41 19.61 Tc 43 2.42 2.54	19.28 21.66 Ru 44 2.56 2.68	20.21 22.72 Rh 45 2.70 2.83	21.18 23.82 Pd 46 2.84 2.99	22.16 24.94 Ag 47 2.98 3.15	23.17 26.09 Cd 48 3.13 3.32	24.21 27.27 In 49 3.29 3.49	25.27 28.48 Sn 50 3.44 3.66	26.36 29.72 Sb 51 3.61 3.84	27.47 30.99 Te 52 3.77 4.03	28.61 32.29 I 53 3.94 4.22	29.80 33.64 Xe 54 4.11 4.42
30.97 34.98 Cs 55 4.29 4.62	32.19 36.38 Ba 56 4.47 4.83	57 - 71	55.76 63.21 Hf 72 7.90 9.02	57.52 65.21 Ta 73 8.15 9.34	59.31 67.23 W 74 8.40 9.67	61.13 69.30 Re 75 8.65 10.01	62.99 71.40 Os 76 8.91 10.35	64.89 73.55 Ir 77 9.19 10.71	66.82 75.74 Pt 78 9.44 11.07	68.79 77.97 Au 79 9.71 11.44	70.82 80.26 Hg 80 9.99 11.82	72.86 82.56 Tl 81 10.27 12.21	74.96 84.92 Pb 82 10.55 12.61	77.10 87.34 Bi 83 10.84 13.02	79.30 89.81 Po 84 11.13 13.44	81.53 92.32 At 85 11.42 13.87	83.80 94.88 Rn 86 11.72 14.32
86.12 97.48 Fr 87 12.03 14.77	88.46 100.14 Ra 88 12.34 15.23	90.89 102.85 Ac 89 12.65 15.71	93.33 105.59 Th 90 12.97 16.20	95.85 108.41 Pa 91 13.29 19.70	98.43 111.29 U 92 13.61 17.22	101.00 114.18 Np 93 13.95 17.74	103.65 117.15 Pu 94 14.28 18.28	106.35 120.16 Am 95 14.62 18.83	109.10 123.24 Cm 96 14.96 19.39	111.90 126.36 Bk 97 15.31 19.97	114.75 129.54 Cf 98 15.66 20.56	117.65 132.78 Es 99 16.02 21.17	120.60 136.08 Fm 100 16.38 21.79	Md 101	No 102	Lr 103	Actinides 89-103
Lanthanides 57-71		33.44 37.80 La 57 4.65 5.04	34.72 39.26 Ce 58 4.84 5.26	36.02 40.75 Pr 59 5.03 5.49	37.36 42.27 Nd 60 5.23 5.72	38.65 43.96 Pm 61 5.43 5.96	40.12 45.40 Sm 62 5.64 6.21	41.53 47.03 Eu 63 5.85 6.46	42.98 48.72 Gd 64 6.06 6.71	44.47 50.39 Tb 65 6.28 6.98	45.99 52.18 Dy 66 6.50 7.25	47.53 53.93 Ho 67 6.72 7.53	49.10 55.69 Er 68 6.95 7.81	50.73 57.58 Tm 69 7.18 8.10	52.36 59.35 Yb 70 7.41 8.40	54.06 61.28 Lu 71 7.65 8.71	

Actinium - Ac 89 (10.07)
Aluminum - Al 13 (2.70)
Americium - Am 95 (11.87)
Antimony - Sb 51 (6.62)
Argon - Ar 18 (0.001783)
Arsenic - As 33 (5.73)
Astatine - At 85
Barium - Ba 56 (3.5)
Berkelium - Bk 97
Beryllium - Be 4 (1.85)
Bismuth - Bi 83 (9.78)
Boron - B 5 (2.53)
Bromine - Br 35 (0.007139)
Cadmium - Cd 48 (8.65)
Calcium - Ca 20 (1.55)
Californium - Cf 98
Carbon - C 6 (2.25-G; 3.51-D)
Cerium - Ce 58 (6.90)
Cesium - Cs 55 (1.87)
Chlorine - Cl 17 (0.003220)
Chromium - Cr 24 (7.14)
Cobalt - Co 27 (8.71)
Copper - Cu 29 (8.96)
Curium - Cm 96
Dysprosium - Dy 66 (8.55)
Einsteinium - Es 99
Erbium - Er 68 (9.066)
Europium - Eu 63 (5.234)
Fermium - Fm 100
Fluorine - F 9 (0.00169)
Francium - Fr 87
Gadolinium - Gd 64 (7.90)
Gallium - Ga 31 (5.93)
Germanium - Ge 32 (5.46)
Gold - Au 79 (19.32)
Hafnium - Hf - 72 (13.3)
Helium - He 2 (0.0001785)
Holmium - Ho 67 (8.795)
Hydrogen - H 1 (0.0000899)
Indium - In 49 (7.28)
Iodine - I 53 (4.94)
Iridium - Ir 77 (22.42)
Iron - Fe 26 (7.88)
Krypton - Kr 36 (0.00368)
Lanthanum - La 57 (6.15)
Lawrencium - Lr 103
Lead - Pb 82 (11.34)
Lithium - Li 3 (0.534)
Lutetium - Lu 71 (9.84)
Magnesium - Mg 12 (1.74)
Manganese - Mn 25 (7.41)
Mendelevium - Md 101
Mercury - Hg 80 (13.55)
Molybdenum - Mo 42 (10.22)
Neodymium - Nd 60 (6.96)
Neon - Ne 10 (0.000900)
Neptunium - Np 93 (20.4)
Nickel - Ni 28 (8.88)
Niobium - Nb 41 (8.57)
Nitrogen - N 7 (0.001251)
Nobelium - No 102
Osmium - Os 76 (22.5)
Oxygen - O 8 (0.001429)
Palladium - Pd 46 (12.16)
Phosphorus - P 15 (1.83-Y 2.20-R)
Platinum - Pt 78 (21.45)
Plutonium - Pu 94 (19.8)
Polonium - Po 84 (9.27)
Potassium - K 19 (0.86)
Praseodymium - Pr 59 (6.48)
Promethium - Pm 61
Protactinium - Pa 91 (15.4)
Radium - Ra 88 (5.0)
Radon - Rn 86 (4.4)
Rhenium - Re 75 (21.0)
Rhodium - Rh 45 (12.44)
Rubidium - Rb 37 (1.53)
Ruthenium - Ru 44 (12.1)
Samarium - Sm 62 (7.75)
Scandium - Sc 21 (3.02)
Selenium - Se 34 (4.82)
Silicon - Si 14 (2.42)
Silver - Ag 47 (10.49)
Sodium - Na 11 (0.97)
Strontium - Sr 38 (2.56)
Sulphur - S 16 (1.92)
Tantalum - Ta 73 (16.6)
Technetium - Tc 43 (11.5)
Tellurium - Te 52 (6.25)
Terbium - Tb 65 (8.229)
Thallium - Tl 81 (11.86)
Thorium - Th 90 (11.3)
Thulium - Tm 69 (9.321)
Tin - Sn 50 (7.3)
Titanium - Ti 22 (4.5)
Tungsten - W 74 (19.3)
Uranium - U 92 (18.7)
Vanadium - V 23 (5.98)
Xenon - Xe 54 (0.00585)
Ytterbium - Yb 70 (6.965)
Yttrium - Y 39 (3.8)
Zinc - Zn 30 (7.1)
Zirconium - Zr 40 (6.4)

(density in g/cm^3 at NTP)

Figure 11: X-ray chart from Amptek.

Z	Element	$K_{\alpha 2}$	$K_{\alpha 1}$	$K_{\beta 1}$	$K_{\beta 2}$	ω_K
10	Ne	848.61	848.61	857.89		
11	Na	1040.98	1040.98	1071.12		
12	Mg	1253.437	1253.688	1302.20		
13	Al	1486.295	1486.708	1557.57		
14	Si	1739.394	1739.985	1835.96		
15	P	2012.70	2013.68*	2139.1		
16	S	2306.700	2307.885	2464.07		0.049
17	Cl	2620.846	2622.44	2815.60		0.065
18	Ar	2955.566	2957.682	3190.49		0.081
19	K	3311.1956	3313.948	3589.63		0.099
20	Ca	3688.128	3691.719	4012.76		0.120
21	Sc	4085.9526	4090.735	4460.44		0.143
22	Ti	4504.9201	4510.899	4931.827		0.170
23	V	4944.671	4952.216	5427.320		0.198
24	Cr	5405.5384	5414.805	5946.823		0.229
25	Mn	5887.6859	5898.8010	6490.585		0.261
26	Fe	6391.0264	6404.0062	7058.175		0.293
27	Co	6915.5380	6930.3780	7649.445		0.327
28	Ni	7461.0343	7478.2521	8264.775		0.359

Z	Element	$K_{\alpha 2}$	$K_{\alpha 1}$	$K_{\beta 1}$	$K_{\beta 2}$	ω_K
29	Cu	8027.8416	8047.8227	8905.413		0.393
30	Zn	8615.823	8638.906	9572.03	9658.05	0.43
31	Ga	9224.835	9251.674	10264.19	10366.42	0.46
32	Ge	9855.42	9886.52	10982.19	11100.97	0.49
33	As	10507.50	10543.2674	11725.73	11864.34	0.52
34	Se	11181.53	11222.52	12496.03	12652.29	0.55
35	Br	11877.75	11924.36	13291.56	13469.60	0.58
36	Kr	12595.424	12648.002	14112.815	14315.0	0.60
37	Rb	13335.88	13395.49	14961.42	15185.54	0.63
38	Sr	14098.03	14165.20	15835.89	16084.68	0.65
39	Y	14882.94	14958.54	16738.08	17015.6	0.67
40	Zr	15690.645	15774.914	17666.578	17970.3	0.70
41	Nb	16521.28	16615.16	18622.68	18952.9	0.71
42	Mo	17374.29	17479.372	19608.34	19965.27	0.73
43	Tc	18250.9*	18367.2*	20619.0*	21005.4*	0.75
44	Ru	19150.49	19279.16	21656.75	22074.3	0.77
45	Rh	20073.67	20216.12	22723.59	23173.0	0.78
46	Pd	21020.15	21177.08	23818.69	24299.4	0.79
47	Ag	21990.30	22162.917	24942.42	25456.71	0.80
48	Cd	22984.05	23173.98	26095.44	26644.07	0.82
49	In	24002.03	24209.75	27275.55	27861.20	0.83

Figure 12: Table of the X-ray K-series energies from NIST.

Z	Element	$K_{\alpha 2}$	$K_{\alpha 1}$	$K_{\beta 1}$	$K_{\beta 2}$	ω_K
50	Sn	25044.04	25271.36	28486.26	29109.64	0.84
51	Sb	26110.78	26358.86	29725.53	30389.84	0.85
52	Te	27201.99	27472.57	30995.97	31700.76	0.86
53	I	28317.52	28612.32	32295.05	33041.7	0.86
54	Xe	29458.250	29778.78	33624.23	34414.7*	0.87
55	Cs	30625.40	30973.13	34987.3	35821.7	0.88
56	Ba	31816.615	32193.262	36377.445	37257.7	0.88
57	La	33034.38	33442.12	37801.45	38730.3	0.89
58	Ce	34279.28	34720.00	39257.77	40233.1	0.89
59	Pr	35550.59	36026.71	40748.67	41774.4	0.90
60	Nd	36847.502	37360.739	4227.090	43335*	0.90
61	Pm	38171.55	38725.11	438255*	44937*	0.91
62	Sm	39523.39	40118.481	45413.0	46575	0.91
63	Eu	40902.33	41452.63	47038.4	48256.6	0.92
64	Gd	42309.30	42996.72	48696.9	49960.6	0.92
65	Tb	43744.62	44482.75	503829	51724*	0.92
66	Dy	45208.27	45998.94	52119.7	53510*	0.93
67	Ho	46699.98	47547.10	53877.1	55325*	0.93
68	Er	48221.61	49127.24	55673.52	57214*	0.93
69	Tm	49772.67	50741.475	57508.76	59095*	0.93
70	Yb	51354.60	52389.48	59367.1	60985*	0.94

Z	Element	$K_{\alpha 2}$	$K_{\alpha 1}$	$K_{\beta 1}$	$K_{\beta 2}$	ω_K
71	Lu	52965.57	54070.39	61283*	62967*	0.94
72	Hf	54612.0#	55790.8#	63234*	64980*	0.94
73	Ta	56277.6	57533.2	652233	670135#	0.94
74	W	57981.77	59318.847	67245.0	691013	0.94
75	Re	59718.57	61141.00	693103	71232.1	0.95
76	Os	61487.27	63001.07	714139	734032	0.95
77	Ir	63287.29	64896.2	73561.7	756193	0.95
78	Pt	651233	668329	75749.1	778783	0.95
79	Au	66990.73	68804.5	7797980	801862	0.95
80	Hg	68895.1	70819.5	802542	82545	0.95
81	Tl	708325	728725	825767	849485	0.95
82	Pb	72805.42	74970.11	84939.08	873669	0.96
83	Bi	74816.21	77109.2	87344.1	898618	0.96
84	Po	76864.4*	79292.9*	89797*	92400*	0.96
85	At	78944*	81514*	92304*	94991*	0.96
86	Rn	81066*	83783*	94867*	97639*	0.96
87	Fr	83232*	86105*	97478*	100326*	0.96
88	Ra	85436	88476	100136	103045	0.96
89	Ac	87676*	908848*	102847*	105868*	0.96
90	Th	89957.04	93347.38	105601.51	108718	0.96
91	Pa	92283.4	95866.4	108417.3	111625*	0.96
92	U-238	94650.84	98431.58	111295.08	114607#	0.96

Figure 13: Table of the X-ray K-series energies from NIST.

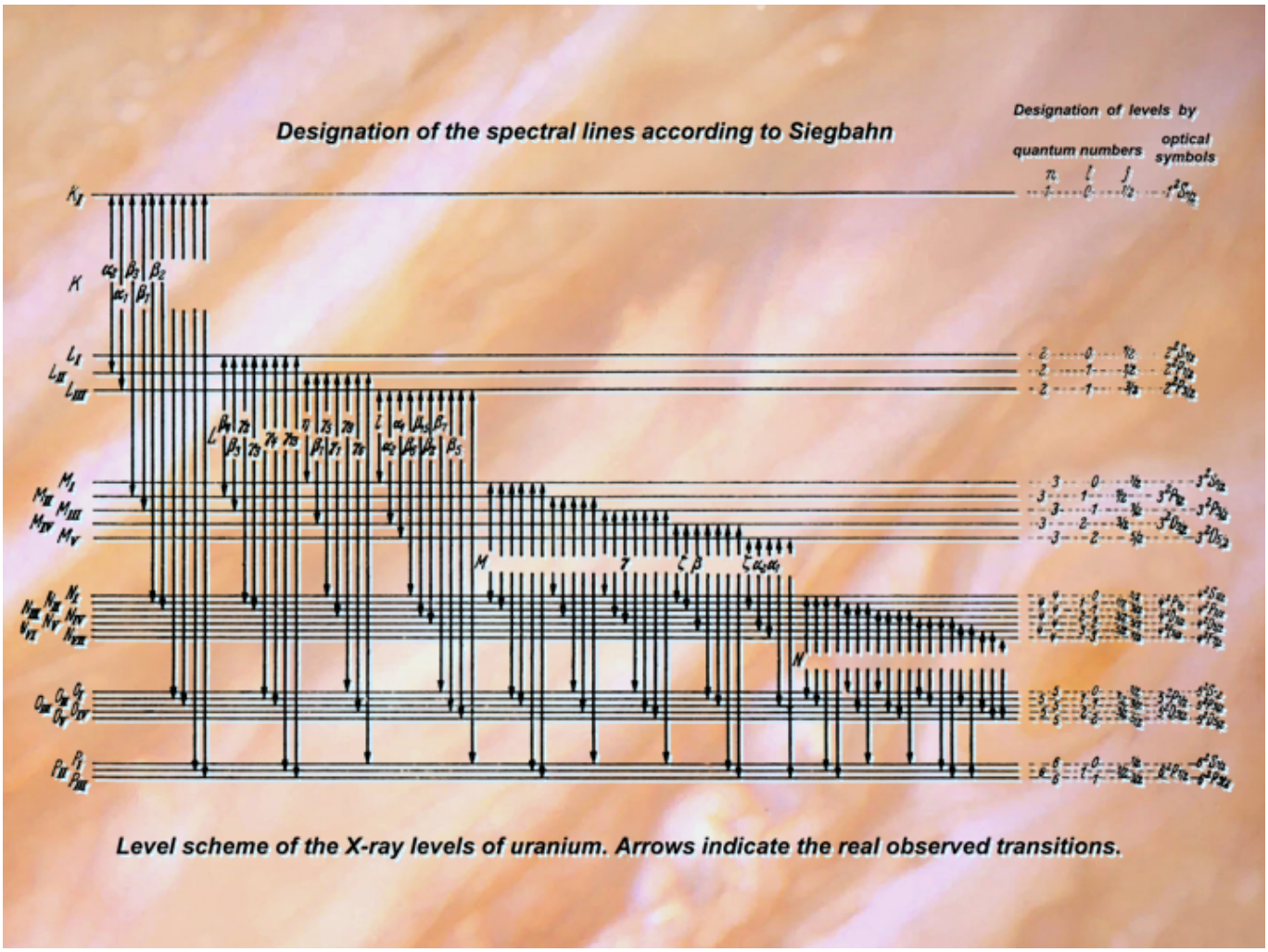


Figure 14: X-ray transitions for the L-series in uranium. The designation of the observed lines is according to Siegbahn.

Most intense L-X-ray lines of some heavy elements

Element Symbol (Z)	Tantalum Ta (73)	Tungsten W (74)	Platinum Pt (78)	Gold Au (79)	Mercury Hg (80)	Lead Pb (82)	Thorium Th (90)	Uranium U (92)
Line*	**Energies in electron-volts [eV]**							
α_1 (L_3M_5)	8146.17	8398.242	9442.39	9713.44	9988.91	10551.6	12967.937	13614.87
α_2 (L_3M_4)	8087.93	8335.34	9361.96	9628.05	9897.68	10449.59	12809.49	13438.97
β_1 (L_2M_4)	9343.19	9672.575	11070.84	11442.45	11822.7	12613.8	16201.556	17220.15
β_2 (L_3N_5)	9651.89	9964.133	11250.66	11584.75	11924.2	12622.8	16024.6	16428.44
β_3 (L_1M_3)	9487.62	9818.91	11230.89	11610.5	11995.4	12793.4	16423.855	17455.17
β_4 (L_1M_2)	9212.47	9525.23	10854.41	11204.81	11563.1	12305.9	15639.54	16575.51
γ_1 (L_2N_4)	10895	11286	12942	13381	139830	14764	18978	20167
γ_2 (L_1N_2)	11217	11610	13270	13709	14162.3	15218.2	19302	20484
γ_3 (L_1N_3)	11277.68	11680.49	13361.5	13809.1	14264.8	15218.2	19503	20712.95
γ_5 (L_2N_1)	10570	10948	12552	12974	13410	14307	18364	19506
l (L_3M_1)	7173.2	7387.8	8268.2	8494.03	8721.32	9184.56	11118.06	11618.41
η (L_2M_1)	8428.09	8724.42	9975.2	10308.41	10651.4	11349.4	14510.327	15399.81

* Siegbahn notation (modern notation)

F. Discussion of Results

1. Discuss the energy spectra of the ^{57}Co, ^{137}Cs, ^{54}Mn and ^{241}Am sources.
2. Construct the energy calibration.
3. Explain the energy spectra of the different elements.
4. Plot the energy of the X-rays as a function of nuclear charge number Z.
5. Plot the energy resolution as a function of energy.
6. Plot the detector response function as a function of energy.
7. Check Moseley's law and compute the shielding constants.

8. Identify the unknown materials based on Moseley's law.

9. Explain the obtained X-ray L-spectra

G. Example Questions

1. How are X-rays created?

2. What is the difference between X-rays and γ-rays?

3. What is the Auger effect?

4. What is a fluorescence yield ω_K?

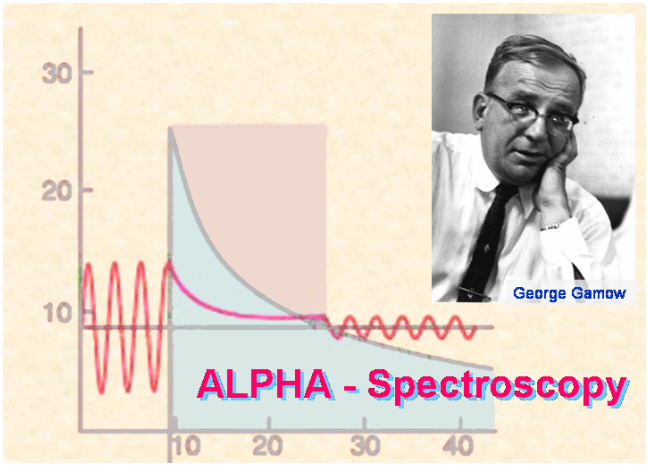
5. Explain Moseley's formula.

6. How is the material analysis performed?

7. Why does the silicon-detector have to be cooled?

8. Which other methods of X-ray spectroscopy are known?

6 Alpha Spectroscopy



Location: room Jordan 308

A. Short description

α-spectroscopy is related to the α-decay of nuclei which is described by the Gamow theory and the tunneling effect. These effects are also important for fusion reactions, for example in the nucleosynthesis of the chemical elements. Using a modern high resolution silicon detector (resolution 11 keV at about 5 MeV) one can explore the fine structure of specific α decays or determine the line energy of unknown samples. Through this the identity of the unknown nuclide can be determined. Furthermore the relative intensities within an alpha-spectrum can be measured as well.

In this experiment a small vacuum chamber is evacuated by an oilfree forepump and it houses the detector, the optional foil and the α emitter. To reach high resolution the α sources used have to be very thin.

Energy loss in matter is used to determine the thickness of foils and thin layers, an important application of particle spectroscopy. The energy loss of α particles in matter is described by the Bethe-formula and more recently simulated by the TRIM or the SRIM codes.

B. Necessary knowledge

Physics :

- Gamow-theory of α-decay
- Tunneling-effect at barriers
- Compare with Sub-Coulomb-barrier astrophysical particle reactions

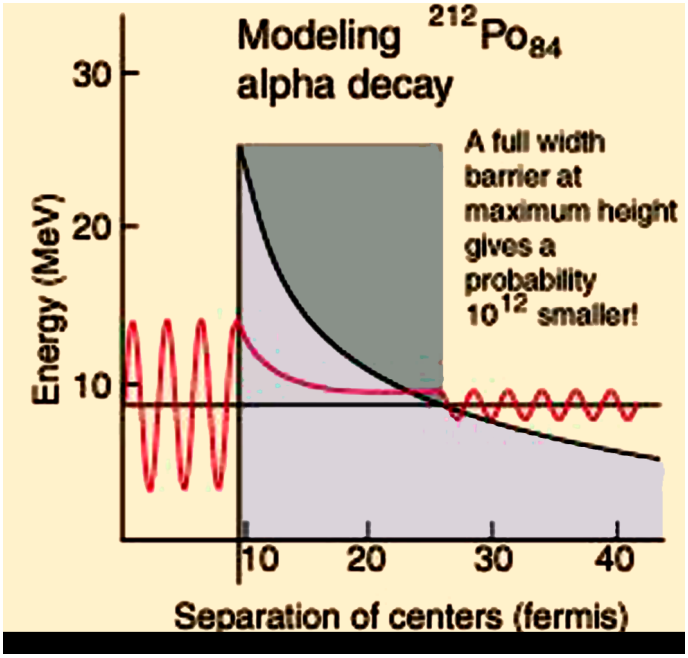


Figure 15: Gamow model of Alpha-decay. The alpha particles exist as a substructure inside the nuclear potential (see α cluster model) and can escape through the barrier by the tunneling effect. Depending on the primary energy the alpha particles are facing a different barrier depth which leads to the dependence of the half-lives according to the Geiger-Nuttal rule.

- Geiger-Nuttal rule
- Compare with age of the universe and cosmic clocks
- Interaction of particles with matter
- Bethe-formula for energy loss and energy straggling
- TRIM- or SRIM-code
- ^{241}Am decay scheme

Technique :

- Principles of solid state detectors
- Principles of spectroscopy
- What "makes" energy resolution?
- What is Stopping Power?
- Technical applications of energy loss
- Compare with other methods for thin layers or foils
- Principles of vacuum technology

- Multi channel analyzer (MCA) and analog-digital converter (ADC)

C. References

[1]	**Gamow, G. :** . Z. Phys. **51**, 204 (1928)	Original article
[2]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics
[3]	**Firestone, R. B. :** Table of Isotopes Vol. II John Wiley & Sons, New York, 1996	Current reference book of nuclear data
[4]	**Leo, W. R. :** Techniques for Nuclear and Particle Physics Experiments Springer Verlag, Berlin, 1994	Text book of measuring techniques
[5]	**Knoll, H. G. :** Radiation Detection and Measurements, S. 360 ff John Wiley & Sons, New York, 1989	Standard work on detectors
[6]	**C. M. Lederer *et al.* :** Energy levels of ^{237}Np Nucl. Phys. **84**, 481 (1966)	Original work of ^{237}Np
[7]	**Ziegler...:** Stopping powers	
[8]	**:** Manual for the SRIM code	

D. Experimental Tasks

- Set-up of detector and α-source
- Produce vacuum ($\approx$ 0.5 mbar)
- Set-up of electronics, bias voltage, depending on the type of detector (ask TA!) (+25 – +75 Volts) and set-up of main amplifier (time constant, pole-zero cancellation !)
- Measure the energy resolution of the semiconductor detector as a function of the operating (bias) voltage. Vary the operating voltage between $\mathrm{u} = 10\ --\ \mathrm{max.\ allowed\ voltage}$ V in 10 V steps.
- Determine the optimum energy resolution
- Determine energy calibration using zero-point and the single-α-source
- Determine all the α lines and from that the unknown isotope; explain the spectra with the level schemes

- Determine the energies and relative intensities of all the lines.

  Measure energy loss in some thin foils:

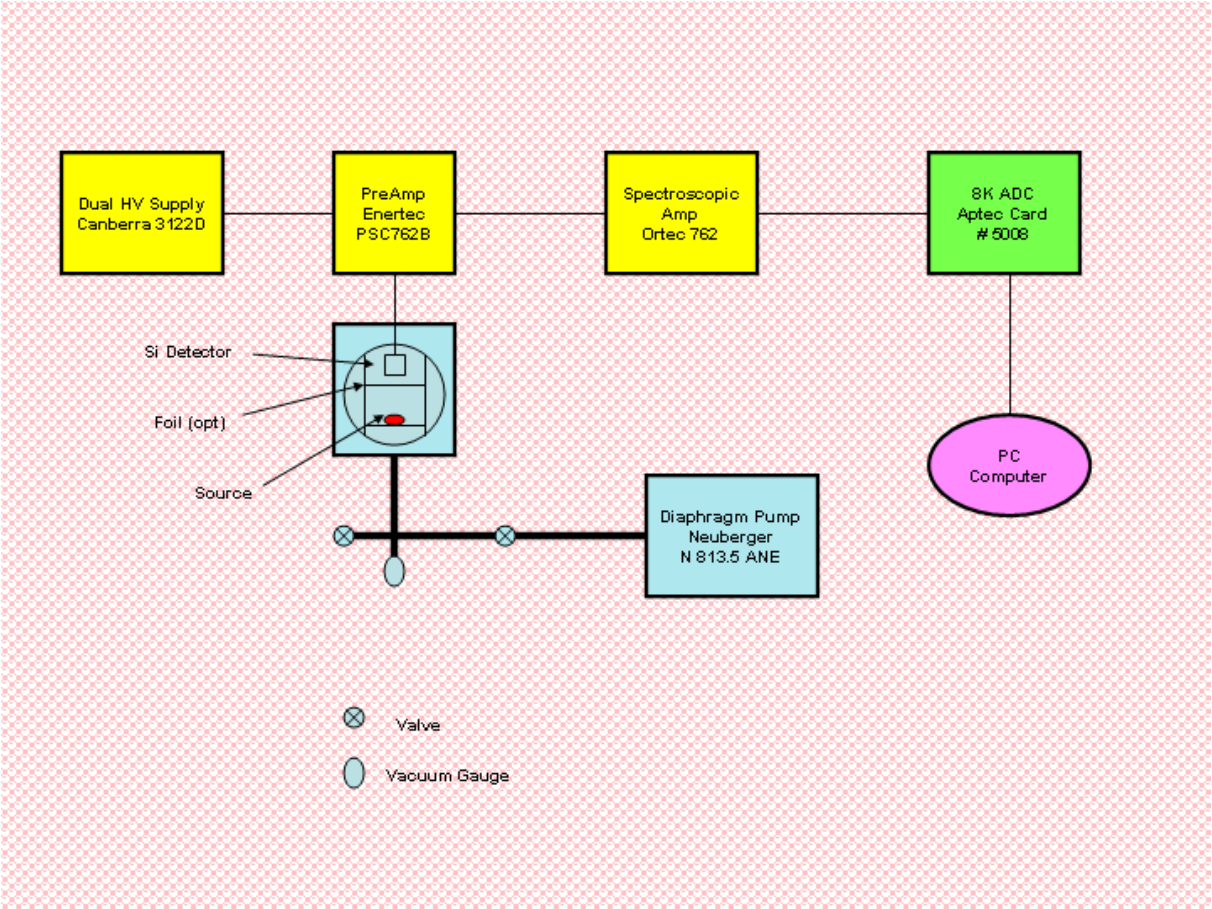
- Determine foil thickness
- Compare energy straggling with theory

WARNINGS:

- Be careful with bias voltage : never exceed maximum voltage, never apply when vacuum bad.
- Shut down bias before venting and when done with spectroscopy
- Never touch surface of α-source or surface of detector
- Remove source after measurement
- Never expose a biased detector to light!

E. Information Regarding the Experimental Setup

Sketch of the experimental setup



Legend:

Detector :		High resolution Si surface barrier detector (original resolution 11 keV at 5.48 MeV)
Bias :		Operating biass voltage for the detector, $u \simeq +30$ V ; Dual HV Supply Canberra # 3122D
Pre-amp	:	Preamplifier Enertec # PSC762B
MA :		Main spectroscopic amplifier Ortec # 762
APTEC-5008 :		MCA and ADC (Analogue to digital converter) on one ISA computer card
Computer :		Computer with Aptec -Card (ISA bus !) and Canberra Genie 2000 multichannel analyzing program (with dongle!)
Vacuum-pump :		Diaphragm Pump (dry, oilfree) Neuberger # N 813.5 ANE

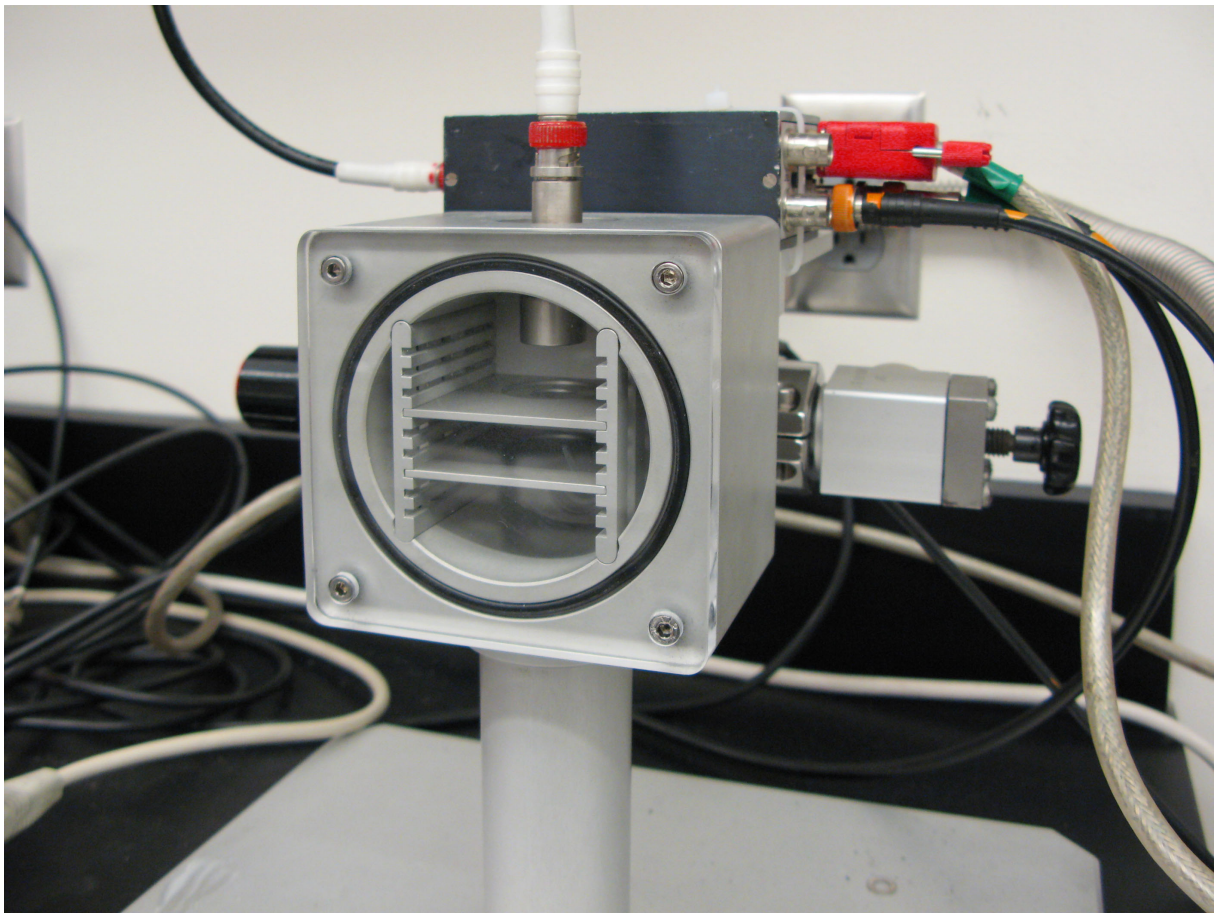


Figure 16: Vacuum chamber for α-spectroscopy.

Information Regarding the Experimental Procedure

The particle counter is light sensitive, therefore the chamber must be covered with the cap when the detector is biased.
The pressure in the chamber should be kept under 1 mbar during the measurement – why?

Radioactive sources

One source is a mixed α source, containing ^{241}Am and an unknown nuclide. The decay pattern of the known nucleus is in the appendix to this experiment.
The other source is a very thin single isotope source with ^{241}Am.

Additional Data

Energies of the most intense α lines:

^{237}Np			^{241}Am	
E_α (keV)	Intensity		E_α (keV)	Intensity
4790	47.0 %		5486	85.2 %
4773	25.0 %		5443	12.8 %
4642	6.2 %			

F. Discussion of Results

1. Discuss and sketch the energy resolution of the semiconductor detector as function of the voltage. Determine the conditions for the best energy resolution (relative and absolute).
2. Measure the energy spectrum and identify the α lines. Include a diagram of the linear calibration.
3. Compute the relative line intensities.
4. Identify the unknown nuclide
5. Compute the theoretical radioactive half-lives using the Gamow theory and compare with the actual radioactive half-lives of the two nuclides. Discuss what effects are neglected in the theory. The following applies for the decay constant λ:

$$
\begin{aligned}
\lambda &= \lambda_0 \cdot e^{-2\,\mathrm{G}} \\
\lambda_0 &= \sqrt{\frac{E}{2mR_K^2}} \\
G &= \sqrt{\frac{2m(Z_1 Z_2 e^2)^2}{(4\pi\varepsilon_0\hbar)^2\, E}} \cdot (\arccos\sqrt{x} - \sqrt{x(1-x)}) \\
x &= \frac{R_K}{R'} = \frac{E}{V_C} \\
R_K &= r_0(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}}) \quad \text{mit} \quad r_0 = 1.19\,\mathrm{fm}
\end{aligned}
$$

$Z_{1,2}$: Charge number
$A_{1,2}$: Mass number
E : Decay energy
m : Reduced mass

G. Example Questions

- α-emission and the tunneling-effect; connection to nuclear astrophysics?
- Compare Geiger-Nuttal rule and the age of stars
- Charged particle detection
- Principal difference between particle- and γ- or -(X)-detection
- Slowing down of particles
- Why evacuate the little measuring chamber, what vacuum is sufficient, how can it be achieved, why oilfree pump?
- Why cover the window of the measuring chamber?
- Resolution of the silicon detector, understanding of how is resolution accomplished

H. Appendix

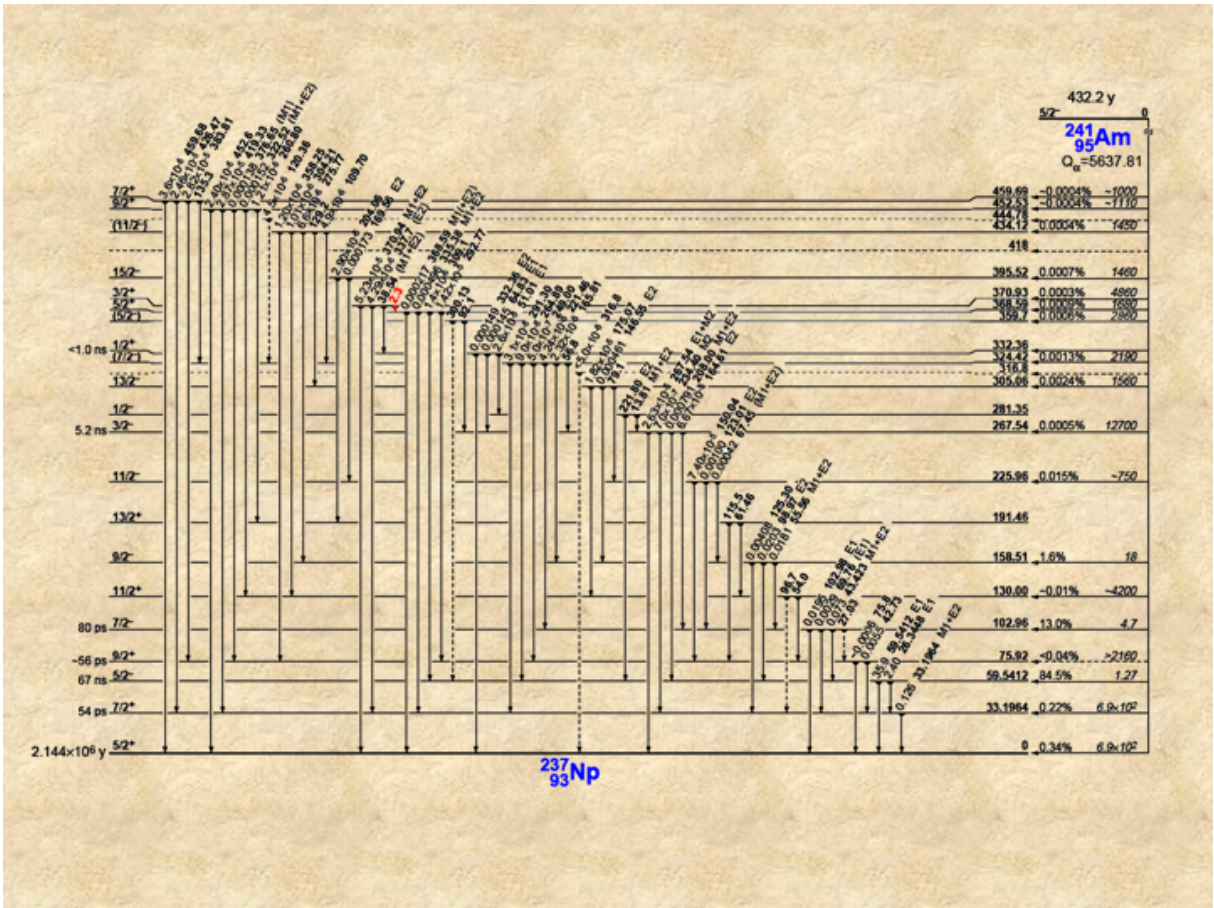
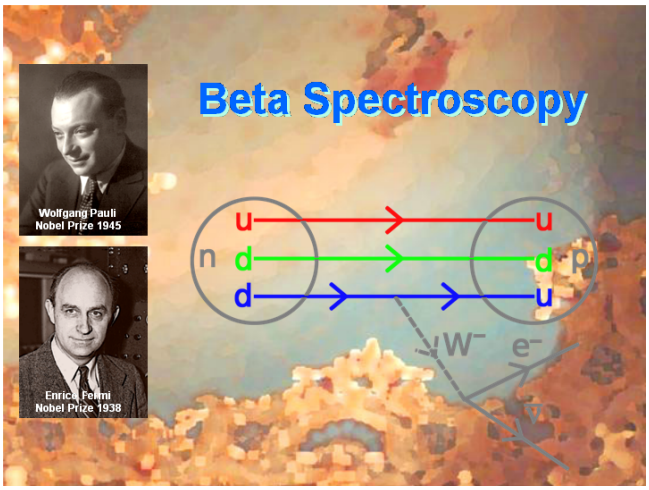


Figure 17: Decay scheme of ^{241}Am from [8].

Similar schemes of neptunium-237 and plutonium-239

7 Beta Spectroscopy



Location: room Jordan 308

A. Short Description

β-decay is one of the prominent decay modes of nuclei caused by the so-called weak interaction. In the β^- and β^+ decay, energy and momentum are shared with the accompanying neutrino to fulfill lepton number-, momentum-, energy- and angular momentum conservation. In β-decay three partners in the outgoing channel are involved, the e$\pm$, the neutrino, and the final nucleus, therefore β-spectra are continuous and they can be described in simple cases by Fermi-theory of β-decay. Phase-space considerations together with the application of Pauli-principle (Fermi-Dirac statistics) lead to the shape of the β-spectrum; the nuclear matrix element having no influence. β-decay violates parity conservation.

The double focusing magnetic β-spectrometer is a classical instrument for the measurement of continuous or discrete β-spectra with magnetic fields. It is a scanning spectrometer which measures the momenta of the beta's by varying the electric current through the coils of the magnet. Double focusing is achieved by choosing a toroid-sector-field spectrometer. The obtained β-spectra are displayed in a so-called Fermi-Kurie-plot from which after a correction for the forbideness (form factor) the endpoint energy of the spectrum can be obtained. In this experiment the double-forbidden β-decay of ^{99}Tc is investigated.

B. Nuclear β-decay

We define the Q value to be the difference between the initial and final nuclear mass energies.
For the following case **n** $\rightarrow$ p + e^- + $\bar{\nu}$,
the Q value would be: **Q** = (m_n - m_p - m_{e^-} - m_0) c^2
Let us consider the three cases of β-decay in a nucleus:

β^-–decay

In the case of 'regular' β^--decay we obtain,

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + e^- + \bar{\nu}\,, $$

$$ Q_{\beta^-} = [m_n({}^{A}_{Z}X) - m_n\,({}^{A}_{Z+1}X') - m_e]c^2. $$

In the above case m_N indicates nuclear masses. In order to use the tabulated atomic masses we have to convert these using the following

$$ m\,({}^{A}X)\,c^2 = m_n\,({}^{A}X)\,c^2 + Z\,m_e\,c^2 - \sum_{i=1}^{Z} B_i, $$

B_i is the binding energy of the i^{th} electron. Replacing in the formula above we obtain :

$$ Q_{\beta^-} = [m\,({}^{A}X) - m\,({}^{A}X')]\,c^2 $$

The Q value represents the energy shared by the electron and the antineutrino

$$ Q_{\beta^-} = T_e + E_{\bar{\nu}} $$

β^+–decay

Using similar arguments in the case of positron decay we obtain :

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X' + e^+ + \nu $$

$$ Q_{\beta^+} = [m\,({}^{A}X) - m\,({}^{A}X') - 2\,m_e]\,c^2 $$

EC–decay

The electron-capture process is represented by :

$$ {}^{A}_{Z}X + e^- \rightarrow {}^{A}_{Z-1}X' + \nu. $$

We obtain :

$$Q_{\beta^-} = [m(^AX) - m(^AX')]c^2 - B_n$$

where B_n is the binding energy of the captured electron

All the above expressions assume β-decay between a specific state and the ground state. If the final state is an excited state, this must be taken into account.

C. Necessary Knowledge

Physics :

- Discovery of β-decay and of the continuous spectrum (history)
- Why is the β-spectrum continuous?
- Pauli principle and Fermi theory of β-decay
- Is the knowledge of the nuclear matrix element necessary?
- Some ideas about forbidenness in β-decay, rules, log ft-value
- Characterize weak force and weak interaction, weak coupling constants
- Symmetries and parity
- Helicity, left-handedness and right-handedness, Parity violation, Wu experiment, Goldhaber experiment
- What is Internal Conversion, and how can one make use of it?

Measuring Technique :

- Particles in electromagnetic fields, how is momentum, energy and velocity selection achieved?
- Principles of β-spectrometers
- Focusing techniques
- How does an electromagnet work?
- Some vacuum techniques, how is a clean vacuum achieved?
- Techniques of thin source preparation

- Electron backscattering and energy loss: Bethe-Landau equation
- Electronic set-up, noise, pre-amp, main amp, MCA

Mathematics : Method of least squares

References

[1]	**Schüpferling, H.M. :** Bau eines Toroid-Sektorfeld-Spektrometers Diploma thesis, University of Stuttgart 1966	Thesis on the design and construction of the present β-spectrometer
[2]	**Reich, M. :** Untersuchung des 2-fach verbotenen β-Zerfalls von Technetium-99 Diploma thesis, University of Stuttgart 1973	Thesis on the β-decay of the source used in the present experiment
[3]	**Reich, M. and H.M. Schüpferling :** Formfaktor des β-Spektrums von ^{99}Tc Z. Phys. **271**, 107 (1974)	Article on the form factor of ^{99}Tc, the source used in the present experiment
[4]	**Schattat, Beate:** Praktikumsversuch zur β-Spektroskopie Thesis of high school teachers, University of Stuttgart 1998	Original thesis on this teaching lab experiment with some more references
[5]	**Siegbahn, K., Ed.:** Alpha-, Beta-, Gamma-Ray Spectroscopy North Holland, Amsterdam 1965	Detailed textbook on Nuclear Spectroscopy
[6]	**Landolt–Börnstein, Eds.:** Numerical Tables for Beta-Decay and Electron Capture, Vo. I/4, pp. 30, 86 Springer-Verlag, Berlin	Detailed tables on Beta-decay
[7]	**Schatz, G. and A. Weidinger:** Nuclear Condensed Matter Physics John Wiley & Sons, Chichester, New York etc. 1996	Textbook on Nuclear Methods and Applications in Condensed Matter Physics
[8]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[9]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard work on detectors
[10]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics

Experimental Tasks

- Produce and check vacuum; about 3 x 10^{-5} mbar should be achieved in the chamber; after check: switch off ionization vacuum gauge (interference with the spectroscopy)

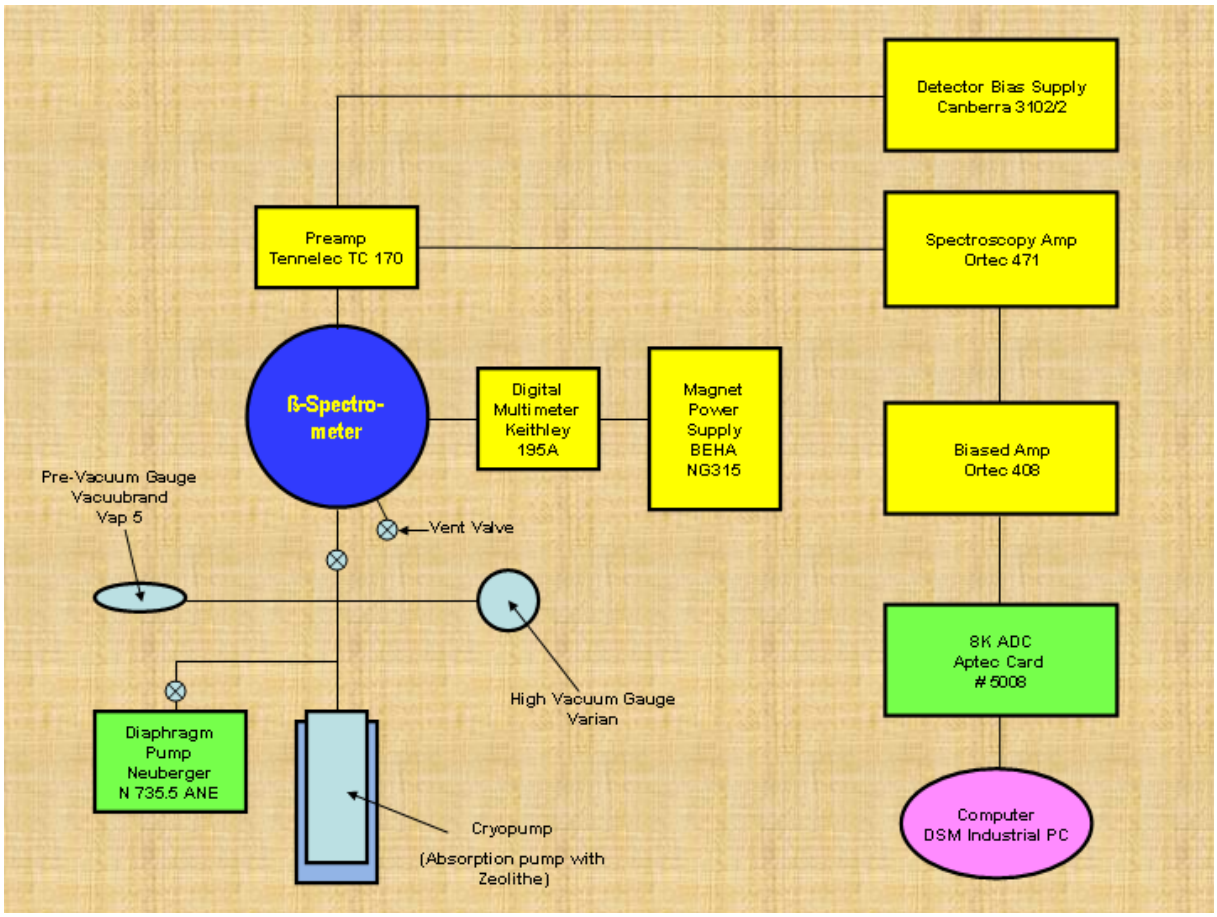
- The current through the spectrometer coils is in the range of 8-30mA and should be kept constant (current mode). To be at a well-defined level of the hysteresis curve, one should run through the hysteresis twice clock-wise and finally stay on the branch with positive coercitive force.
- Detector bias is +60 Volts (turn the dial slowly to approach this value)
- Signals are noisy, therefore threshold for ADC at about 8-9%
- The line of the β's should be clearly visible at the MCA in the whole range of coil currents
- Set the MCA to 512 channels
- Measure the momentum spectrum of ^{99}Tc by taking spectra for every mA of the coil current between 8 and 30 mA
- ^{99}Tc has no conversion lines, so the spectrometer has to be calibrated by the endpoint energy of the spectrum
- Calculate the Fermi-Kurie-Plot for the measured ^{99}Tc spectrum, a double forbidden β-decay

WARNINGS

- Shut down bias when measuring has been finished.
- Close the gate valve after finishing.
- Don't forget filling of the dewar every 10 hours.

D. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

Beta-spec : Classical Toroid-Sectorfield-β-Spectrometer, momentum resolution about 4 %, transmission about 4 %; brass vacuum chamber with aluminum liner, soft iron choke

vacuum : The vacuum system for the β-spectrometer is hydrocarbon-free and safe (open radioactive β-source), the main pump is a Zeolite sorption pump, cooled down to liquid nitrogen temperature when used. Two gauges provide pre- and main vacuum indication and a diaphragm pump is used to regenerate the absorber, which then will be heated up. The β-spectrometer can be separated from the vacuum system by a gate valve.

magnet :	The two magnet coils of the β-spec have a resistance of 585 + 591 = 1176 Ohms. The current is provided by a power supply working in current mode (BEHA # NG 315), and the applied current is monitored by a Keithley digital multimeter mod. # 195A. The required voltage is around 36 V at 30 mA.
detector :	The detector is a Si(Li)-detector working at room temperature with sufficient intrinsic zone to measure electrons up to 2 MeV.
bias :	Bias power supply Canberra # 3102/2, bias voltage + 60 Volts.
pre-amp :	Pre-amplifier Tennelec # TC 170 (works best together with the Si(Li)-detector)
main-amp :	Main spectroscopic amplifier Ortec # 471
bias-amp :	Optional biased amplifier Ortec # 408 to cut off the noise signals
MCA :	MCA-card with Gatti ADC 8k Aptec # 5008 working with Canberra Genie 2000 software with dongle
PC :	Industrial PC from DSM-computer with passive backplane to accommodate ISA and PCI cards, with a slot-CPU.

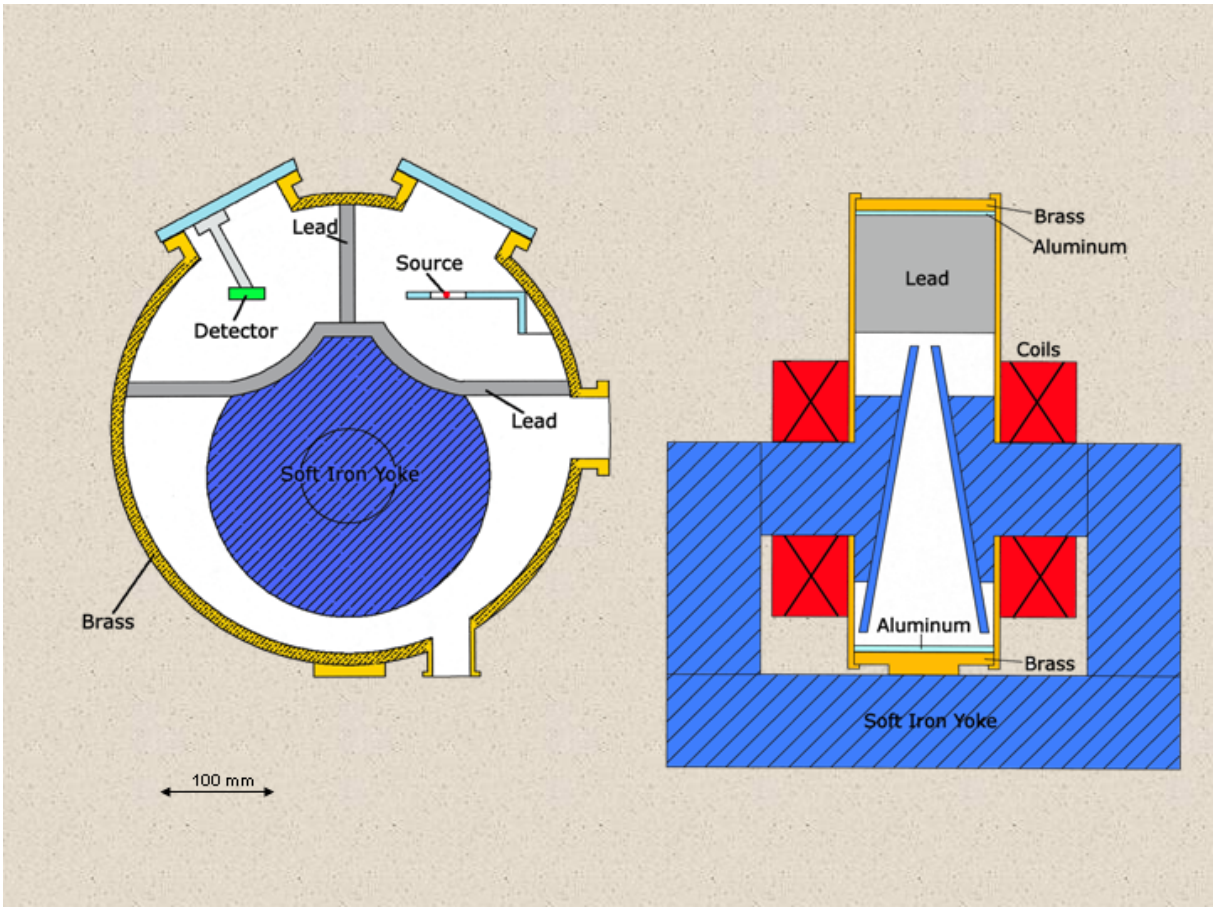


Figure 18: Two cross section schemes of the β-spectrometer showing details of the construction, the arrangement of source and detector, the lead shield, the inclined pole shoes to produce the double focusing field properties (orange type), the vacuum chamber and the iron choke with the two coils.

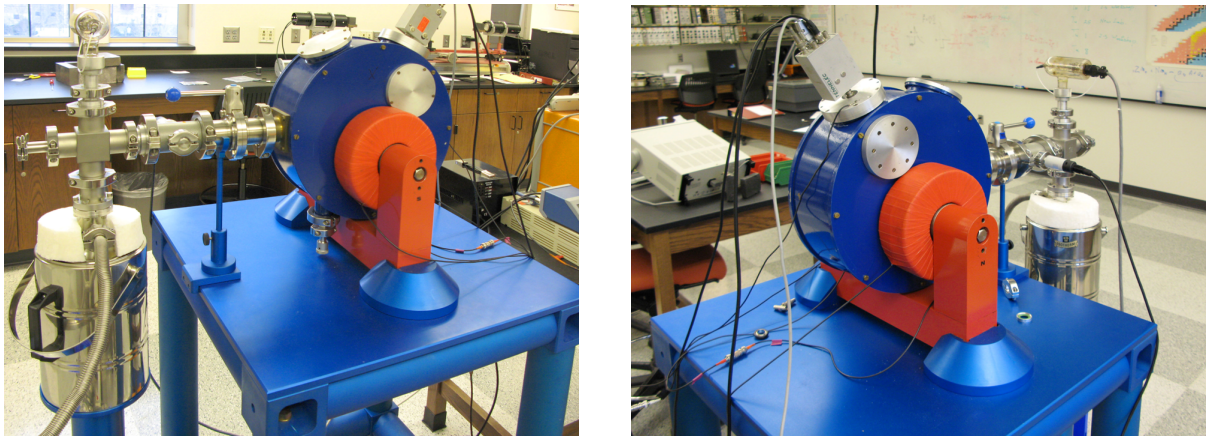


Figure 19: Two views of the Toroid-Sectorfield-β-spectrometer (orange type) with vacuum system.

Figure 20: Advanced Physics Teaching Lab with β-spectrometer in the fore-ground.

Information about the source used

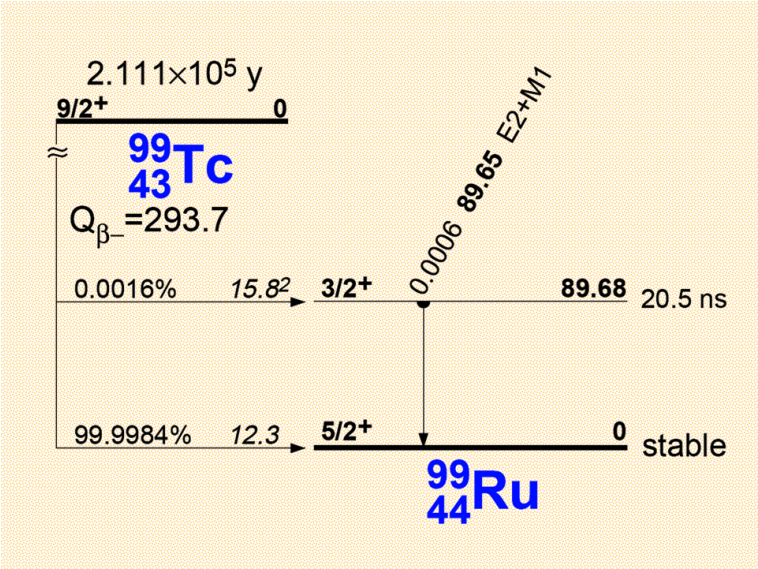


Figure 21: Decay scheme of ^{99}Tc from [8]. Note that this source is free of γ-transitions, therefore the radiation level outside the spectrometer is zero.

An alternative source would be ^{137}Cs, from which one obtains also conversion lines for the calibration of the spectrometer and the determination of the momentum resolution. The disadvantage is the emission of the 662 keV γ line, which produces a certain radiation level.

E. Discussion of Results

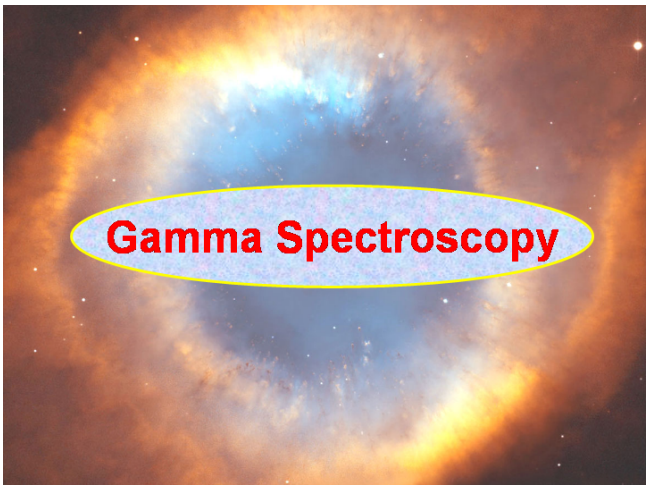
- Provide example spectra of the β-lines
- Provide a plot of the momentum spectrum, a Fermi-Kurie-plot with calibration on the endpoint energy with and without the form-factor correction
- Calculate the uncertainties

F. Example Questions

- Why is a β-spectrum a continuous spectrum?
- Principles of β-decay theory; what are the basic ideas, what makes the shape of an allowed β-spectrum? Is it necessary to know the nuclear matrix element?

- Discovery of the neutrino
- Principles of β-spectrometers
- Trajectories of particles in electromagnetic fields
- Why not use a simple silicon-detector for the electrons?
- What can β-spectrometers do for γ-spectroscopy? (spec. of conversion electrons)

8 Gamma Spectroscopy



Location: room Jordan 305

A. Short Description

Gamma spectroscopy is the most important tool to study properties of excited nuclei, to determine decay schemes and explore nuclei with respect to nuclear models. In our experiment a high purity germanium detector with a typical resolution of about 0.15 % (or 2.2 keV for the 1.33 MeV Co-line) is used. The largest of our three detectors has a relative efficiency of 30 % compared to a standard 3 x 3 " NaI detector. The term γ-spectroscopy comprises these technical aspects, but even more it considers theoretical understanding and interpretation of the underlying models. In the present experiment a rotational band in the nucleus ^{166}Er is measured and from a precise determination of the gamma energies the momentum of inertia of the erbium nucleus can be calculated and then compared with the model of a rigid or a liquid drop rotator. Alternative studies can be made for complicated decay schemes of some heavy nuclei, the determination of a level scheme applying the Ritz' combination method.
Further by making use of a large passive shield one can measure weak radiation from samples taken in the environment for material analysis using neutron activation techniques. In general gamma spectroscopy is often used for the study of nuclear reactions, high spin states, gamma's resulting from capture reactions (charged particle or neutron capture). Gamma spectroscopy has also very important applications in material analysis (NAA), geological exploration or in computer tomography (CT-scan).

B. Necessary Knowledge

Physics :
- Theory of multipole radiation and selection rules

- The rotational nuclear model
- Other nuclear models
- Exploration of a nuclear level scheme; Ritz' combination method
- γ-shielding passive and active
- low level γ-detection methods to find weak radioactivity
- Use of LN_2 as a cooling agent
- Typical γ-spectra of calibration and test sources
- Some important examples of nuclear level schemes

Measuring Technique :

- γ-spectroscopic techniques
- scintillation detectors
- semiconductor detectors
- Bragg type detectors
- Resolution of detectors and efficiency
- The HPGe detector, physics and properties
- Noise reduction using appropriate pre-amps and spectroscopy amps; electronic filters and filter theory, application of Fourier or Laplace transform for circuit design
- Calibration and evaluation of γ-spectra

Mathematics : Method of least squares, line fitting, background determination and subtraction

References

[1]	**Debertin, K., and R.G. Helmer :** Gamma- and X-ray spectrometry with semiconductor detectors North Holland, Amsterdam, 1988	Standard textbook for Gamma Spectroscopy with semiconductor detectors
[2]	**Heath, G. L., and R.G. Helmer :** Gamma Ray Spectrum Catalogue, Fourth Edition, 1998 Idaho National Engeneering and Environmental Laboratory	Comprehensive collection of gamma spectra of the isotopes together with decay schemes and tables
[3]	**Reus, U., and W. Westmeier :** Catalog of Gamma Rays from Radioactive Decay Atomic Data and Nuclear Data Tables Vol. 29 p. 1-406 (1983)	Comprehensive catalog of gamma ray energies and related isotopes

[4]	**Vegors Jr., ST.H., Marsden, L.L., and Heath, R. L. :** Calculated Efficiencies Of Cylindrical Radiation Detectors Report IDO-16370, Phillips Petrolium Company, Atomic Energy Division, Idaho Falls, Idaho, 1958	Report on the efficiencies of NaI-γ-detectors
[5]	**Siegbahn, K., Ed. :** Alpha-, Beta-, Gamma-Ray Spectroscopy North Holland, Amsterdam 1965	Detailed textbook on Nuclear Spectroscopy
[6]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics
[7]	**Eisenberg, J.M.,and W. Greiner :** Nuclear Theory Vol. 1 Nuclear Models, Vol. 2 Excitation Mechanisms of the Nucleus, Vol. 3 Microscopic Theory of the Nucleus North Holland, Amsterdam, Oxford etc. 3rd Ed. 1987, 1988	Comprehensive textbook on nuclear theory
[8]	**Hamilton, W.D. :** The Electromagnetic Interaction in Nuclear Spectroscopy North Holland Publishing Comp., Amsterdam, New York etc. 1975	Standard textbook
[9]	**Cerny, J., Ed. :** Nuclear Spectroscopy and Reactions, Part A,B,C,D Academic Press, New York, 1974 and 1975	Standard compendium for Nuclear Spectroscopy
[10]	**Casten, R.F. :** Nuclear Structure from a Simple Perspective Oxford University Press, New York, Oxford etc. 1990	.....
[11]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[12]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard textbook on detector technology

Experimental Tasks

- Set-up of the γ-detector
- Make sure that the crystal is at least for one hour at LN_2-temperature
- Make sure that the pre-amp has power ($\pm$ 12 V_; $\pm$ 24 V_)
- Check sign of HV very carefully! Different detectors!
- Switch on HV, raise HV slowly from 0 to the nominal voltage by watching the output of the main amp on the oscilloscope

- After reaching the nominal voltage, check all settings of the main amp: time constant 3μs; amplification such that the 1.46 MeV ^{40}K line has 8 V amplitude
- Set the pole zero cancellation very carefully
- Get the following calibration sources: ^{44}Ti; ^{133}Ba; ^{22}Na; ^{137}Cs; ^{54}Mn; ^{60}Co; ^{40}K (salt containers)
- Chose appropriate distance for each source that all lines are clearly visible but the total count-rate must not exceed 2kHz
- Calibrate the detector in the whole energy range 0 .... 1500 keV with the calibration sources all at once in one spectrum
- Determine the standard detector resolution using a weak ^{60}Co-source, determine the line shape and the peak/Compton ratio.
- Determine a background-free single line spectrum of ^{40}K using 4 or 5 salt containers in the lead shield.
- Measure the ^{166m}Ho-source (= states in ^{166}Sm) and evaluate the lines of the rotational band
- Evaluate the momentum of inertia
- Compare with the theoretical values for a rigid rotator and a liquid drop
- Alternative tasks: Evaluate sample spectra of thorium and uranium ore or their compounds
- Determine background spectra as well and find out which lines are present.
- Alternative: Determine the decay scheme of ^{152}Gd from measuring the ^{152}Eu spectrum and applying the Ritz' combination principle.
- Alternative: Determine gamma spectra of neutron activated material in the "Big Shield"
- Alternative: Determine environmental samples by a low level gamma spectrum measurement ("Big Shield").
- Alternative tasks: Compare the performance of the Ge-detector with that of a standard 3x3" NaI-detector. Determine the standard resolution of the NaI-detector using a weak ^{137}Cs-source. Compare multiple line spectra taken with the Ge- and the NaI-detector.

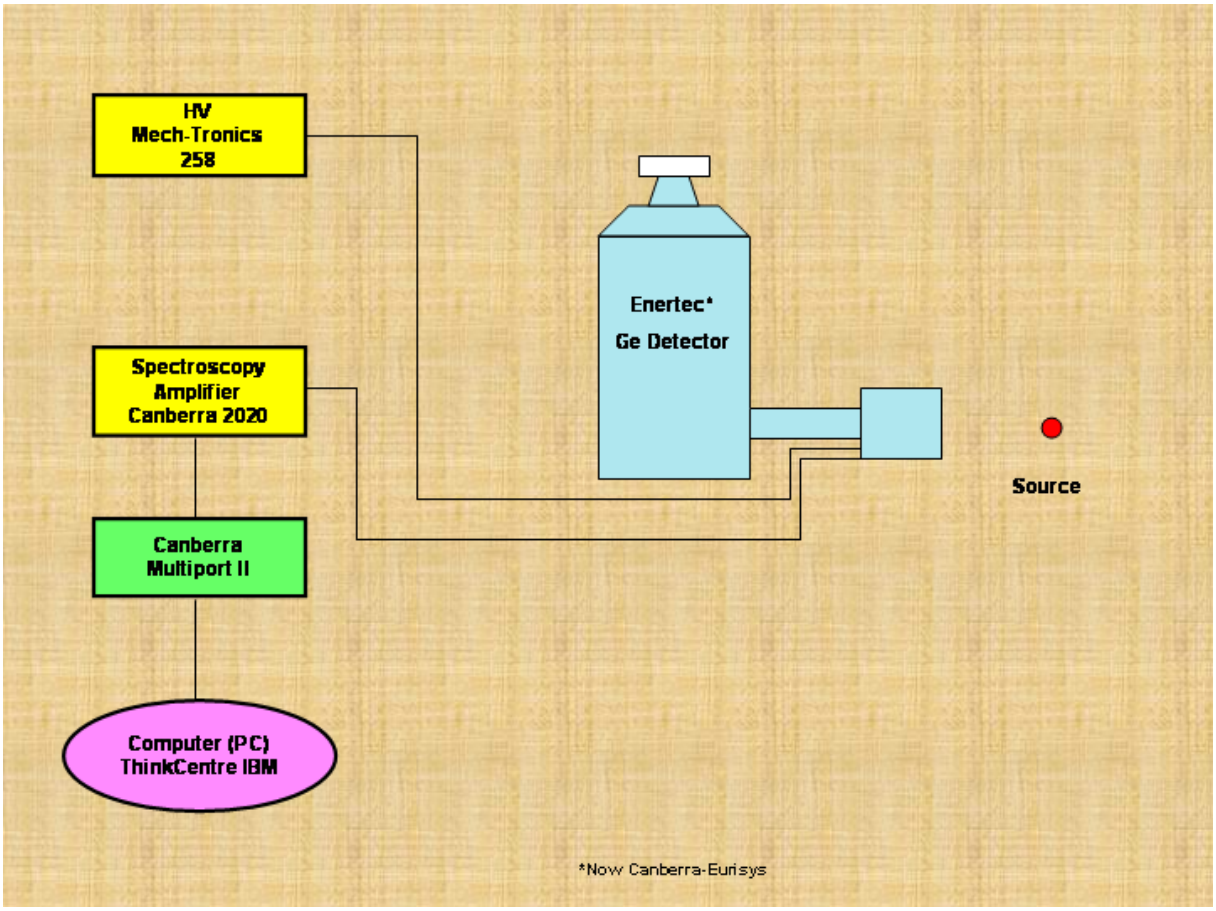
- Determine the relative efficiency of one of our Ge-detectors with that of a standard 3x3" NaI-detector using a ^{60}Co-source at 25 cm source-crystal distance.

WARNINGS

- Make sure that the Ge detector is at liquid nitrogen temperature
- Turn on and set the bias voltage slowly by watching the detector signals
- Never disconnect power from the pre-amp, the FET transistor might die!
- Never turn off bias voltage abruptly
- After finishing measurement turn down bias slowly
- Move the door of the "Big Shield" slowly and controlled, its weight is nearly 100 kg!
- Never apply pressure or tension to the cup of a Ge-detector.

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

Ge-detector : There are three Ge-detectors available:

A. Eurisys n-type detector with transistor reset preamp, high voltage negative - 3000 Volts; relative efficiency about 30 %; resolution 2.2 keV, symmetric line shape.

B. Princeton Gammatech p-type detector with resistive feedback pre-amp, high voltage positive + 2500 Volts; relative efficiency about 15(?) %; resolution 2.1 keV, symmetric line shape.

C. Eurisys n-type detector with transistor reset preamp, high voltage negative - 3000 Volts; relative efficiency 18 %;

	resolution about 2.7 keV ; asymmetric line shape due to imperfect crystal.
HV :	High Voltage for the Detectors, Mechtronics #258 or better CAEN # N471, double high voltage power supply.
Amp :	Main Spectroscopy amplifier Canberra #2020, set to 3 μs time constant, set properly pole-zero and baseline restoration
MCA :	Canberra Multiport II multichannel analyzer with 2 separate ADC's, special green dongle required for the GENIE 2000 software "multi-input" connected to the printer jack, USB connection to PC
PC :	Standard PC

There is a standard 3x3" NaI(Tl)-detector available for measurements and for comparison of its performance with that of the Ge-detector. The detector is sitting in an aluminum stand and it is shielded by a lead cylinder of about 20 mm thickness. The high voltage for this detector is +800 Volts. The dynode signals of the NaI-detector are connected to a preamp and then to a simple main amplifier (f.e. Canberra # 2022). The amplified bipolar signals (max. 8 V) are connected to the ADC of a Canberra Multiport II using 256 or 512 channels.

Information about the "Big Shield"

Diameter : 49 cm
Length (without the door) : 56 cm ; with door : 61.5 cm
Inner diameter (without the supporting steel ring): 29 cm
Lead thickness of the mantle : 10 cm
Lead thickness of the door : 5.5 cm Thickness of copper liner : 1.5 mm
Thickness of the front lead cover : 7.5 cm
Weight of the lead (without stand etc.) : ca. 882 kg

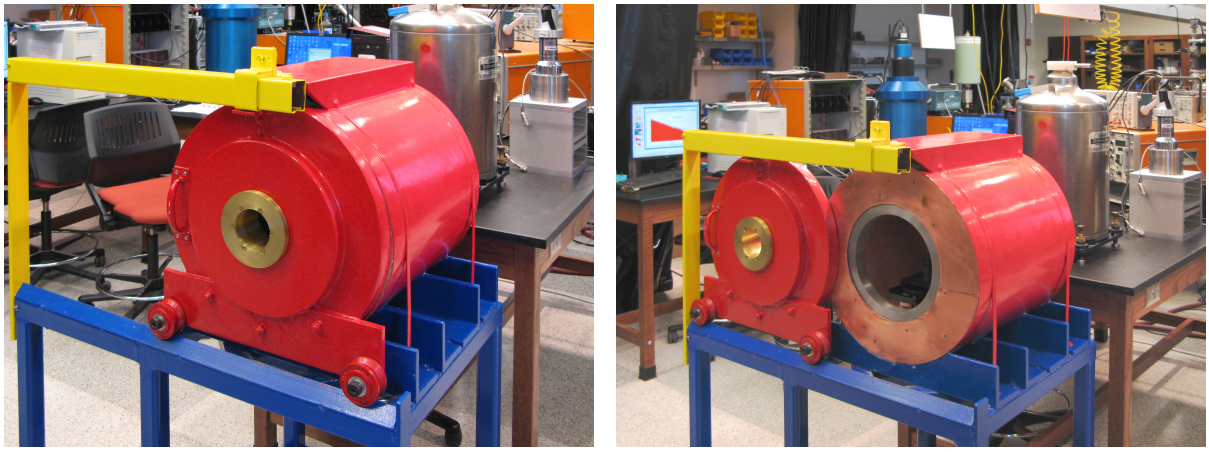


Figure 22: Photo of the "Big Lead Shield" showing the door closed and open, and the closed front side with one of the Ge-detectors looking inside the shield. All inner lead parts are covered with a 1.5 mm copper liner to absorb lead X-rays. There are openings in the front side and in the door for Ge-detectors, the detector diameter is matched with brass inserts. This shield makes low radiation level measurements possible as for example environmental investigations or neutron activation analysis (NAA).

Figure 23: 3x3" NaI-detector with stand and lead shield on the right side, HPGe-detector (30 % rel. efficiency) in the middle and the "Big Lead Shield" on the left side. The performance of both detectors can be measured and compared.

Information about the radioactive sources

Calibration Sources

Gamma Rays Used as Energy Calibration Standards

Source	Half Life	Energy (keV)	Source	Half Life	Energy (keV)
^{241}Am	432 years	59.536 ± 0.001	^{198}Au	2.696 days	411.792 ± 0.008
^{44}Ti	59.0 ± 0.6 years	67.875 ± 0.005	^{192}Ir	73.810 ± 0.019 days	468.060 ± 0.010
^{44}Ti	59.0 ± 0.6 years	78.337 ± 0.004	m_0c^2		511.003 ± 0.002
^{109}Cd	463.26 ± 0.63 days	88.034 ± 0.010	^{207}Bi	11523. ± 15. days	569.690 ± 0.030
^{182}Ta	114.43 days	100.106 ± 0.001	^{208}Tl	3.053 minutes	583.139 ± 0.023
^{57}Co	272 days	122.046 ± 0.020	^{192}Ir	73.810 ± 0.019 days	604.378 ± 0.020
^{144}Ce	284.534 ± 0.032 d	133.503 ± 0.020	^{192}Ir	73.810 ± 0.019 days	612.430 ± 0.020
^{57}Co	272 days	136.465 ± 0.020	^{137}Cs	30.0 years	661.615 ± 0.030
^{141}Ce	32.5 days	145.442 ± 0.010	^{54}Mn	312.5 days	834.840 ± 0.050
^{182}Ta	114.43 days	152.435 ± 0.004	^{88}Y	106.6 days	898.023 ± 0.065
^{139}Ce	137.6 days	165.852 ± 0.010	^{207}Bi	11523. ± 15. days	1063.655 ± 0.040
^{182}Ta	114.43 days	179.393 ± 0.003	^{60}Co	5.27 years	1173.231 ± 0.030
^{182}Ta	114.43 days	222.110 ± 0.003	^{22}Na	2.60 years	1274.550 ± 0.040
^{212}Pb	10.64 hours	238.624 ± 0.008	^{60}Co	5.27 years	1332.508 ± 0.015
^{203}Hg	46.6 days	279.179 ± 0.010	^{140}La	40.293 ± 0.012 h	1596.200 ± 0.040
^{192}Ir	73.810 ± 0.019 days	295.938 ± 0.010	^{124}Sb	60.20 days	1691.022 ± 0.050
^{192}Ir	73.810 ± 0.019 days	308.440 ± 0.010	^{88}Y	106.6 days	1836.127 ± 0.050
^{192}Ir	73.810 ± 0.019 days	316.490 ± 0.010	^{208}Tl	3.053 minutes	2614.708 ± 0.050
^{131}I	8.02 days	364.491 ± 0.015	^{24}Na	15.0 hours	2754.142 ± 0.060

Figure 24: List with a selection of common radioactive sources for gamma ray spectroscopy.

Radioactive Gamma Sources

Source	Energy [keV]	$T^{1/2}$
M_0c^2	511.006 ± 0.002	
^{7}Be	477.57 ± 0.05	53 d
^{22}Na	1274.55 ± 0.04	2.6 y
^{24}Na	1368.526 ± 0.044 2753.92 ± 0.12	15.0 h
^{51}Cr	320.080 ± 0.013	27.8 d
^{54}Mn	834.81 ± 0.03	314 d
^{60}Co	1173.23 ± 0.04 1332.49 ± 0.04	5.26 y
^{65}Zn	1115.40 ± 0.12	246 d
^{88}Y	898.04 ± 0.04 1836.13 ± 0.04	106.6 d
^{137}Cs	661.635 ± 0.076	30 y
^{198}Au	411.795 ± 0.009	2.70 d
^{207}Bi	569.62 ± 0.06 1063.44 ± 0.09 1769.71 ± 0.13	30 y
^{208}Tl (ThC")	510.723 ± 0.020 583.139 ± 0.023 2614.47 ± 0.10	(1.91 y)
^{198}Au	26.348 ± 0.010 59.543 ± 0.015	433 y

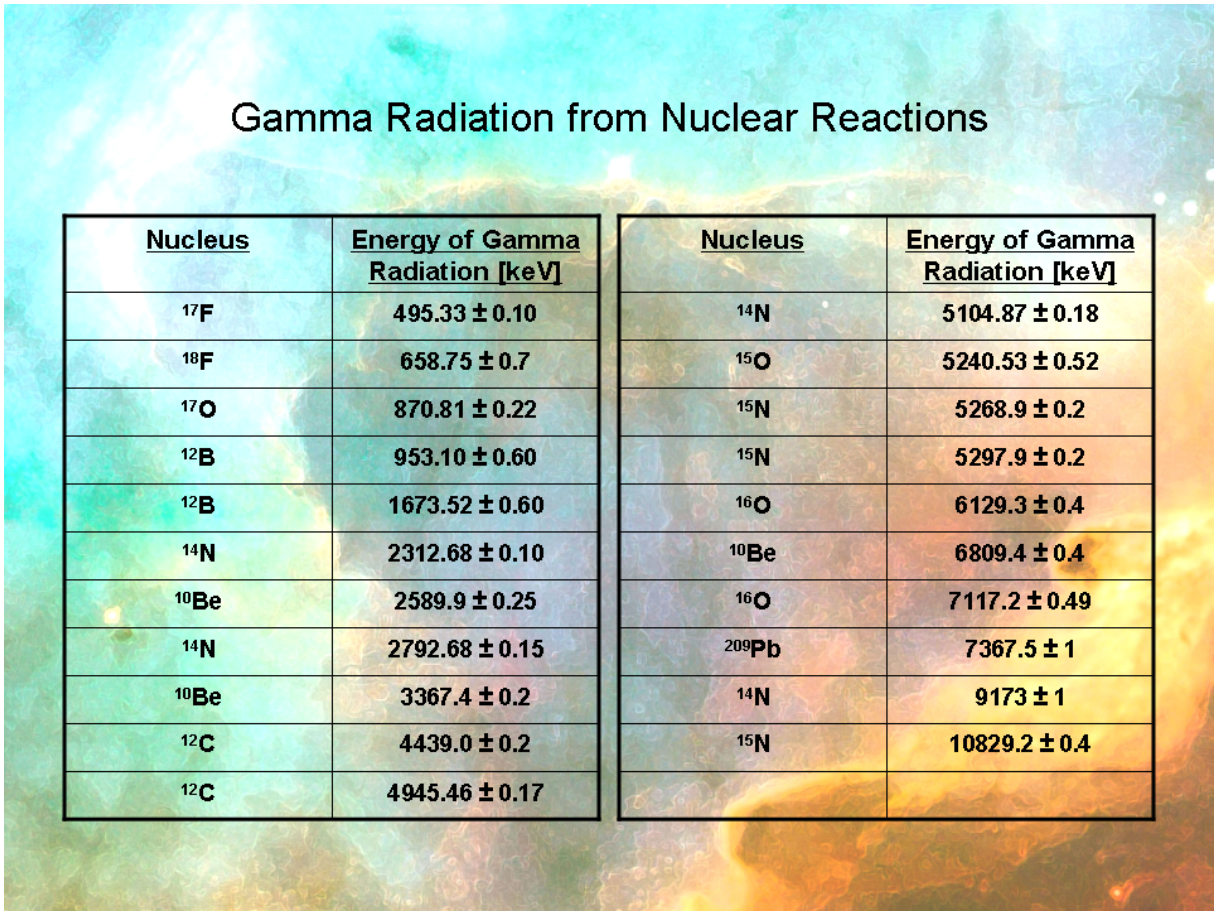
Co^{56} Energy [keV]	Co^{56} Relative Intensity
733.79 ± 0.19	0.1 ± 0.05
787.92 ± 0.15	0.40 ± 0.11
846.76 ± 0.05	100
977.47 ± 0.13 1037.97 ± 0.07	1.52 ± 0.16 13.02 ± 0.35
1175.26 ± 0.13	1.86 ± 0.23
1238.34 ± 0.09	69.35 ± 1.47
1360.35 ± 0.09 1771.57 ± 0.10	4.38 ± 0.16 15.30 ± 0.53
1964.88 ± 0.45	0.72 ± 0.08
2015.49 ± 0.20 2035.03 ± 0.12	2.93 ± 0.16 7.33 ± 0.30
2113.00 ± 0.10	0.37 ± 0.08
2598.80 ± 0.12	16.77 ± 0.57
3009.99 ± 0.24 3202.25 ± 0.19 3253.82 ± 0.15	0.84 ± 0.16 3.15 ± 0.16 7.70 ± 0.34
3273.38 ± 0.18 3452.18 ± 0.22 3548.11 ± 0.25	1.55 ± 0.11 0.88 ± 0.10 0.18 ± 0.01

Figure 25: Alternative list of radioactive sources for gamma ray spectroscopy together with the list of lines from a ^{56}Co source.

Multiple Gamma Rays Emitted in the Decay of ^{152}Eu

Energy (keV)	Relative Intensity
121.8	141. ± 4.
244.7	36.6 ± 1.1
344.3	127.2 ± 1.3
367.8	4.19 ± 0.04
411.1	10.71 ± 0.11
444.0	15.00 ± 0.15
488.7	1.984 ± 0.023
586.3	2.24 ± 0.05
678.6	2.296 ± 0.028
688.7	4.12 ± 0.04
778.9	62.6 ± 0.6
867.4	20.54 ± 0.21
964.0	70.4 ± 0.7
1005.1	3.57 ± 0.07
1085.8	48.7 ± 0.5
1089.7	8.26 ± 0.09
1112.1	65.0 ± 0.7
1212.9	6.67 ± 0.07
1299.1	7.76 ± 0.08
1408.0	100.0 ± 1.0
1457.6	2.52 ± 0.09

Figure 26: List of the gamma lines of a radioactive ^{152}Eu source used as a calibration standard for efficiencies.



Gamma Radiation from Nuclear Reactions

Nucleus	Energy of Gamma Radiation [keV]
^{17}F	495.33 ± 0.10
^{18}F	658.75 ± 0.7
^{17}O	870.81 ± 0.22
^{12}B	953.10 ± 0.60
^{12}B	1673.52 ± 0.60
^{14}N	2312.68 ± 0.10
^{10}Be	2589.9 ± 0.25
^{14}N	2792.68 ± 0.15
^{10}Be	3367.4 ± 0.2
^{12}C	4439.0 ± 0.2
^{12}C	4945.46 ± 0.17

Nucleus	Energy of Gamma Radiation [keV]
^{14}N	5104.87 ± 0.18
^{15}O	5240.53 ± 0.52
^{15}N	5268.9 ± 0.2
^{15}N	5297.9 ± 0.2
^{16}O	6129.3 ± 0.4
^{10}Be	6809.4 ± 0.4
^{16}O	7117.2 ± 0.49
^{209}Pb	7367.5 ± 1
^{14}N	9173 ± 1
^{15}N	10829.2 ± 0.4

Figure 27: List of gamma lines produced by nuclear reactions for standard calibration purposes.

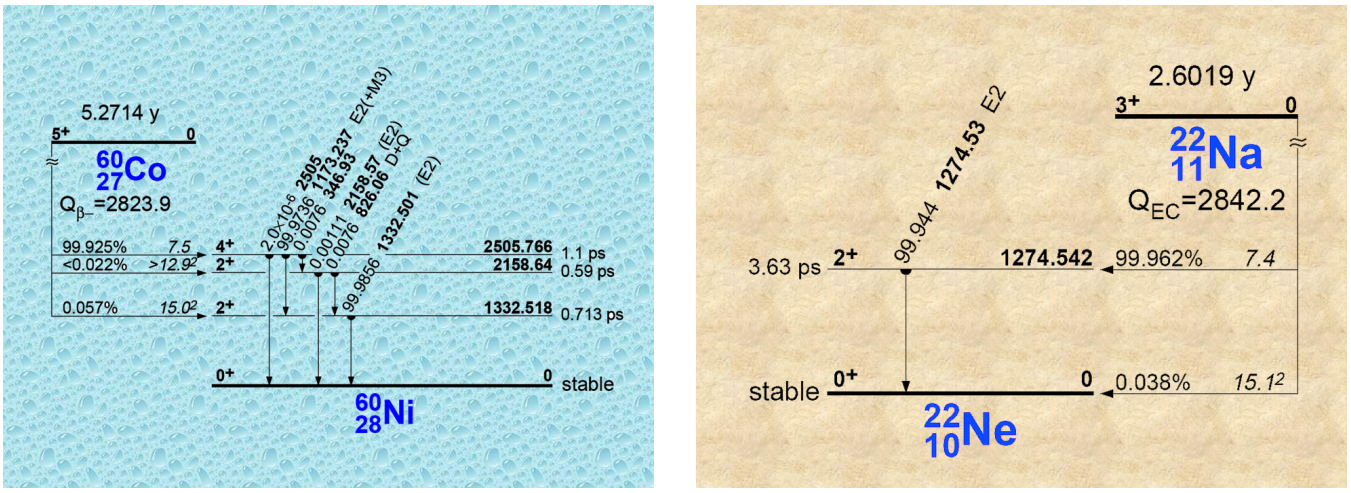


Figure 28: Decay scheme of ^{60}Co (^{60}Ni) and ^{22}Na (^{22}Ne) used as standard calibration sources.

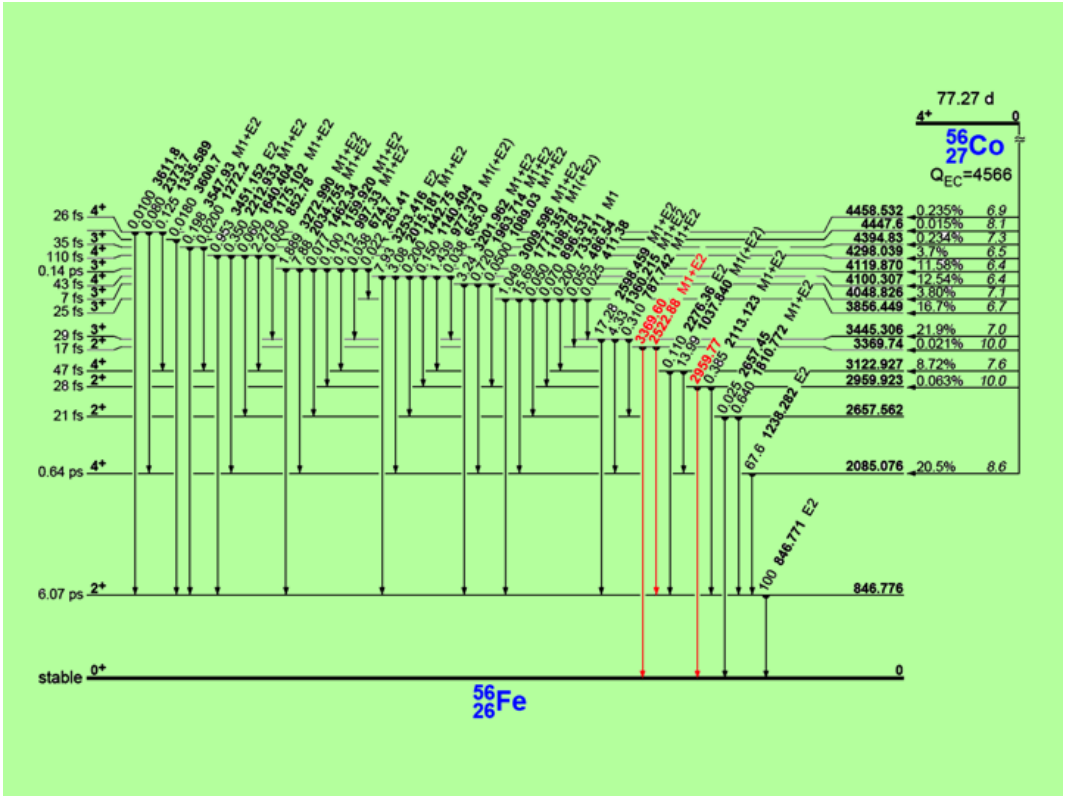


Figure 29: Decay scheme of ^{56}Co from [11], a common used multiline source with gamma-lines up to 3.5 MeV.

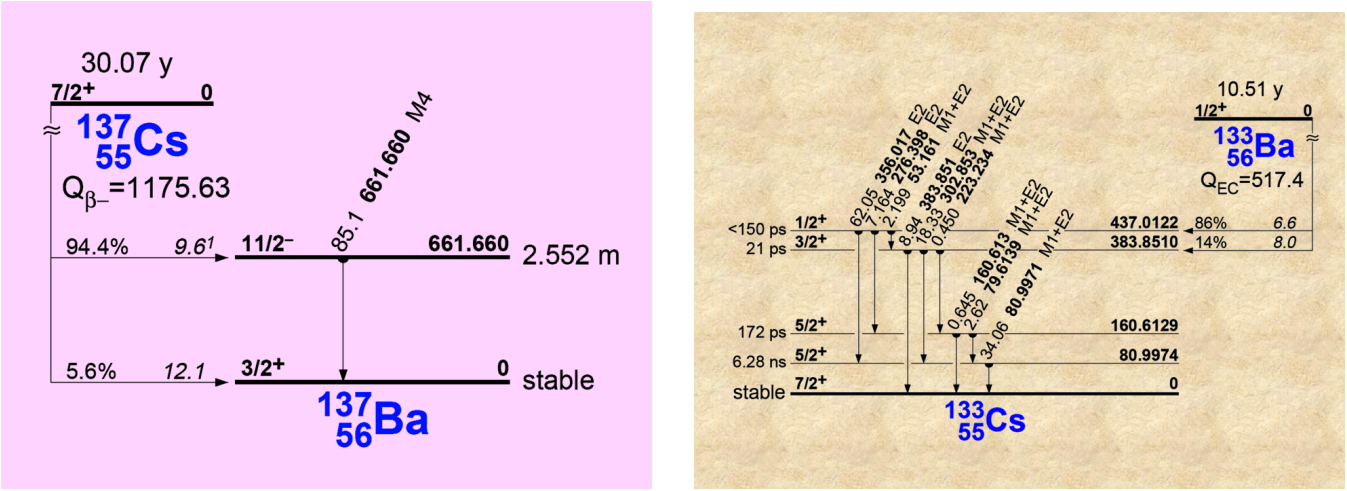


Figure 30: Decay scheme of ^{137}Cs and ^{133}Ba, calibration sources useful for the medium energy range.

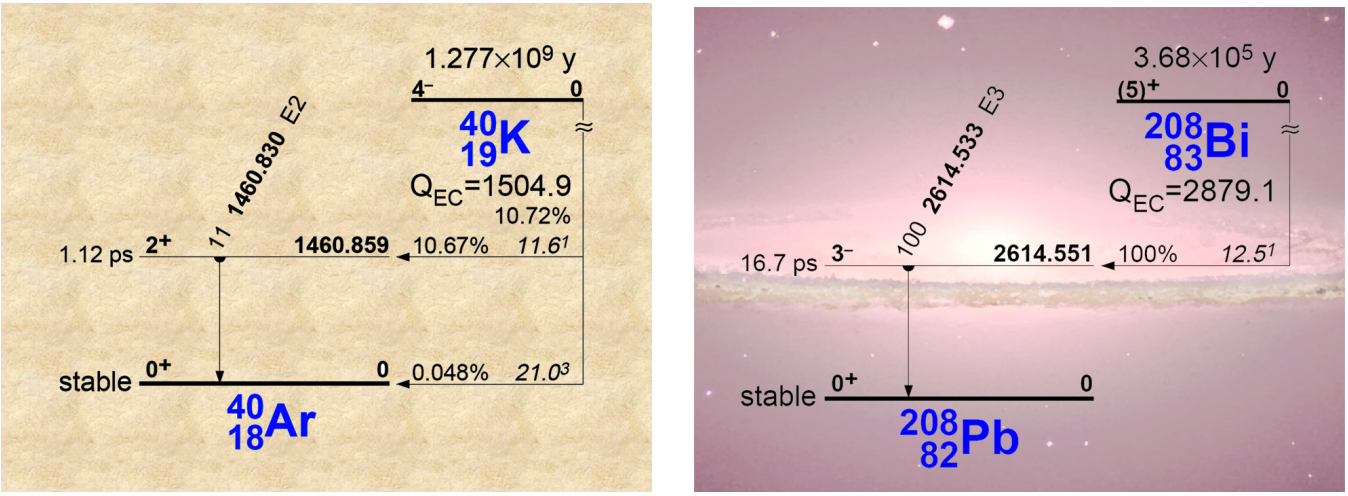


Figure 31: Decay scheme of ^{40}K and ^{208}Bi, two long living natural radioactive sources used for calibration purposes.

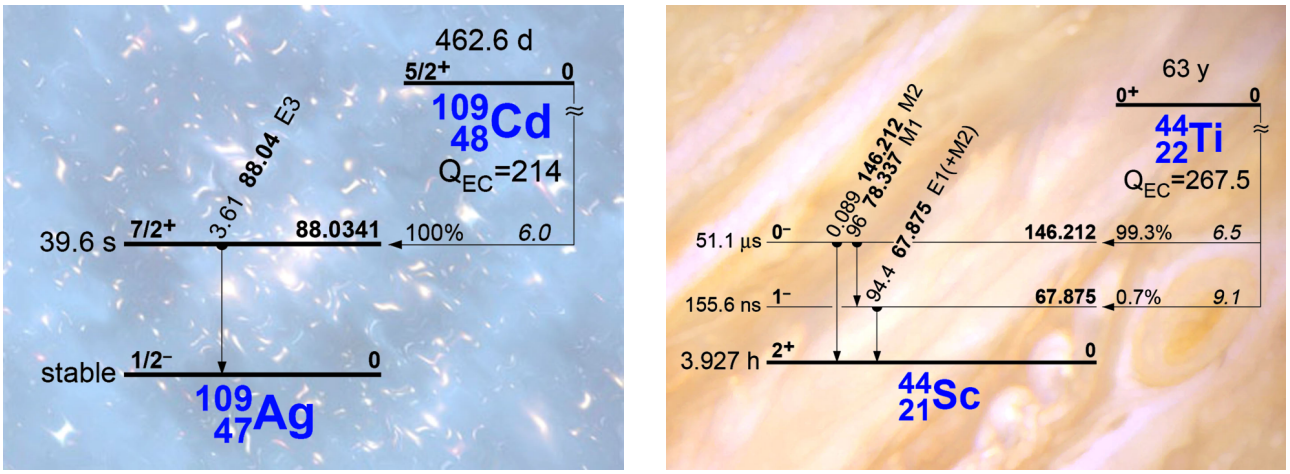


Figure 32: Decay scheme of ^{109}Cd and ^{44}Ti, two standard calibration sources for the lower energy range.

Sources for the measurement task

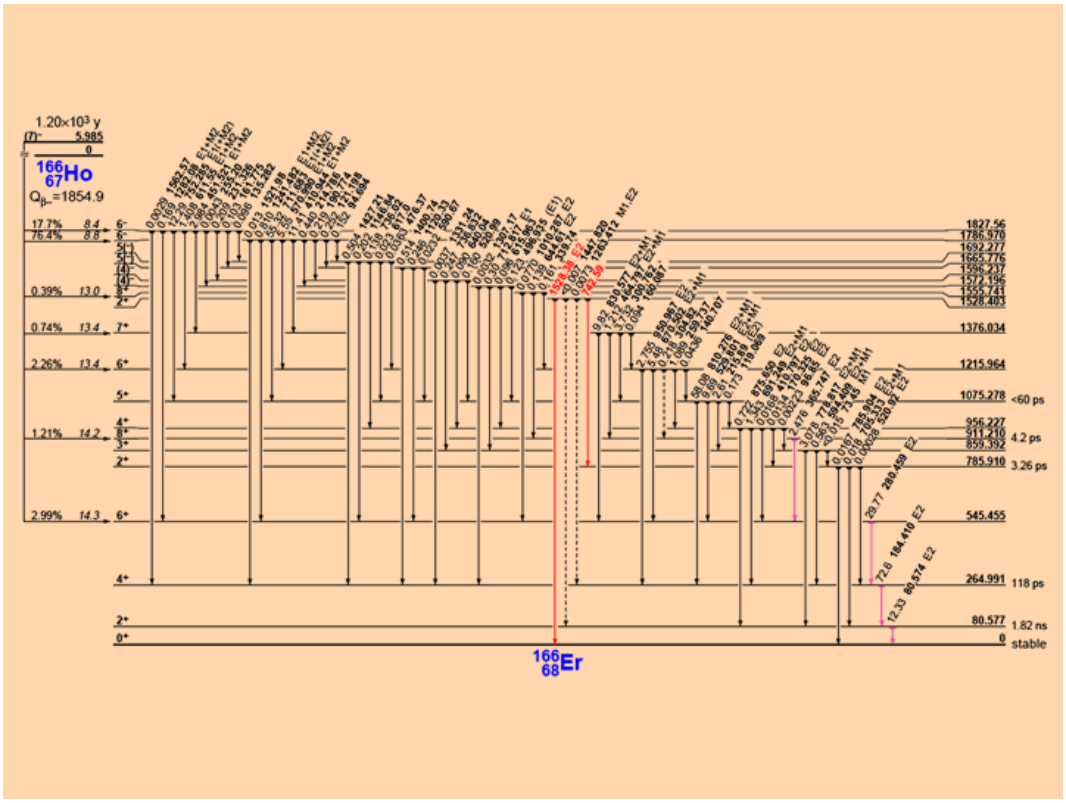


Figure 33: Decay scheme of ^{166m}Ho from [11], used to measure the ground state rotational band of ^{166}Er and for the determination of the momentum of inertia of the ^{166}Er nucleus.

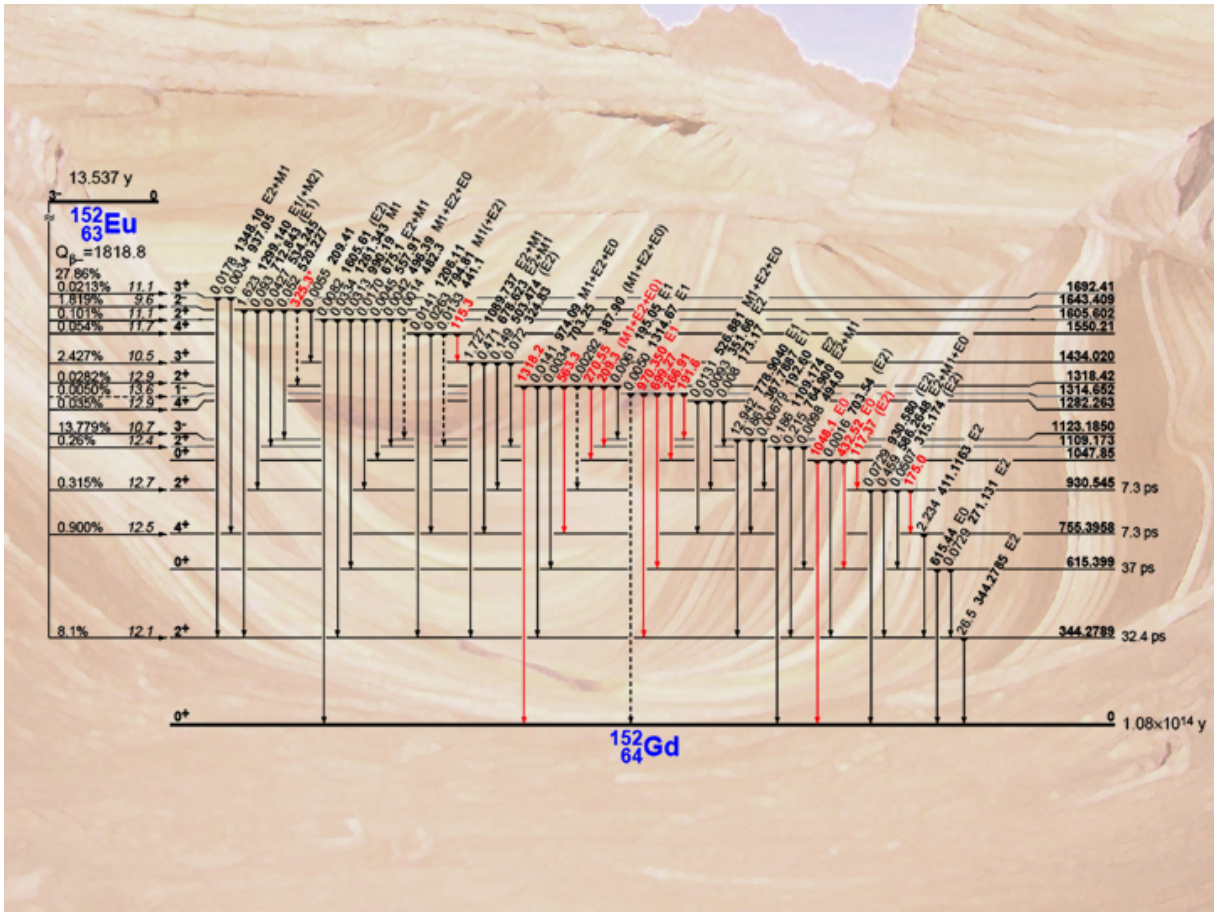


Figure 34: Decay scheme of ^{152}Eu from [11], used to exercise the determination of a decay scheme.

D. Discussion of Results

- Provide a documentation of the calibration measurement (graphs) and the measurement of the main spectrum of Ho-166m
- Evaluate the lines of the members of the rotational band
- Apply the model of a rigid rotator and a liquid drop rotator and compare with your results

E. Example Questions

- What is multipole radiation and which rules are valid concerning γ-transitions?
- Why is it multipole-radiation in the case of γ's and not simply dipole radiation as in the case of visible light from atoms?
- What is the difference between X-rays and γ-rays? Production mechanism : atom/nucleus
- Which parameters of nuclei can be studied from γ-spectroscopy? (E_γ, τ, J_π, conversion coefficient α, mixing, $\gamma\gamma$-angular correlation, polarization (Compton))
- What is internal conversion?
- What is the "natural line width" and how can it be observed?
- How can the polarization of γ-rays be determined?
- Nuclear models and γ-spectroscopy
- What kinds of γ-detectors do you know?
- Which effects are used for γ-detection?
- Describe these effects, dependence on atomic number Z and on E_γ?
- How is a Ge-detector working (like a semiconductor ionization chamber)
- What makes the resolution of a detector, compare several with different resolution?
- Describe the scintillation detector and some different types of crystals and their properties
- What is efficiency of a detector?
- What is the principal difference between the detection and spectroscopy of gammas and of charged particles?

- What is the purpose of a main spectroscopic amplifier?
- What is a line shape and how is it defined?
- What device is usually used to extract information from a scintillating material? Describe briefly its operation.
- How is the peak intensity derived from a gamma-spectrum for usual peaks?
- What are the practical methods of background consideration (subtraction) when evaluating a gamma-spectrum?
- What is the best method for measuring precise gamma-energies?
- What is the purpose of so-called detector-balls, what can be measured?

9 Compton Effect

Location: room Jordan 308

A. Short Description

The Compton effect is one of the most fundamental effects: scattering of high energetic photons off a free or bound electron. It is important for the understanding of basic quantum mechanical effects and it demonstrates that light cannot be explained purely as a wave phenomenon. Thomson scattering, the classical theory of an electromagnetic wave scattered by charged particles, cannot explain any shift in wavelength. Light must behave as if it consists of particles in order to explain the Compton scattering. The discovery of Compton effect established the wave - particle dualism.
In this experiment the energy shift of the scattered gamma radiation and the scattering cross-section are examined in relation to the scattering angle. In the present set-up the probes are ring-shaped, allowing one to get a much higher scattered yield than with standard geometry.
Using angles from 20 to 165 degrees, the Compton relationship can be determined for the energy shift with an error of 3%. The Klein-Nishina formula provides an accurate prediction of the angular distribution of X-rays and gamma-rays which are incident upon a single electron. The Klein-Nishina formula, derived in 1929 by Oskar Klein and Yoshio Nishina, describes the differential cross section or in other words the probability of incoherent or Compton scattering. It was one of the first results obtained from the study of quantum electrodynamics. The validity of the Klein-Nishina formula for the effective cross-section can be proven in this experiment with an error of approximately 10%.

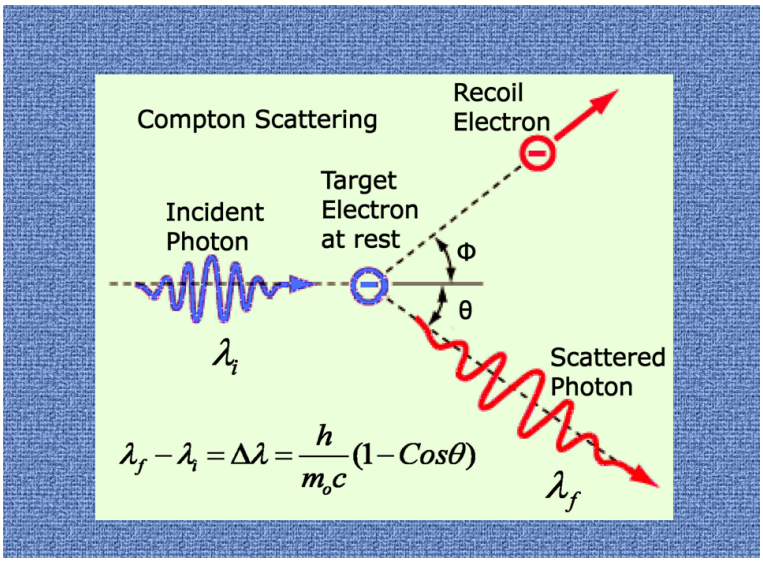


Figure 35: Scheme of Compton Scattering = scattering of a photon off bound or free electrons.

B. Necessary Knowledge

Physics :

- Theory of the Compton effect = Scattering of γ's off electrons
- Energy and momentum conservation
- Klein-Nishina formula
- Interaction of γ's with matter
- Absorption of γ's in matter
- Corrections required for the chosen set-up : Multiple scattering; absorption in the ring samples; variable solid angles; virtual source is off-axis which modifies the efficiency, efficiency for a collimated detector.

Measuring Technique :

- Principles of Gamma detectors, especially NaI(Tl) detectors
- Principles of γ-spectroscopy
- Photomultipliers and basic electronics
- Advantage of collimated detector geometry (compare with anti-Compton shield)

- Advantage of ring samples (compare with other methods for the Compton effect measurement)

Mathematics : Method of least squares, spectrum stripping, peak evaluation with background subtraction

Energy Shift

Applying energy and momentum conservation one obtains:

$$E'_\gamma = \frac{E_\gamma}{1 + (E_\gamma/mc^2)(1 - cos\,\theta)}$$

Some formulae

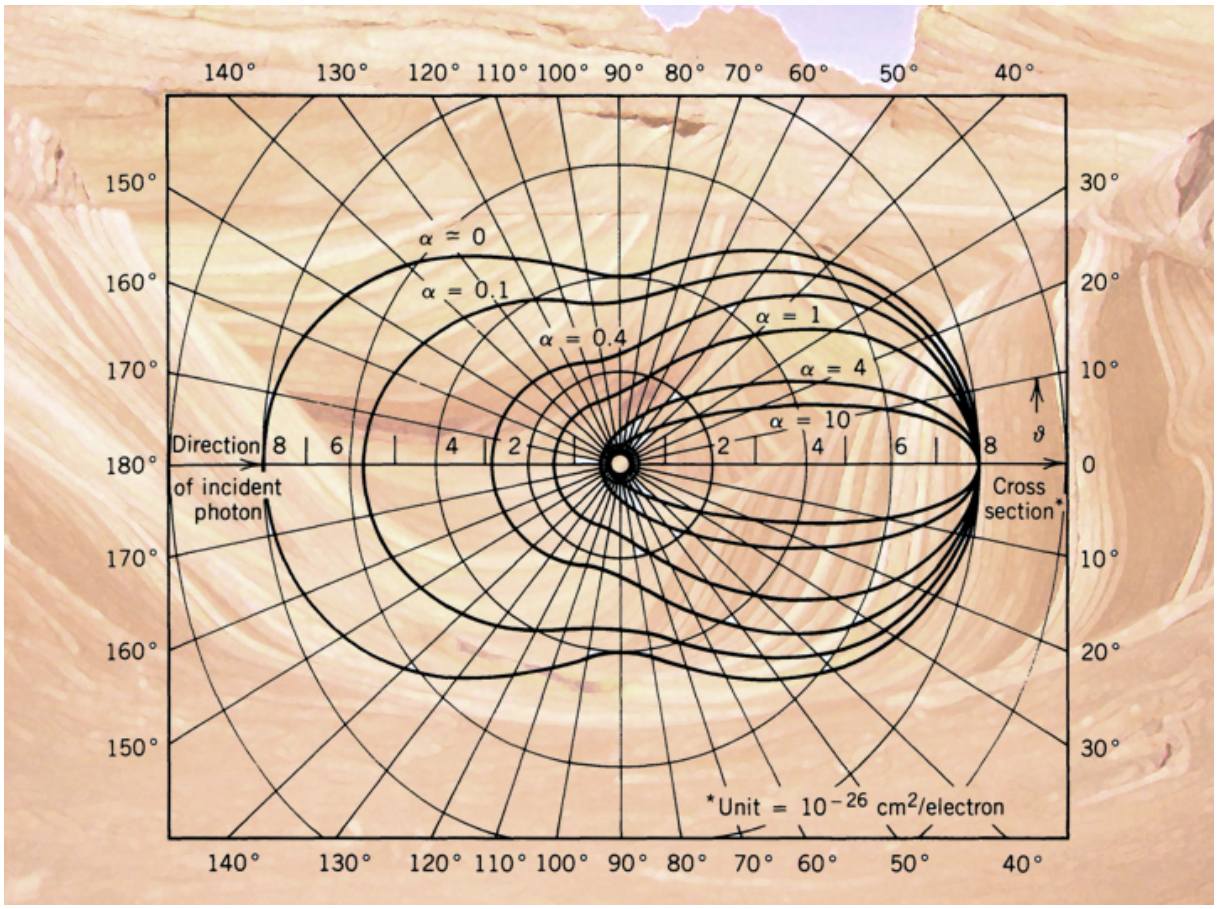


Figure 36: Compton-scattering cross section for various incident energies. This cross section is described by the Klein-Nishina formula. The polar plot shows the intensity of the scattered radiation as a function of the scattering angle θ. (From R.D. Evans, *The Atomic Nucleus*, Mc. Graw Hill 1955).

Klein-Nishina Cross Section

$$\frac{d\sigma_c}{d\Omega} = r_0^2 \left[\frac{1}{1 + \alpha\,(1 - cos\,\theta)}\right]^3 \left[\frac{1 + cos\,\theta}{2}\right] \times \left[1 + \frac{\alpha^2\,(1 - cos\,\theta)^2}{(1 + cos^2\theta)\,[1 + \alpha\,(1 - cos\,\theta)]}\right]$$

The photon energy is given in units of the electron rest energy $\alpha = E_\gamma/mc^2$ and r_0 is the *classical electron radius* $r_0 = e^2/4\,\pi\,\epsilon_0\,mc^2$ = 2.818 fm

References

[1]	**Compton, A., H. :** A Quantum Theory of the Scattering of X-rays by Light Elements Phys. Rev. **21**, 483 (1923)	Original article on the 'Compton' effect
[2]	**Döbling, Elke :** Der Compton-Effekt als Praktikumsversuch Thesis of high school teachers, University of Stuttgart 1997	Original thesis on this teaching lab experiment
[3]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics
[4]	**Melissinos, A. C. and Napolitano J.:** Experiments in Modern Physics Academic Press, Amsterdam etc. 2003	Textbook on Modern Physics Experiments
[5]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[6]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard work on detectors

Experimental Tasks

- Set-up of detector and electronics using a weak ^{137}Cs source, put source above the end of the shadow bar. Never change the detector position and holder!
- Calibrate the detector with 662 keV line and the Ba K_α-line from the Cs-137 source
- Determine standard detector resolution
- Set MCA to 512 channels
- Align source, sample, shadow bar and detector very precisely to the optical axis
- First think about an optimal setting for the scattering angles, work out a scheme

- Measurement of 2 angular distributions using the strong ^{137}Cs source for Cu or Al:
  1. Energy of scattered γ's in dependence of scattering angle
  2. Angular distribution of the scattering cross section (Klein-Nishina)
- Always use differential measurement with equal time for ring-sample-in and Űout spectra; use subtraction (stripping) function for the spectra
- Determine uncertainties

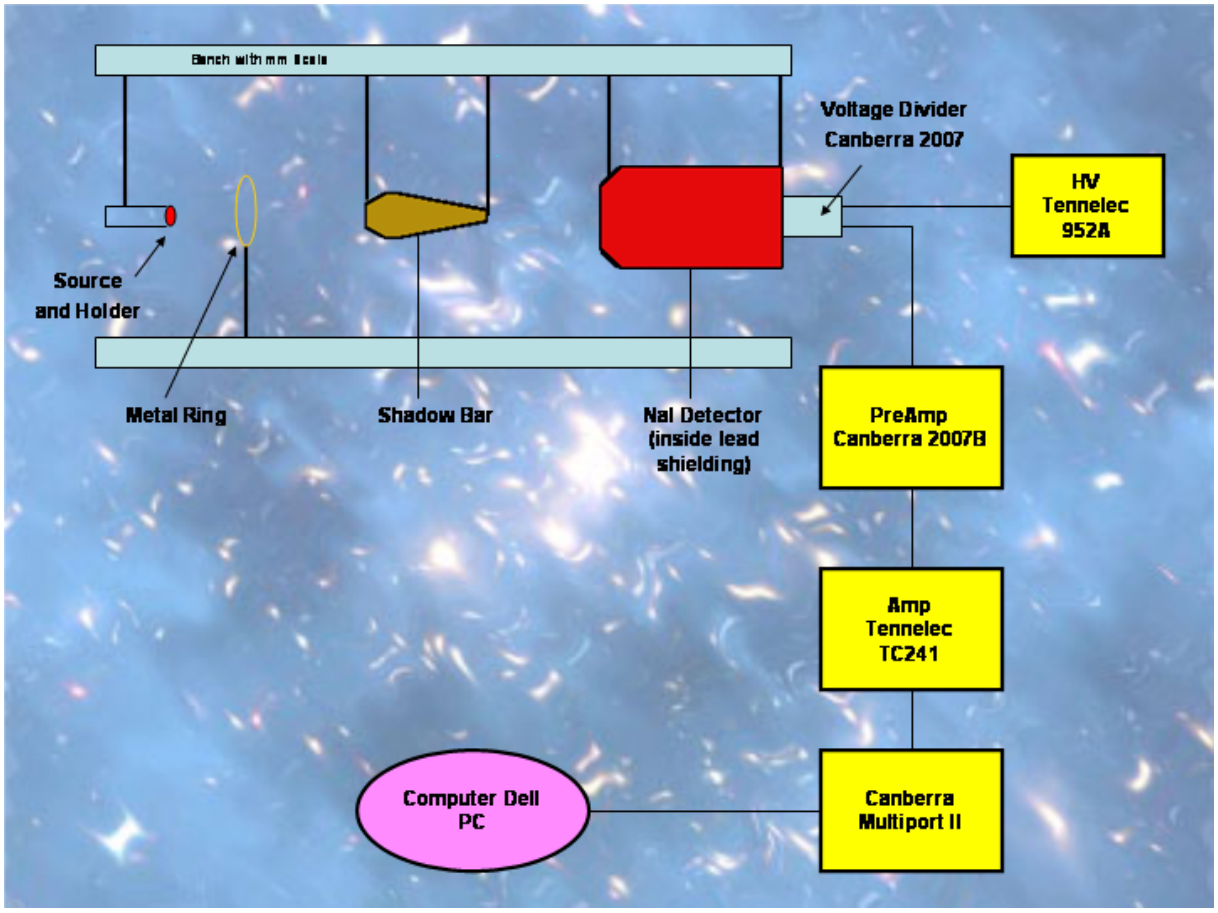
- Compare Compton effect for Cu and Al at one convenient angle

WARNINGS

- Keep distance from the strong ^{137}Cs source, stay behind lines marked on the floor!
- Be careful when moving the shadow bar so it doesn't fall (don't loosen the screws too much).

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

source :	Pointlike ^{137}Cs source for the scattering
ring :	There are 3 ring samples with (neutral) diameters 10, 14 and 20cm for copper and and for aluminum, they are pre-aligned in holders "A", "B" and "C"; exact alignment being very important, also the gap on top for sliding the other holders. Material diameter of the ring samples is 8mm.
shadow :	Shadow bar made of brass to hold off direct radiation from the source to the detector, make sure that the shadow bar doesn't limit the path of the scattered photons, use a slab
det :	NaI(Tl) detector 3x3" in a lead collimator with opening 50mm

Div :	Voltage divider Canberra 2007 for positive voltages, here apply + 830 Volts
HV :	High Voltage power supply for the detectors, Tennelec # 952A
Preamp :	Preamp to match the output impedance to 50 Ohms
amp :	Amplifier Tennelec # 241, used in bipolar mode
MCA :	USB-port Multichannel Analyzer Canberra Multiport II using the Genie 2000 software with dongle

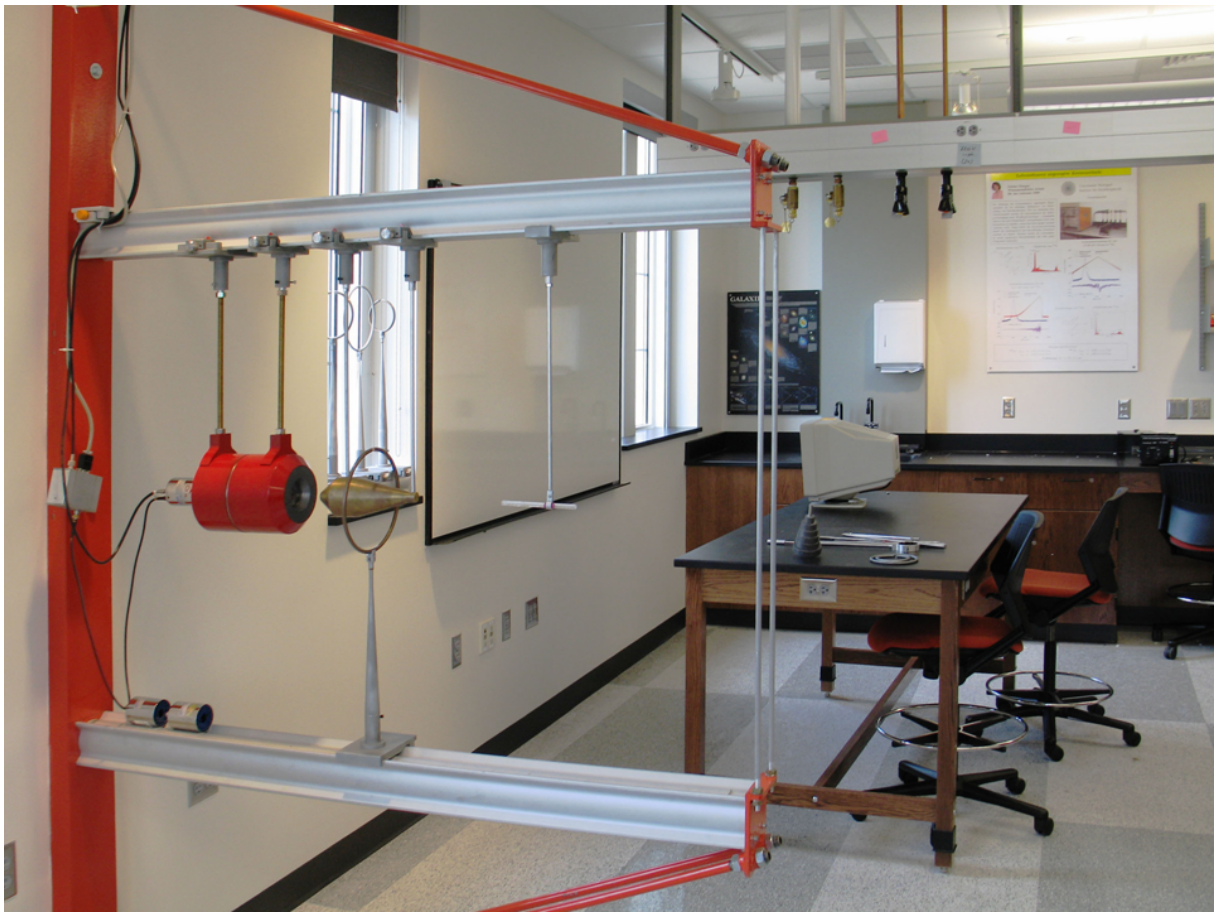


Figure 37: Set-up of the the Compton experiment with ring geometry for cross section determination. Note the considerable distances for all structural elements which contribute to background.

Figure 38: Other view of the Compton experiment setup with central parts: source, ring-sample, shadow-bar, detector.

Information regarding the Experimental Procedure

1. Scattering spectra should be taken for the following parameters: (t = Measuring time, s = Distance from source to detector, s_1 = Distance from source to the ring, r = Ring radius):

2. For the angle $\theta = 60°$ collect an additional scattering spectrum using the copper ring with cm $r = 7$ instead of the aluminum ring.

θ	20°	30°	45°	60°	75°	90°	105°	120°	135°
r [cm]	5	5	7	7	10	10	10	10	10
s [cm]	60	60	44	30	30	30	30	40	40
s_1 [cm]	21,9	10,1	11,6	7,6	8,3	3,8	0,7	-3,0	-6,5
t [s]	600	300	300	300	300	300	300	300	600

Table 1: r = ring radius, s = distance from source to detector, s_1 = distance from source to ring, t = run time.

Additional Formulae

Calculation of the scattering angle θ with respect to s, s_1 and r:

$$\tan\theta = \frac{rs}{s_1(s-s_1) - r^2}$$

Calculation of the quanta emitted per second of the source Q:

$$Q = \frac{4\pi Z}{\Omega\epsilon(E)},$$

where

$$\Omega = \frac{\pi {r_{\mathrm{Det}}}^2}{a^2},$$
$$\epsilon(E) = 1,102\mathrm{e}^{-2,4408E/1000},$$

with:

a:	Distance between the source and detector
E:	Energy of the quanta emitted by the source in keV
ϵ:	Efficiency of the detector
Ω:	Solid angle that the detector covers
r_{Det}:	Radius of the detector
Z:	Number of the quanta registered per second in the photo peak

Calculation of the differential cross section W:

$$W = \frac{Z_\theta\, 4\pi\, (s_1^2 + r^2)}{Q\, \Omega_2\, \epsilon(E_\theta)\, N_e},$$

where

$$N_e = \frac{V \rho \, Z N_L}{A},$$

$$\Omega_2 = \frac{\pi \, {r_{\mathrm{Det}}}^2}{r^2 \, + \, (s - s_1)^2},$$

with:

A:	Atomic mass
E_θ:	Energy of the scattered quanta in keV
N_L:	Avogadro's constant
Ω_2:	Solid angle that the detector covers
ρ:	Density of the ring material
V:	Volume of the rings
Z:	Nuclear charge
Z_θ:	Number of the scattered quanta registered per second

Additional Data

Radius of the Aluminum Rings:

r_1 =5 cm

r_2 =7 cm

r_3 =10 cm

Radius of the cross section of the aluminum rings:

$r = 0,4$ cm

Radius of the copper rings:

r =7 cm

Cross section of the aluminum rings:

$q = 2 \cdot 2$ cm^2

Energy of the γ-quanta emitted from ^{137}Cs:

$E = 662$ keV

Energy of the Pb Line:

E =75 keV

Energy of the ^{57}Co-Line:

E =122 keV

The computed cross-sections are to be multiplied by the correction factors (due to self absorption of the scattered quanta) c

θ	20°	30°	45°	60°	75°	90°	105°	120°	135°
c	1.57	1.582	1.613	1.658	1.705	1.745	1.795	1.87	1.934

Information about radioactive sources

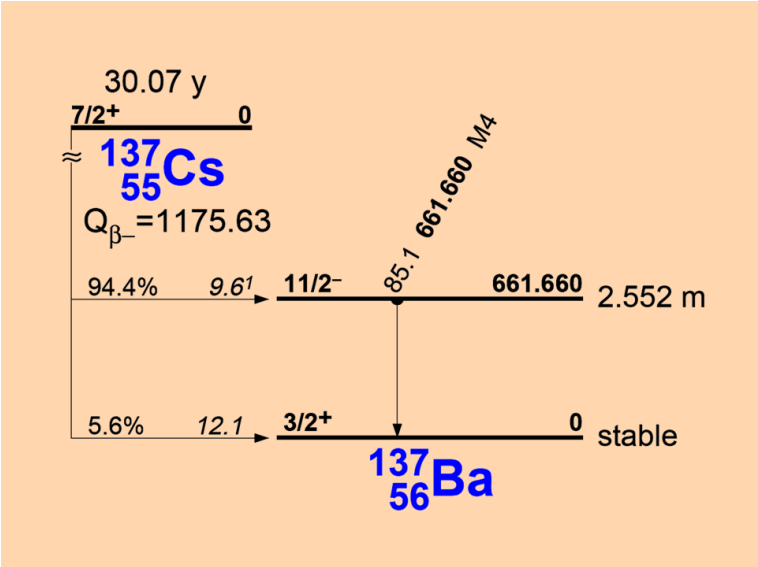


Figure 39: Decay scheme of ^{137}Cs from [5].

D. Discussion of Results

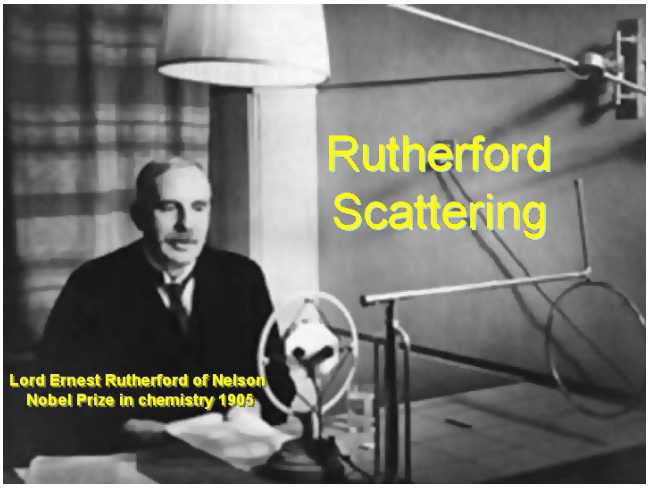
- Provide diagrams of both angular distributions: energy shift and Klein-Nishina cross section
- Calculate the corrections and the uncertainties
- Show at least three examples of Compton scattering spectra (at 20°, 75° and 135°, total and background subtracted

E. Example Questions

- What principal interactions are known for gamma's with solid matter, energetic dependencies and range of importance?
- What is the Compton effect and how can it be studied?
- What dependences can be observed in a Compton experiment?
- Discuss different geometries of a setup, advantages and disadvantages.
- Would we need a Ge-detector for this experiment?

- Discuss necessary corrections for this measurement. (Finite geometry, correction of varying solid angle, correction of absorption in the sample).
- Explain the detector used in the Compton experiment.
- What is the advantage using that kind of collimator?
- Explain the energy dependence of the Compton effect
- What Z-dependence can be observed?

10 Rutherford Scattering



Location: room Jordan 308

A. Short Description

Rutherford scattering is based on the elastic deflection of charged particles in the Coulomb field of an atomic nucleus. It can be observed and measured by radiating α-particles on a thin metallic foil and measuring the angular distribution of the scattered α's behind that foil. The intensity of the α-particle beam varies with the deflection angle and the proton number of the used material (see formula). Rutherford's measurement was the basis of Bohr's atomic model and determined the size of the nucleus for the first time.
In this experiment both the angular and the Z-dependence can be measured in a broad dynamic range (up to six orders of magnitude!). However some corrections due to the thickness of the foil which causes multiple scattering and angular straggling are necessary. For this purpose a special scattering chamber has been designed with fixed detector, rotational α source from -44°.... 0°..... +144° and a sliding frame with three foils and one empty frame to measure also the Z-dependence without breaking the vacuum. Collimators have been provided in front of the strong ^{241}Am source and of the silicon particle detector. Clean vacuum is obtained by the use of an cryo-sorption pump. Nowadays Rutherford scattering is applied for material analysis and as a cross section calibration in nuclear experiments.

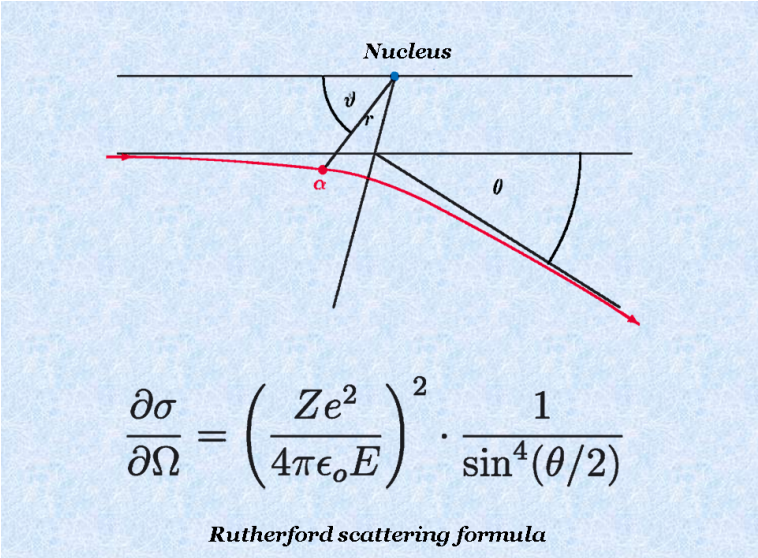


Figure 40: Principle of Rutherford scattering = scattering by the Coulomb force.

B. Necessary Knowledge

Physics :

- Bohr's theory of the atom
- Rutherford's experiment
- Theory of the scattering, two body problem
- Definition of the cross section
- Derivation of the Rutherford scattering cross section σ_{Ruth}
- Z-dependence and angular dependence
- Energy loss and straggling : corrections for the measurements
- Deviations from sRuth at higher energies : nuclear interaction

Measuring Technique :

- Radioactive α-emitters, preparation of α-sources
- Applications: 1. standard cross section for comparison and calibration;
  2. RBS-method
- Finite geometry corrections
- Physics of particle detectors, especially Si-detectors

- Electronics for spectroscopy
- Principles of vacuum techniques

Mathematics : Method of least squares

References

[1]	**Burger, Matthias :** Rutherford Streuung als Praktikumsversuch Thesis of high school teachers, University of Stuttgart 1997	Original thesis on this teaching lab experiment
[2]	**Rutherford, E. :** The Scattering of α and β Particles by Matter and the Structure of the Atom Phil. Mag. **21**, 669 (1911)	Original article on Rutherford Scattering and the Structure of the Atom
[3]	**Geiger, H. and E. Marsden :** On a Diffuse Reflection of the α-Particles Proc. Roy. Soc. **82**, 495 (1909)	Original article on new findings with scattering of α particles off a gold foil
[4]	**Geiger, H. and E. Marsden :** The Laws of Deflection of α-Particles through Large Angles Phil. Mag. **25**, 604 (1913)	Original article
[5]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics
[6]	**Melissinos, A. C. and Napolitano J.:** Experiments in Modern Physics Academic Press, Amsterdam etc. 2003	Textbook on Modern Physics Experiments
[7]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[8]	**Knoll H. G. :** Radiation Detection and Measurements John Wiley & Sons, New York 1989	Standard work on detectors
[9]	**Ziegler, J.F. :** Helium Stopping Powers and Ranges in All Elements Pergamon Press, New York 1977	Standard work on α Stopping Powers, see also the TRIM code
[10]	**Haferung, A :** Geschichte der Blattgoldschlägerei sowie Moderne Blattgoldherstellung Naturstein-Fachblatt für die Natursteinindustrie, Ebner Verlag Ulm **3**, 32 (1997)	Article on the preparation of extreme thin gold foils

Experimental Tasks

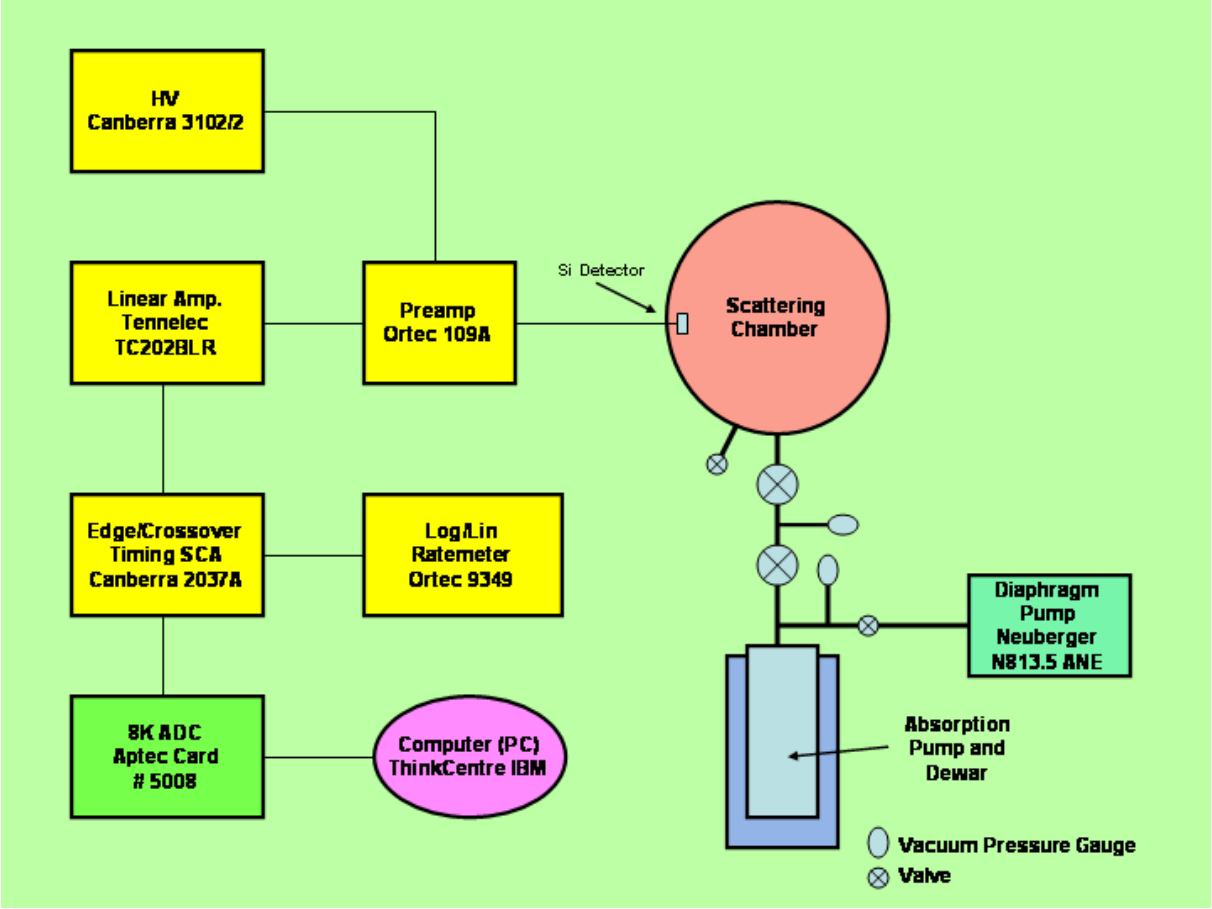
- Produce vacuum in the range 10^{-5} mbar (our instrument shows only 10^{-3} mbar)
- Switch on NIM-power
- Watch detector signal on oscilloscope and turn on slowly bias voltage of Si-detector (+ 25 Volts), angular position of ^{241}Am-source at 5° , gold foil
- Get a signal from the α-line at about 7 Volts and get the line at the MCA (set to 256 or 512 channels)
- Measure the line resolution with and without foil (angle 0°)
- Measure the angular distribution using the gold foil; the larger angles need longer measuring time, evaluate the line always at the MCA, consider background and uncertainties
- Determine the Z-dependence using the three foils Havar, Silver, Gold and an angle of 10°
- Consider energy loss, straggling and double scattering at small angles and correct for those effects

WARNINGS

- Close chamber window with black cover because Si-detector is light sensitive
- Don't forget to fill the dewar. For overnight runs: fill at least at 10-hourly intervals
- After finishing the measurement : hide source behind bar in order to protect the detector, a-source stays in the chamber
- Shut down detector bias
- Close the gate valve
- Never vent the chamber, get help if there is a problem.
- From time to time regeneration of the Zeolite is necessary, heating up with pumping using the forepump, main gate valve closed. Forepump (diaphragm) often starts only after venting. Your TA can help with this.

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

Detector :	Silicon surface barrier detector, about 30 mm dia., light sensitive
Bias :	Bias voltage for the Si-detectors, Canberra # 3102/2, bias voltage + 25 Volts.
pre-amp :	Preamplifier Ortec # 109A
Amp :	Main spectroscopy amplifier Tennelec # 202BLR
TSCA :	Timing single channel analyzer Canberra # 2037A to derive a standard signal for the ratemeter
Ratemeter :	Log/Lin Ratemeter Ortec # 9349 for quick evaluation and demonstration

MCA :	Multichannel Analyzer Aptec 5008A (ISA board in an industrial computer with passive backplane) working with Canberra Genie 2000 software (dongle!)
PC :	Industrial PC (DSM) with passive backplane and a so-called slot-CPU on a card board
forepump :	Two stage diaphragm pump, dry and oilfree, Neuberger N 813.5 ANE; endpressure about 25 mbar
Abs.pump :	Absorption pump with zeolite 5 Angstrom and stainless-steel-dewar, end pressure about 10^{-5} mbar.

Information about Havar

Havar, a heat treatable cobalt base alloy, provides very high strength at high temperatures, has excellent corrosion resistance and is non-magnetic. Applications have included pressure diaphragms, power springs, gap spacers in magnetic heads, and target foils in nuclear physics.

Analysis of the Havar-alloy in percent:

Co	Fe	Cr	Ni	W	Mo	Mn	C
42	bal.	19.5	12.7	2.7	2.2	1.6	0.2

Typical Physical Properties:

Density: 8.3 g/cm^3
Melting Point: 1480 °C
Electrical Resistivity (20 °C): 92 microhm $\cdot$ cm
Thermal Expansion Coefficient (0 °C to 50 °C): 12.5 x 10^{-6}/ °C
Thermal Conductivity: 13.0 W/m $\cdot$ K
Magnetic Attraction: None
Ultimate Tensile Strength: 1860 MPa
Modulus of Elasticity (Tension): 200 GPa

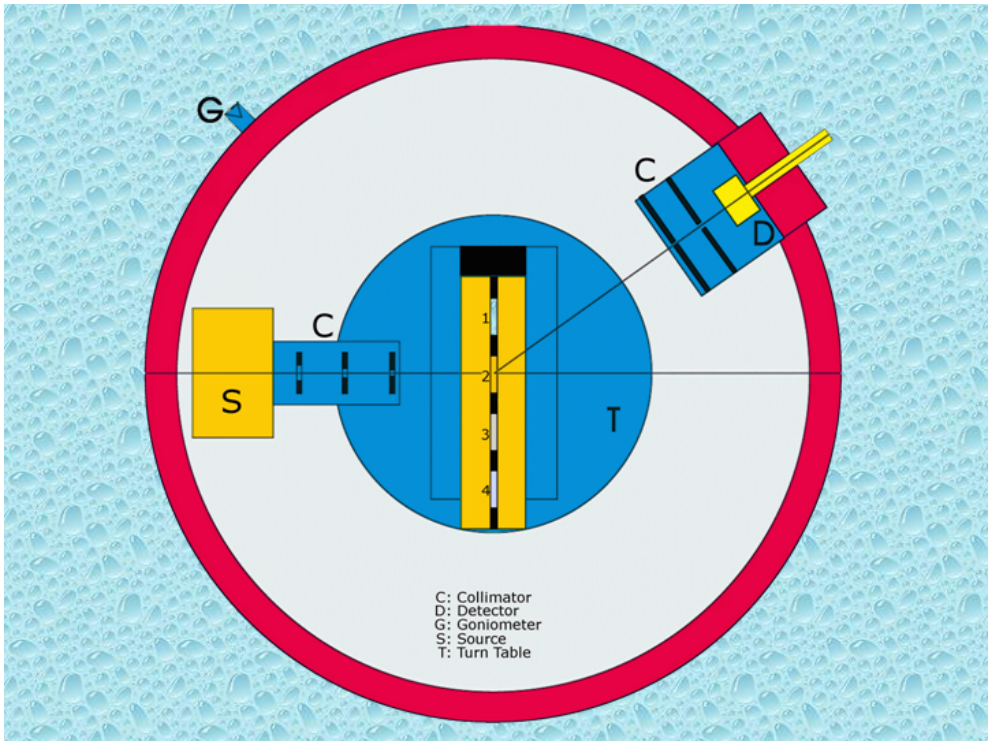


Figure 41: Cross section of the scattering chamber, especially designed for Rutherford scattering using a radioactive α-source. The detector is fixed and the source is moveable in the whole angular range. The incoming and the outgoing beam is collimated by rectangular collimators. At the center three foils (gold, silver, Havar) are located in a frame which can be moved without breaking vacuum, bringing each foil into the beam position, an additional empty frame serves for a measurement without foil.

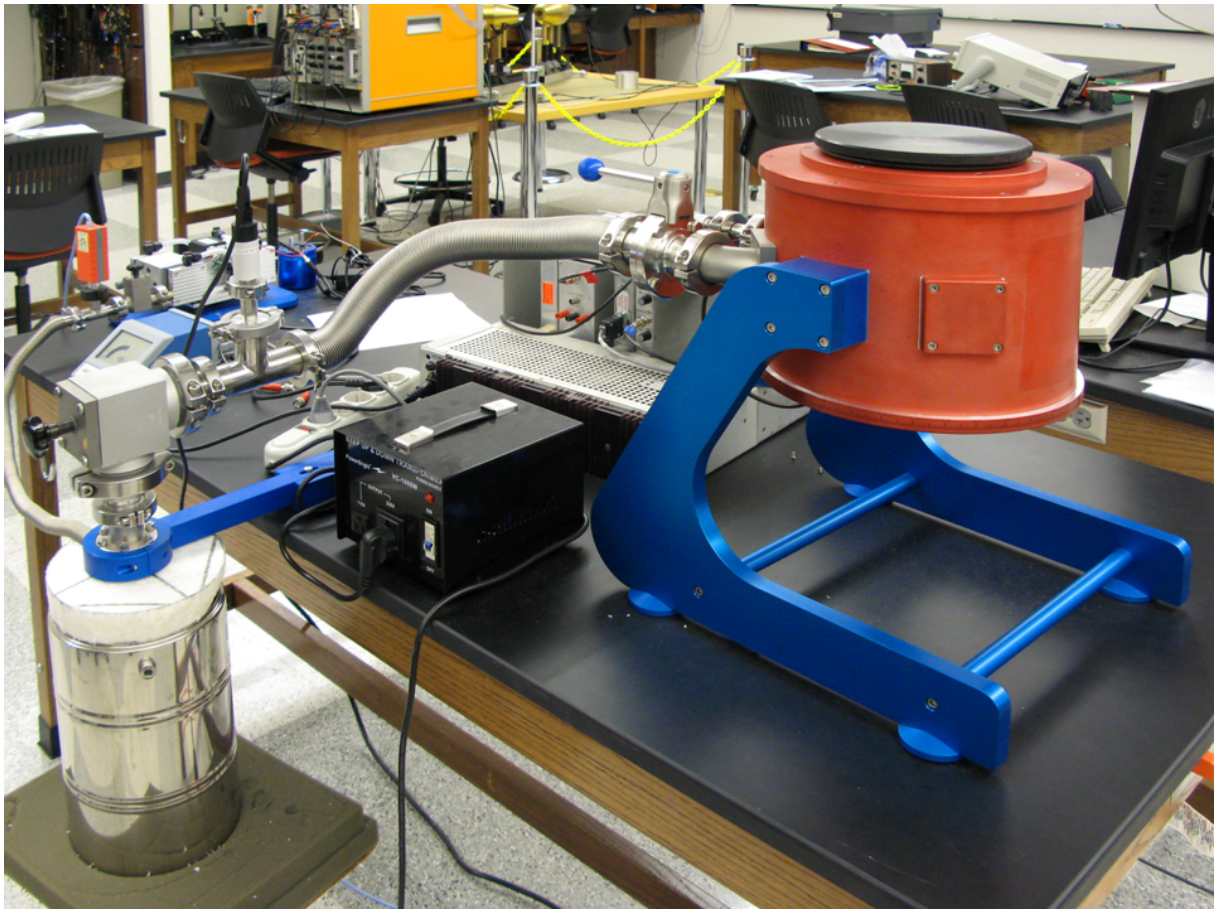


Figure 42: Rutherford scattering chamber and vacuum system.

Information about the radioactive sources

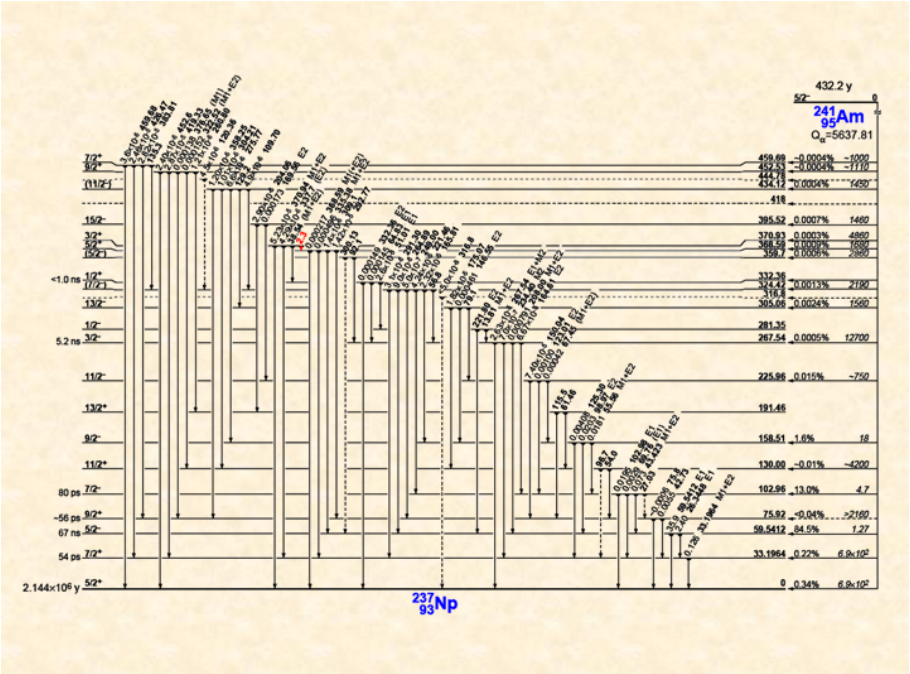


Figure 43: Decay scheme of ^{241}Am from [6].

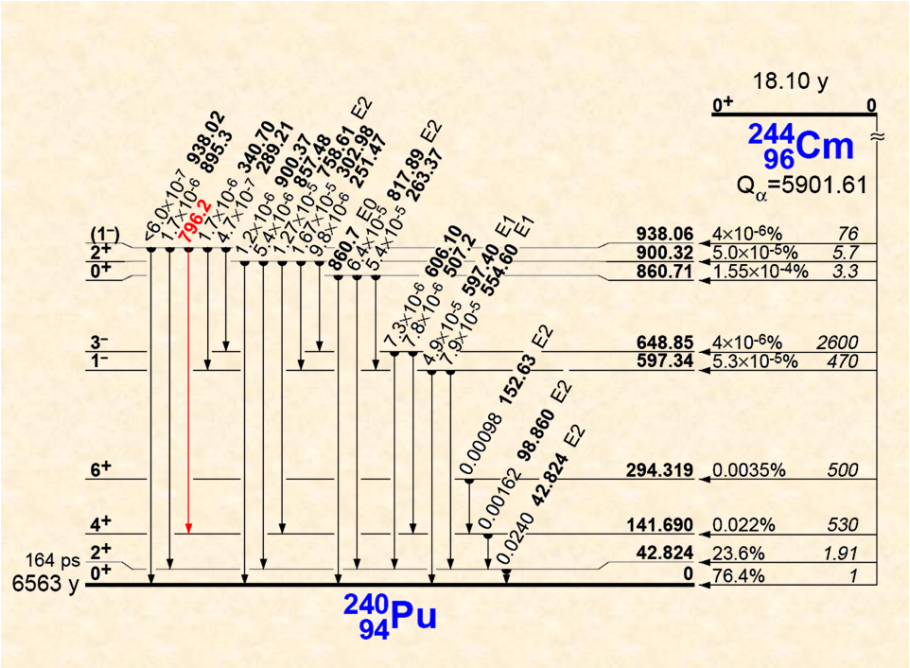


Figure 44: Decay scheme of ^{244}Cm from [6].

D. Discussion of Results

1. Provide a graph with experimental results of the angular distribution of scattered α particles off a gold foil together with a theoretical fit of the curve, present it on a linear and on a double logarithmic scale

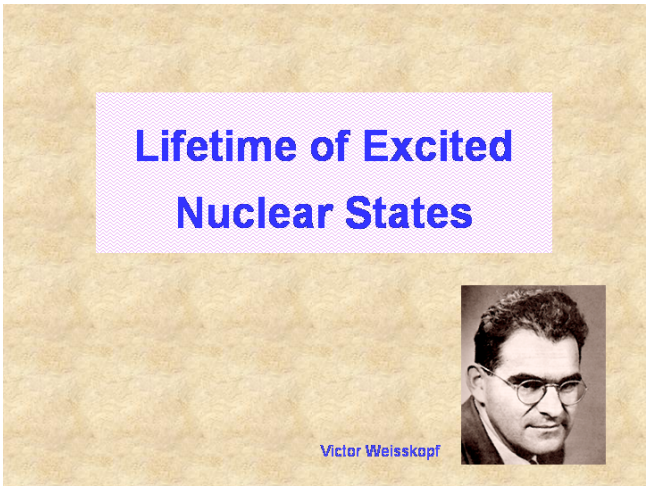
2. Provide some measurements of small angle scattering with derivation of corrections

3. Measure the Z dependence of α scattering for one or two fixed angles using the three foils gold, silver and Havar

E. Example Questions

- Is Rutherford scattering a nuclear physics experiment?
- What can be studied by Rutherford scattering? What was the exciting result of that experiment, when it was discovered the first time?
- Can we learn something about the strong force?
- Which forces do you know?
- Which force makes the Rutherford-scattering?
- Why is the Rutherford scattering still important for research in nuclear physics?

11 Lifetime of Excited Nuclear States



Location: room Jordan 308

A. Short Description

The lifetime of an excited nuclear state (level) is along with its energy, spin and parity an important and characteristic property required for nuclear model description. This experiment which makes use of the so-called delayed coincidence method is well suited for the milli- to nano-second time range. Two γ-transitions to and from an excited nuclear level provide the start and stop signal to measure the individual decay time of that level. Taking the decay time of many nuclei gives the whole decay curve in a major dynamic range to determine the lifetime with precision. For example with a dynamic range of about 1000:1 one obtains 8 half-lives. In this experiment the decays of ^{57}Co and ^{44}Ti are used to determine the lifetime of a level in ^{57}Fe and ^{44}Sc.

B. Necessary Knowledge

Physics :

- Heisenberg uncertainty principle
- Principles of nuclear level schemes
- Principles of γ-spectroscopy, physics, laws and rules
- Lifetime of a nuclear state, partial lifetimes
- Weißkopf model of γ-decay
- Short time measurement methods, overview
- Special: Method of delayed coincidences
- Method of Time-to-Amplitude Converter

Measuring Technique :

- Fast-Slow-method
- Function of NaI(Tl)-detectors
- Modular nuclear electronics: Pre-amplifier, Main Amplifier, Timing single channel analyzer, TAC (=Time-to-Amplitude-Converter), MCA (= Multichannel-Analyzer)
- Types of signals
- Time Calibrator, time resolution
- Energy calibration, energy resolution

Mathematics : Method of least squares

References

[1]	**Manger, Sabine :** Lebensdauern angeregter Kernzustände Thesis of high school teachers, University of Stuttgart 1998	Original thesis on this teaching lab experiment
[2]	**Cerny, J., Ed. :** Nuclear Spectroscopy and Reactions, Part A,B,C,D Academic Press, New York, 1974 and 1975	Standard compendium for Nuclear Spectroscopy
[3]	**Blatt, J.M. and V.F. Weisskopf :** Theoretical Nuclear Physics Dover publications (paperback) 1991	Standard textbook for Theoretical Nuclear Physics
[4]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics
[5]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[6]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard work on detectors

Experimental Tasks

- Set-up of detectors and HV (high voltage): negative HV = - 1800 Volts for both detectors from one power supply
- Check signals after pre-amp and amps choosing one of the two available sources for lifetime measurement ^{57}Co and ^{44}Ti; relevant γ-lines should have an amplitude of 1 – 2 Volts, not more, the anode output of the high voltage divider is not used and has to be closed with a 50 Ohms resistor, else the whole detector doesn't work ! Don't change the input capacitance of the the preamp.

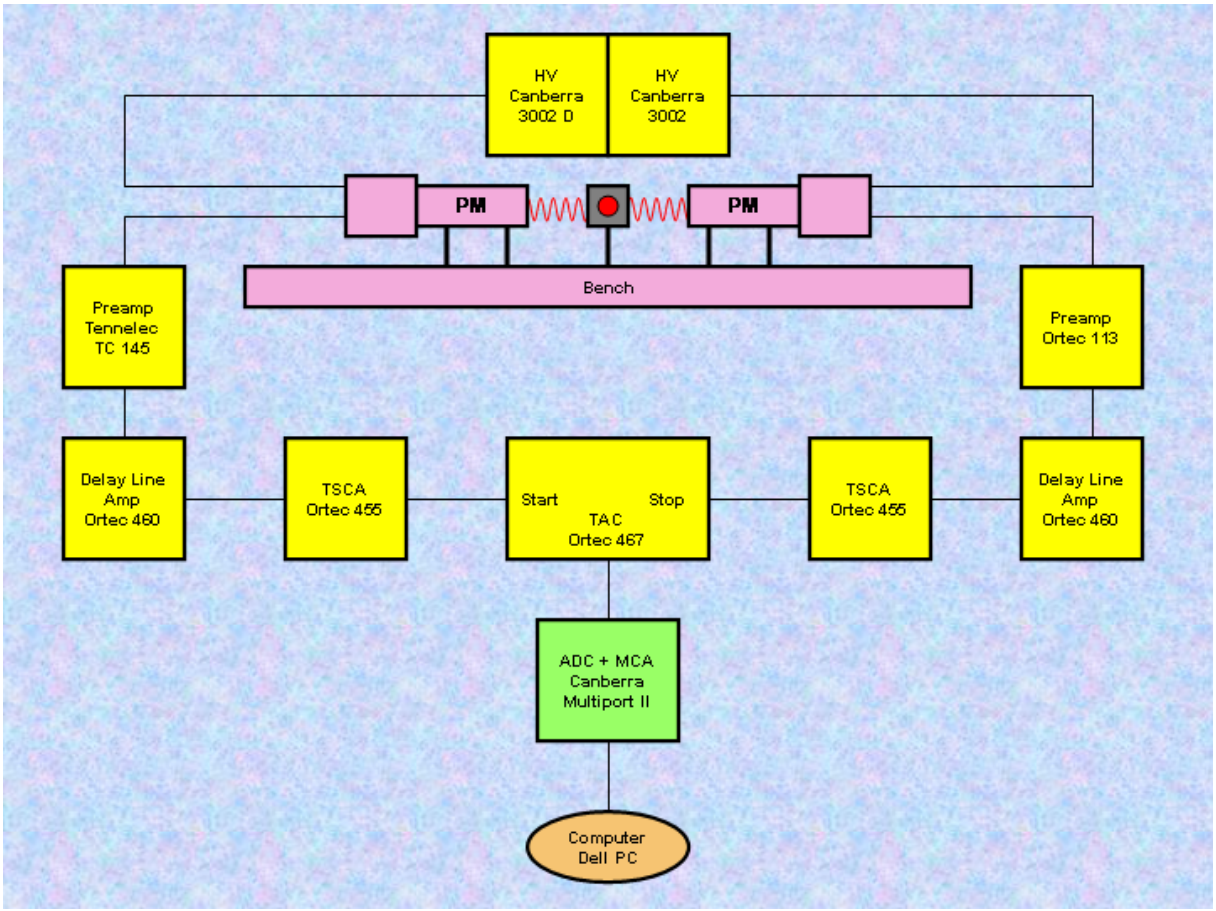
- Set the single channel correctly on the relevant γ-line
- Start time measurement in appropriate range (4 or 8 μs), adjust count rate by choosing proper detector-source distance, when o.k. start
- longer run (overnight)
- Calibrate TAC with time calibrator (about 10 lines should fill the MCA-range)
- Evaluate lifetime from both measurements with error
- Get energy spectrum of the source and some appropriate other calibration lines
- Determine the overall time resolution of the chosen set-up using a radioactive source with a prompt cascade, no lifetimetime in that time-range

WARNINGS

- Caution with high voltage, get the right HV-sign for the detectors
- Order switching on: First NIM-crate and power for pre-amps, second HV with appropriate sign and value
- Order switching off: First HV off, then NIM-power off

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

Detector :	NaI(Tl) detectors $1\frac{1}{2}$" x $\frac{1}{2}$", photomultiplier: Electron Tubes (former EMI company) # 9814KB, assembly home-made, active voltage divider Electron Tubes # TB1106-01,
HV :	High Voltage power supply for the detectors, Canberra # 3002D
pre-amps :	Ortec # 113 and unknown #, input capacitor setting!
Amp :	Main Amplifier Ortec # 460, Double Delay Line Amp for medium fast timing
TSCA :	Timing Single Channel Analyzer for energy selection and time signal derivation Ortec # 455

TAC : Time-to-Amplitude-Converter Ortec # 467

MCA : Multichannel Analyzer Canberra Multiport II (USB)

computer : standard PC

Information about the radioactive sources used

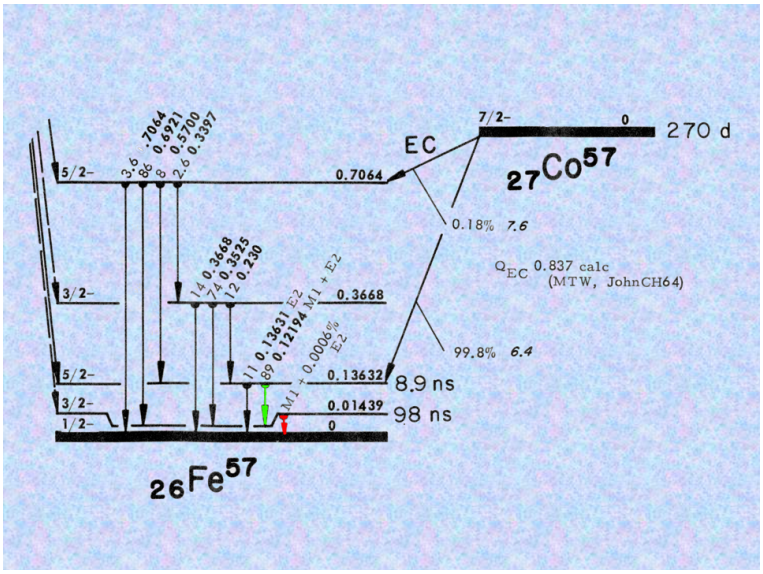


Figure 45: Decay scheme of ^{57}Co from [5].

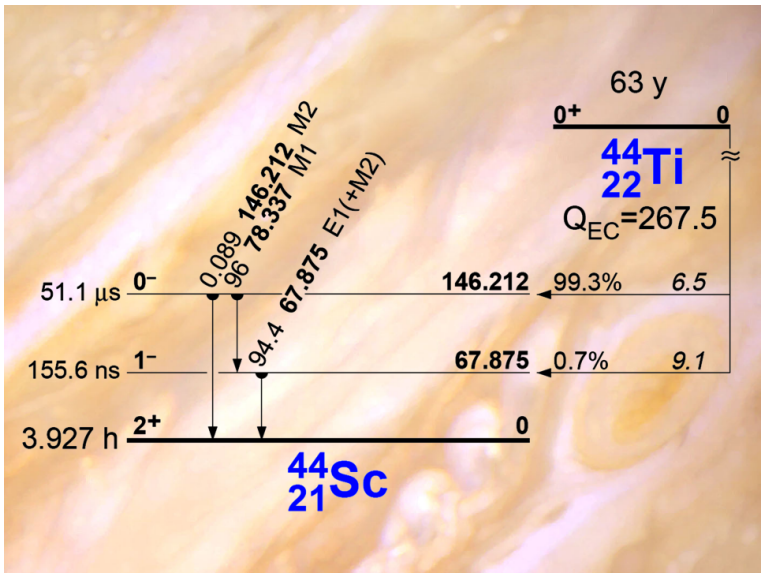


Figure 46: Decay scheme of ^{44}Ti from [5].

D. Discussion of Results

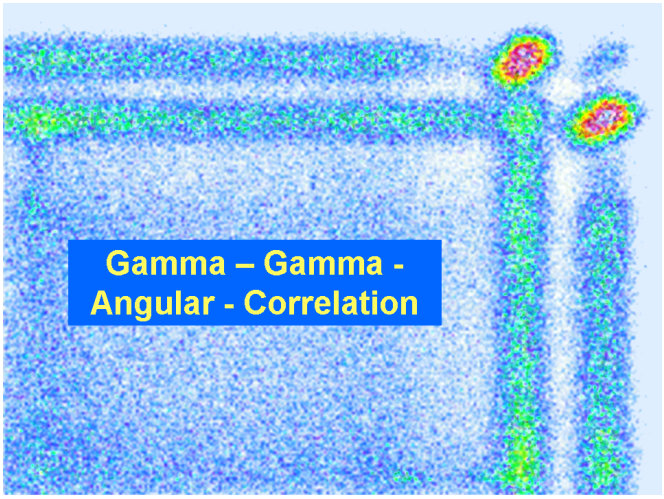
1. Provide diagrams of the energy spectrum, the setting of the windows and on the lifetime measurement (long run),
2. Diagram of the time calibration
3. Evaluation of the lifetime after consideration of chance coincidences, use the whole decay curve for a least square fit
4. Evaluation of the numerical values of the lifetime and the halflife, calculation of the uncertainty and comparison with literature values

E. Example Questions

- Why is the lifetime of a nuclear level interesting?
- Connection between width and lifetime of the level?
- What does the Heisenberg relation mean?
- How can we study lifetimes?
- Which method is used in our experiment and why?

- Explain lifetime and halflife, how can these values be read from a decay curve?
- What makes the lifetime? Give some ideas of the Weisskopf-theory
- What is the influence of E on the lifetime?
- What range of lifetimes do we know?
- How is the method of Delayed Coincidences working?
- What happens when we cannot distinguish the start- and the stop-Gamma?
- How can we shift the time-zero-point to a positive value and why is it necessary?

12 Gamma–Gamma–Angular Correlation



Location: room Jordan 308

A. Short Description

The measurement of γ-angular distributions in coincidence is the standard method of determining the spin of excited nuclear levels. In this experiment the measurement of three-dimensional spectra enables a quick and very accurate determination of the angular distribution characterized by the coefficients of the Legendre polynomials from which the spin of the intermediate level can be deduced. The parity of the states can only be obtained by a separate experiment using a Compton polarimeter.
In the present setup two standard NaI(Tl) detectors (3 x 3" or 4 x 4") are measuring in coincidence, one is fixed in position, the other can be moved to different angular positions with about 0.1° precision. A FAST-COMTEC multi-parameter system provides the collecting of 3-dimensional spectra with an instantaneous contour plot display. Using this, one gets rid of most of the systematic uncertainties because the possible drifts (magnetic fields, time, temperature) are overcome; one can clearly evaluate the three-dimensional peaks correctly.
Two different sources with very different angular distributions are available for this experiment : ^{60}Co and ^{106}Ru. The measurement should be corrected for finite geometry effects and then compared with the theoretical distribution yielding the two coefficients A_2 and A_4 for the Legendre description of the angular distribution.

B. Necessary Knowledge

Physics :

- Theory of γ-decay
- Rules for γ-emission, multipole radiation

- Theory of γ-angular distributions, well presented understanding and explanation
- Finite geometry correction
- Interaction of γ's with matter; 3 effects
- Decay schemes of ^{60}Co and ^{106}Ru

Measuring Technique :

- Scintillation detectors and photomultipliers
- Quasi-Anti-Compton arrangement
- Coincidence measurements, simple or multidimensional
- Multichannel analyzer for singles or three-dimensional spectra
- ADC's
- Fast-slow method (fast circuit for timing, slow circuit for energy selection)

Mathematics : Method of least squares, curve fitting, peak fitting

References

[1]	**Willms, M. :** $\gamma\gamma$-Winkelkorrelation in ^{106}Pd als Praktikumsversuch Thesis of high school teachers, University of Stuttgart 1997	Original thesis on this teaching lab experiment
[2]	**Klema, E.D. :** $\gamma\gamma$-Angular Correlation in ^{106}Pd Phys. Rev, **92**, 1469 (1953)	Original article on a measurement of the ^{106}Pd angular distribution
[3]	**Siegbahn, K., Ed.:** Alpha-, Beta-, Gamma-Ray Spectroscopy North Holland, Amsterdam 1965	Detailed textbook on Nuclear Spectroscopy
[4]	**Cerny, J., Ed. :** Nuclear Spectroscopy and Reactions, Part A,B,C,D Academic Press, New York, 1974 and 1975	Standard compendium for Nuclear Spectroscopy
[5]	**Schatz, G. and A. Weidinger:** Nuclear Condensed Matter Physics John Wiley & Sons, Chichester, New York etc. 1996	Textbook on Nuclear Methods and Applications in Condensed Matter Physics
[6]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics
[7]	**Firestone, R. B. :** Table of Isotopes Vol. II John Wiley & Sons, New York, 1996	Current reference on nuclear data

Experimental Tasks

1. Set-up of the detectors depending on the source used : for a strong source like the ^{60}Co source use the max. source-detector distance (.....cm, equal for both detectors). For a weak source like the ^{106}Ru source use a short distance of about ..... cm. The distance has to be considered in the finite solid angle correction.

2. High voltage for both detectors is positive + 800 Volts.

3. Check the path of the signals for both detectors with the oscilloscope Tektronix #..... The signal amplitude for the 1.33 MeV ^{60}Co-line should be + 6.5 Volts after the DDL main amplifier in bipolar mode (important for the timing).

4. The TSCA Ortec # 455 are working in the "integral" mode, where only the lower level threshold is active and which should be set to about 1 V. Adjust the walk to achieve a minimum time spread for the zero crossing trigger.

5. Several timing conditions have to be set correctly : The fast neg. TSCA 455 output signals are connected to a TAC which generates the coincidence signal. The peak of the coincidences should produce a TAC output of about +4 – 5 V. This can be achieved by appropriate setting of the delay of the stop-signal at the TSCA 455 which yields the stop pulse – the delay at the other TSCA being set to minimum.

6. A further single channel analyzer is set exactly on the coincidence-peak, e.g. the pulses of the TAC by choosing appropriate LL and UL settings. This SCA produces the coincidence and gate signal for the ADC's, which has to be formed by an additional "Gate and Delay Generator" Ortec # 416 to get a gate-signal height of +5 V and length of .... μs to open the gate of the ADC's.

7. The gate signal is delayed by several microseconds with respect to the real events for technical reasons and what cannot be avoided. To compensate this delay the linear signals have to be delayed by the same amount using the delay amplifiers Ortec # 427A (not to be mixed up with the DDL main amps!). Watching both channels (traces) of the oscilloscope showing the linear and the gate signal, the linear signal has to be exactly within the gate signal.

8. The external coincidence is required to reduce random coincidences considerably.

9. Both ADC's Canberra # 8701 are connected to a FAST COMTEC Dual Parameter Box # MCA MPA-3, which itself is connected to an USB-port of a PC.

10. Open the Dual Parameter program ..... on the PC. To obtain the right settings open an old measurement, rename it without erasing the old one and use the settings for the new measurement. The program provides four spectra simultaneously : the "single" spectra of both detectors, the coincidence matrix in 512-channel resolution and another one in 256-channel resolution.

11. Chose an appropriate color coding for the third, the intensity parameter for the map-like or contour-display. The default coding is unfavorable because the small numbers like zero, 1, 2 etc. are dark, making most of the map dark.

12. Measure the angular distribution in one quadrant because of its symmetry, including the angles 90° and 180° in increments of 10°, or at least 15°. Normalize runs to same measuring time. Best results are obtained by measuring the whole distribution on the same day.

13. Evaluate both coincidence peaks (1.33–1.17 and 1.17–1.33 for E_1 and E_2) using the circular region of interest. This circular region should have the same radius for all runs and the evaluation of them. The circular region cannot be dragged, one has to set the coordinates in a menu to adjust the ROI to the peak position. This step is important and is accountable for most of the errors.

14. Determine the 1.33–1.33 (for the ^{60}Co-case) intensity as well and use it as a measure for the random coincidences. The 1.17–1.17 coincidences are not as well representative because of Compton events.

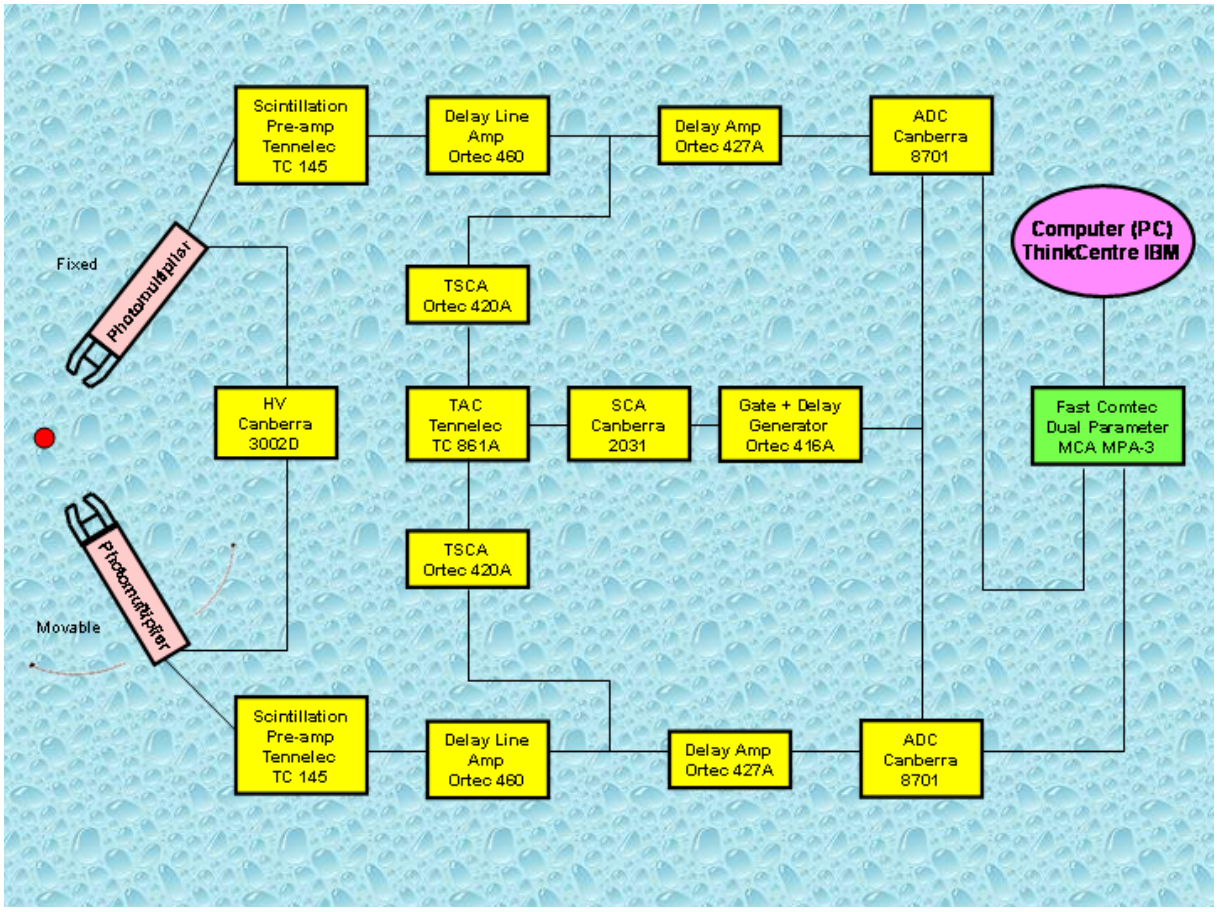
15. Plot immediately the angular distribution to notice inconsistencies and to repeat a run if necessary.

WARNINGS

16. The ^{60}Co source is strong, stay behind the yellow chains!

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

Detectors :	NaI(Tl) detectors 3x3" or 4x4" with brass collimators
Preamp :	Pre-amps Tennelec # TC 145
HV :	One High Voltage power supply for both detectors, Canberra # 3002D
MainAmp :	Delay line amplifier Ortec # 460 to obtain fast bipolar signals for timing and a linear signal for the spectra.
TSCA,TAC :	External coincidence circuit consisting of TSCA Ortec # 420A as timing discriminator used in the "integral" mode, TAC Tennelec # TC 861A to generate a coincidence peak,

	SCA Canberra # 2031 to select only events in the coincidence peak, and the Gate & Delay Generator Ortec # 416A to form the Gate-signal.
DelayAmp :	Delay amplifiers to compensate the delay of the coincidence circuit
ADC :	Two Canberra # 8701 ADC's to digitize the linear signals
MCAMPA3 :	Dual parameter box FAST COMTEC # MCA MPA-3 to generate digital words for the coincident events and for storage in the MCA.
PC :	Standard IBM PC with USB inputs, running the FAST COMTEC dual parameter software .....

$\mathbf{I}_A$	$\mathbf{l}_1$	$\mathbf{I}_B$	$\mathbf{l}_2$	$\mathbf{I}_C$	$\mathbf{a}_2$	$\mathbf{a}_4$	**example**
0	**1**	**1**	**1**	**0**	**1**	**0**	
1	**1**	**1**	**1**	**0**	**-**$\frac{1}{3}$	**0**	
1	**2**	**1**	**1**	**0**	**-**$\frac{1}{3}$	**0**	
2	**1**	**1**	**1**	**0**	$\frac{1}{3}$	**0**	
3	**2**	**1**	**1**	**0**	**-**$\frac{3}{29}$	**0**	
0	**2**	**2**	**2**	**0**	**-3**	**4**	$^{106}_{46}$**Pd**
1	**1**	**2**	**2**	**0**	**-**$\frac{1}{3}$	**0**	
2	**1**	**2**	**2**	**0**	$\frac{3}{7}$	**0**	
2	**2**	**2**	**2**	**0**	**-**$\frac{15}{13}$	$\frac{16}{13}$	
3	**1**	**2**	**2**	**0**	**-**$\frac{3}{29}$	**0**	
4	**2**	**2**	**2**	**0**	$\frac{1}{8}$	$\frac{1}{24}$	$^{60}_{28}$**Ni**

Table 2: Coefficients a_2 and a_4 of several $\gamma\gamma$-angular distributions of γ-cascades; I_A = spin of initial state, I_B = spin of intermediate state; I_C = spin of final state; l_1 = multipole order of first γ-transition, l_2 = multipole order of second γ-transition.

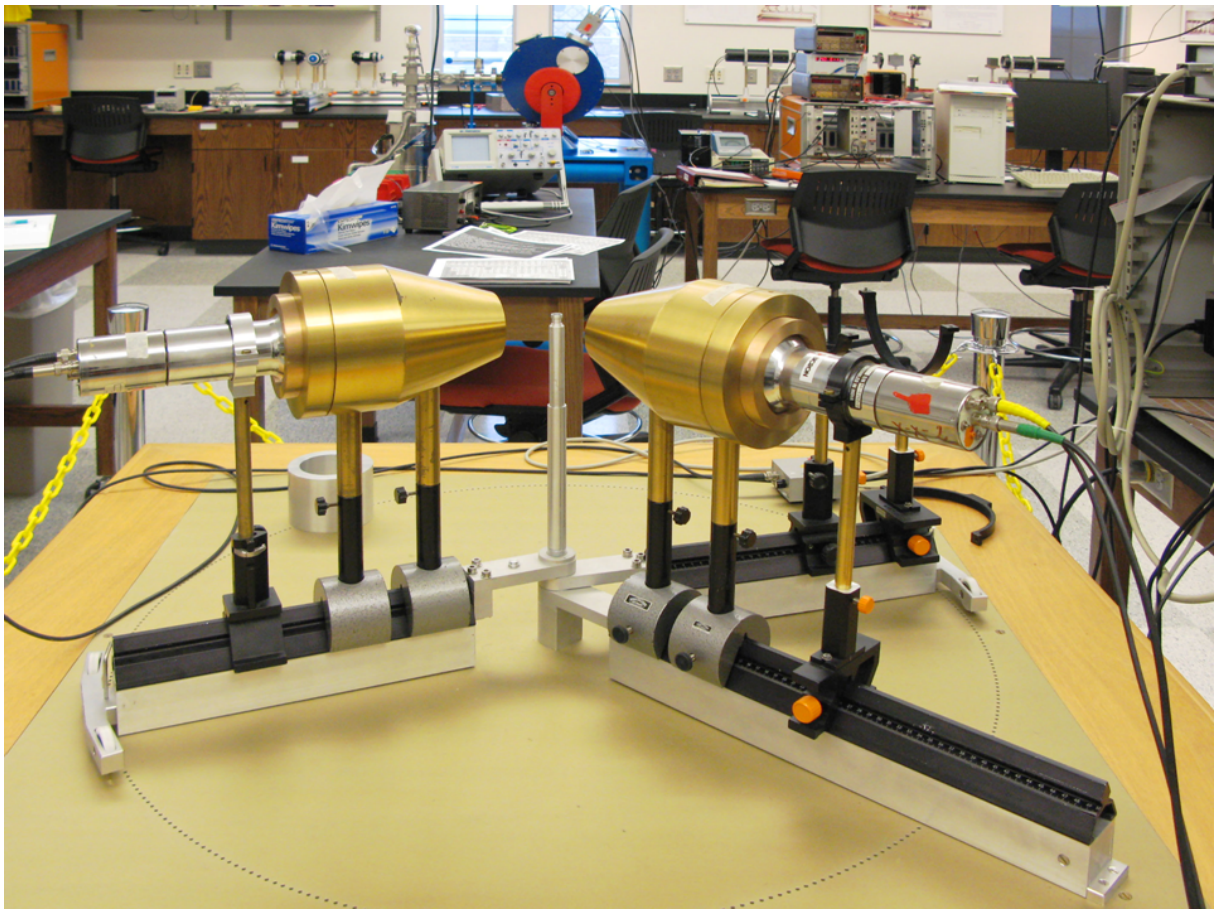


Figure 47: Photo of the set-up for the measurement of gamma-angular distributions with two NaI-detectors. One detector is fixed in its position, the other is moveable by increments of exactly 1°. The angular scale was produced by drilling holes in an aluminum plate on top of the experimental table.

Information about radioactive sources

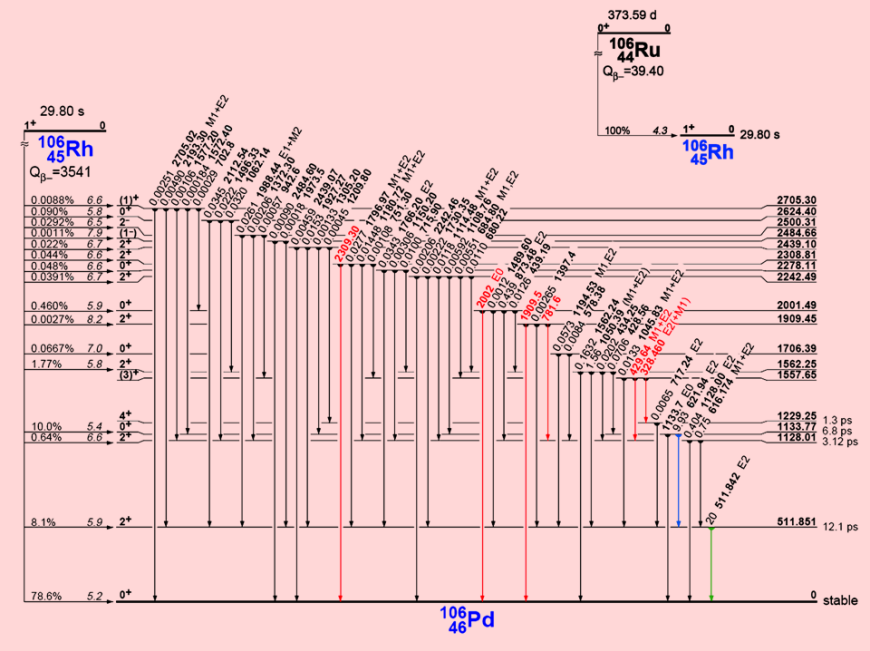


Figure 48: Decay scheme of ^{106}Ru from [6].

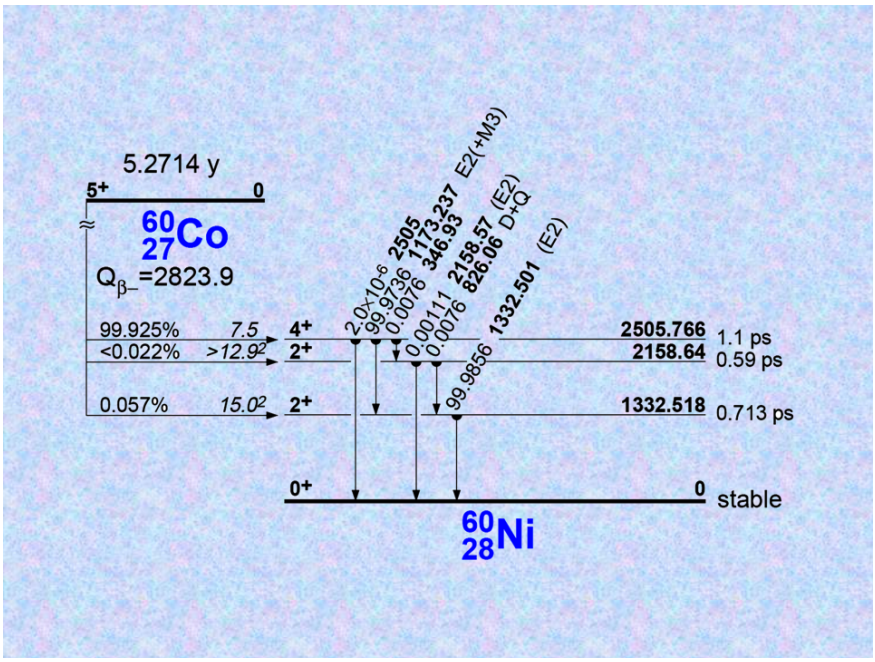


Figure 49: Decay scheme of ^{60}Co from [6].

Corrections for finite solid angle

See thesis Ralf Kunz or Siegbahn

D. Discussion of Results

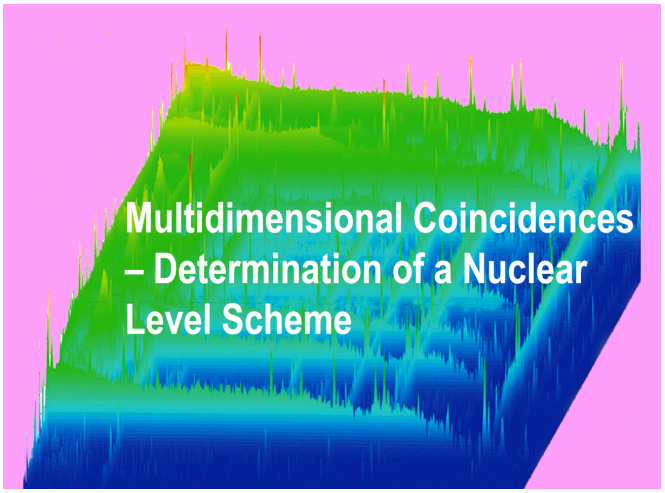
1. Provide a plot of the single, the dual parameter spectra for several angular positions. Provide a plot a plot of the angular distribution uncorrected and corrected.
2. Describe all steps made in the measurement and the evaluation.
3. Determine the coefficients a_2 and a_4 (A_2 and A_4) of the angular distribution and derive from their values the spin of the intermediate state.
4. Determine and calculate all uncertainties of the data and the evaluation (realistic please).
5. Compare your results with those of the literature.

E. Example Questions

- What is the purpose of a $\gamma\gamma$-angular correlation measurement?
- How can the correlation be observed? What is required to measure it?
- What is the advantage of measuring 3-dimensional spectra?
- Can we observe a γ-angular distribution without a coincidence?
- What is finite geometry and how can we correct for it?
- What is the advantage of using the big brass collimators?
- What is its influence on the peak/Compton ratio?
- Compare this effect with the effect of a Compton-suppression detector (Anti-Compton shield)
- From where is the so-called backscatter-peak coming?
- What is the efficiency of a γ-detector?
- What makes the shape of the angular correlation?

- Why is the intensity not zero at any point (Folding of two angular distributions, finite geometry)
- Why is the angular distribution symmetric around 90°?
- Can we determine the parity of a state by this kind of experiment?

13 Multidimensional Coincidences – Determination of a Nuclear Level Scheme



Location: room Jordan 305

A. Short Description

Multidimensional spectra of γ-transitions are useful to observe the logical relations between many γ transitions of a nuclear level scheme within one run. The coincidence peaks make the determination of level schemes much easier. In the present case three-dimensional spectra obtained with the use of two HPGe detectors are measured to exercise the determination of the nuclear level scheme of ^{152}Eu. The resolution of the Ge-detectors allows one to observe even very weak lines. The registration of the events is performed using the FAST three-dimensional MCA (shared with the $\gamma\gamma$ angular correlation experiment) with an online display of the three-dimensional spectra. The FAST MCA software is also used for the analysis of the spectra.

B. Necessary Knowledge

Physics :

- Nuclear level schemes
- Principles and rules of γ decay
- Some basic nuclear models
- Exploration of a nuclear level scheme; Ritz' combination method
- γ-shielding passive and active
- Low level γ-detection methods to find weak radioactivity
- Use of LN_2 as a cooling agent

- Typical γ-spectra of calibration and test sources

Measuring Technique :

- The HPGe detector, physics and properties
- Noise reduction using appropriate pre-amps and spectroscopy amps
- Detector resolution and efficiency
- Calibration and evaluation of γ-spectra
- γ-spectroscopic techniques
- Semiconductor detectors
- Scintillation detectors
- Fast-Slow Coincidence method (one circuit for energy and another for timing)
- Techniques for multidimensional spectra, matrix storage or list mode data

Mathematics : Method of least squares, Ritz' combination principle, peak fitting procedures

References

[1]	**Bischoff, Martina :** Gamma-Kaskaden und multidimensionale Koinzidenzen Thesis of high school teachers, University of Stuttgart 1996	Original thesis on this teaching lab experiment
[2]	**Debertin, K. and R.G. Helmer:** Gamma- and X-ray spectrometry with semiconductor detectors North Holland, Amsterdam, 1988	Standard textbook for Gamma Spectroscopy with semiconductor detectors
[3]	**Cerny, J., Ed. :** Nuclear Spectroscopy and Reactions, Part A,B,C,D Academic Press, New York, 1974 and 1975	Standard compendium for Nuclear Spectroscopy
[4]	**Heath, G. L. and R.G. Helmer:** Gamma Ray Spectrum Catalogue, Fourth Edition, 1998 Idaho National Engineering and Environmental Laboratory	Comprehensive collection of gamma spectra of the isotopes together with decay schemes and tables
[5]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[6]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard work on detectors
[7]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics

Experimental Tasks

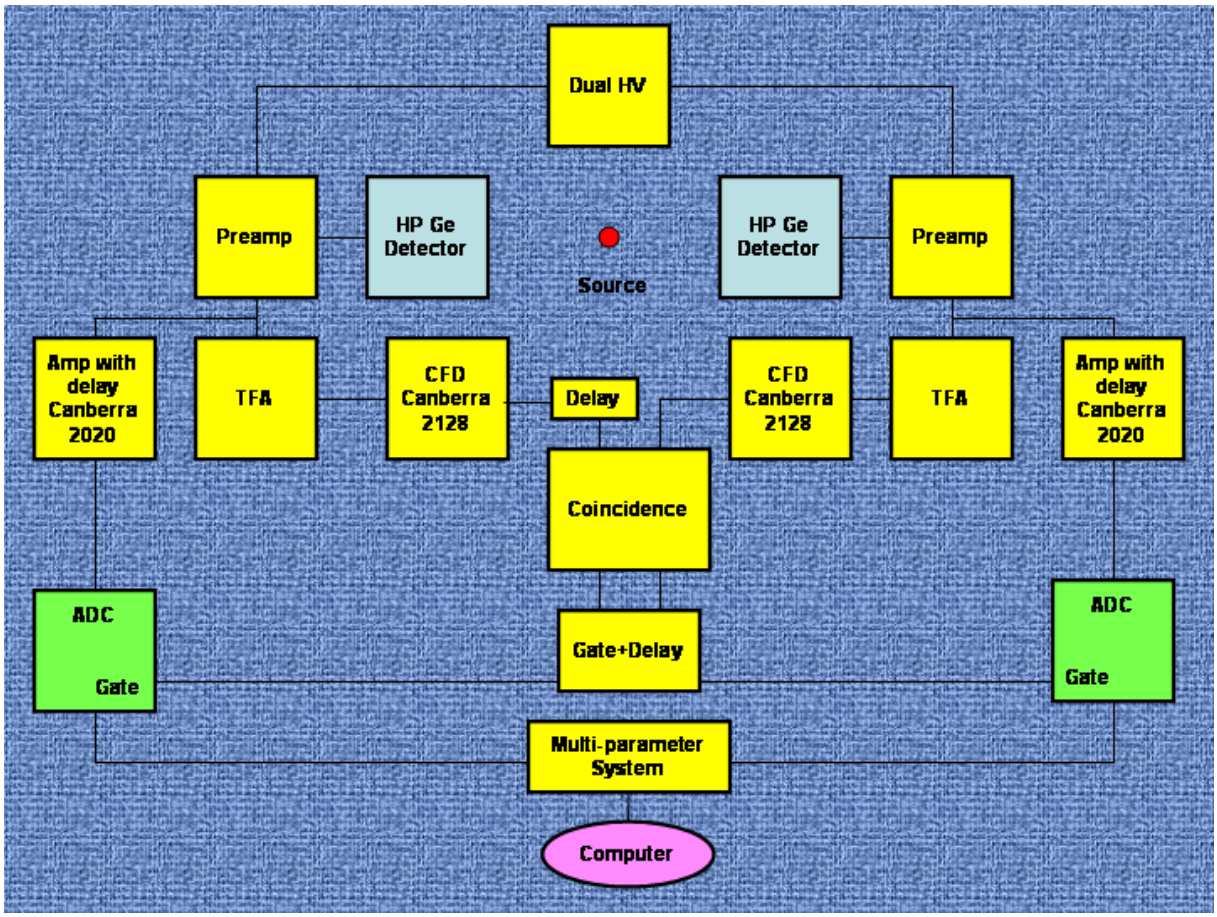
- Make sure that both Ge detectors are at liquid nitrogen temperature and that there is enough LN_2 for the next hours; the pre-amp power has to be turned on and connected all the time
- Set-up of two Ge detectors, appropriate bias high voltage, turn it on very slowly watching the signals on the oscilloscope
- Settings on the main amp
- Set up of the fast circuit with Timing Filter Amplifiers and constant fraction discriminators
- Set-up of correct timing for the gate signal
- Measure 3-dimensional spectra of coincidental events in a matrix with 4096 x 4096 resolution, together with the single spectra of both detectors.

WARNINGS

- After finishing the spectra, turn down the bias high voltage slowly

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

Detectors : There are three Ge-detectors available:

A. Eurisys n-type detector with transistor reset preamp, high voltage negative - 3000 Volts; relative efficiency about 30 %; resolution 2.2 keV, symmetric line shape

B. Princeton Gammatech p-type detector with resistive feedback pre-amp, high voltage positive + 2500 Volts; relative efficiency about 10(?) %; resolution 2.1 keV, symmetric line shape

C. Eurisys n-type detector with transistor reset preamp,

	high voltage negative - 3000 Volts; relative efficiency 18 %; resolution 2.7 keV(?); asymmetric line shape due to imperfect crystal The use of the "Big Shield" is recommended
HV :	Dual High Voltage unit for Ge-detectors, CAEN # N471
Amp :	Main spectroscopic amplifiers Canberra # 2020, shaping time constant 2 or 3 μs, for the linear (energy) signals
TFA :	Timing Filter Amps to get a fast well shaped pulse from which a timing signal for the coincidence is derived
CFD :	Constant fraction discriminators to derive the timing signals, use the positive output pulses, their length is determining the resolution of the overlap-coincidence.
Coinc :	Coincidence unit working after the logical overlap principle
GateGen :	Pulse former to obtain a gating pulse of the right length and shape to open the gates of the ADC's
ADC :	NIM standard ADC Canberra # 8701
FAST :	FAST Comtec Dual Parameter System MCA MP3 (shared with the $\gamma\gamma$ angular correlation experiment); special external box with PC interface card and special PC

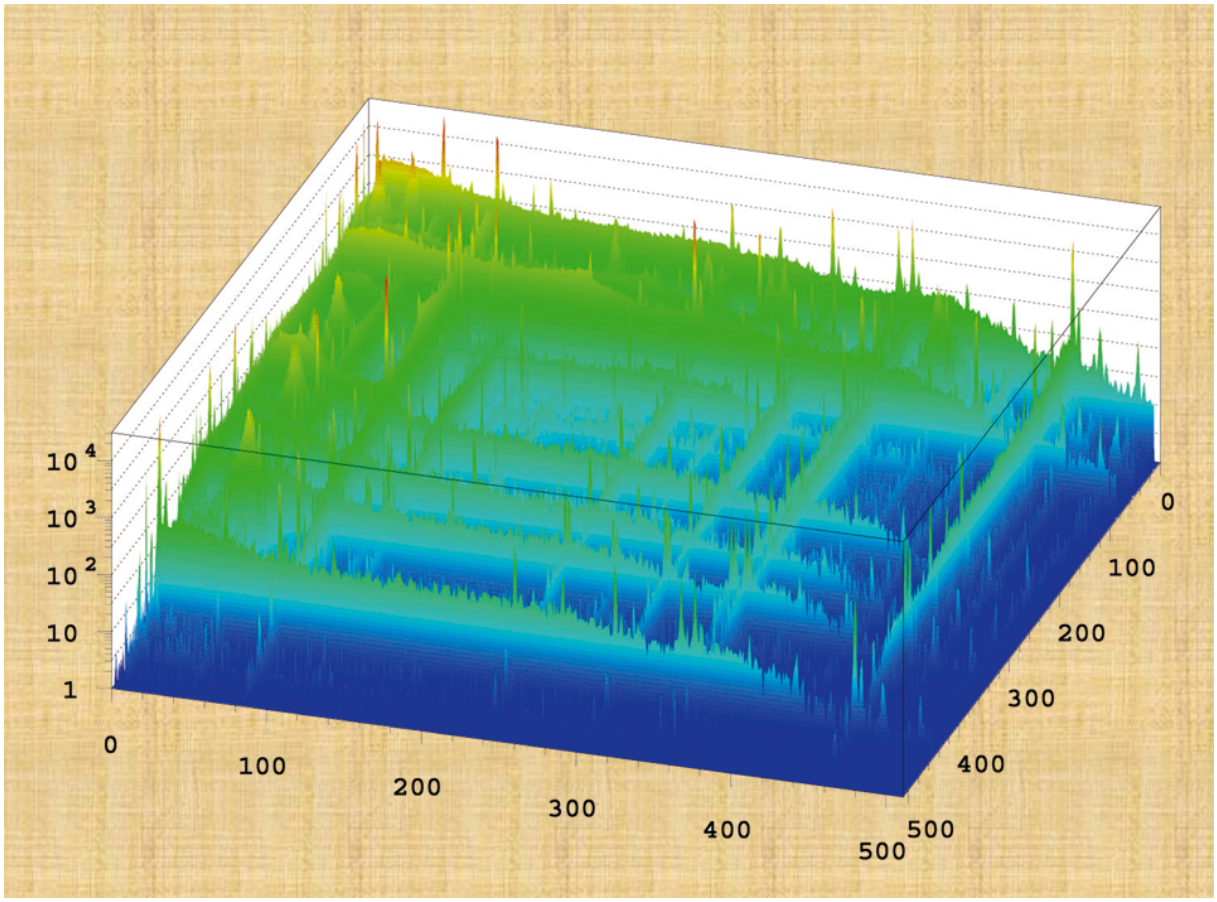


Figure 50: Example of a three-dimensional spectrum obtained with the ^{152}Eu source.

Information about radioactive sources

For information on calibration sources see experiment "Gamma Spectroscopy"

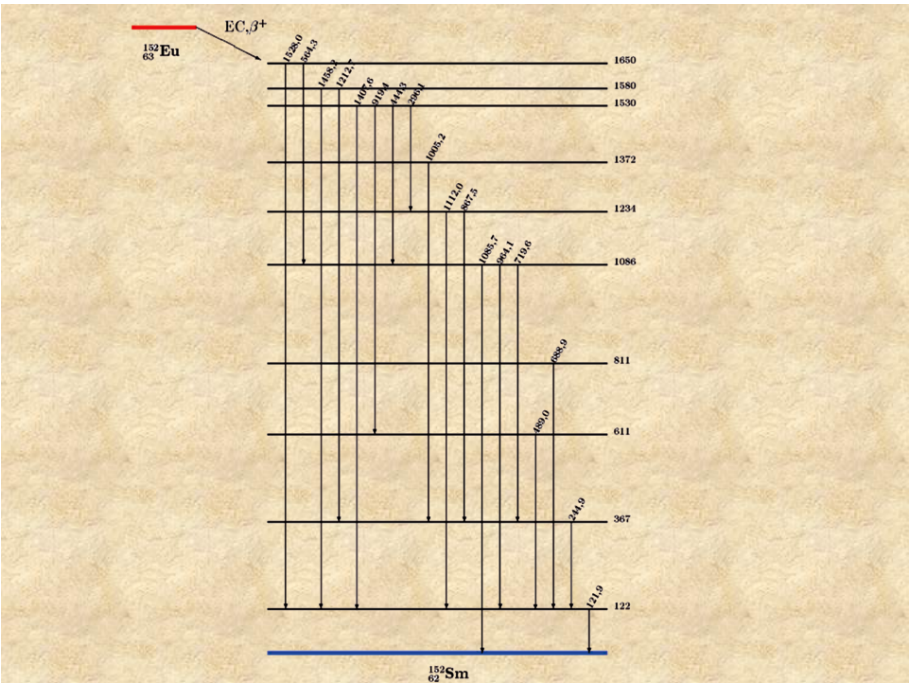


Figure 51: Decay scheme of ^{152}Eu from [5]; only the EC/β^+ branch is shown.

D. Discussion of Results

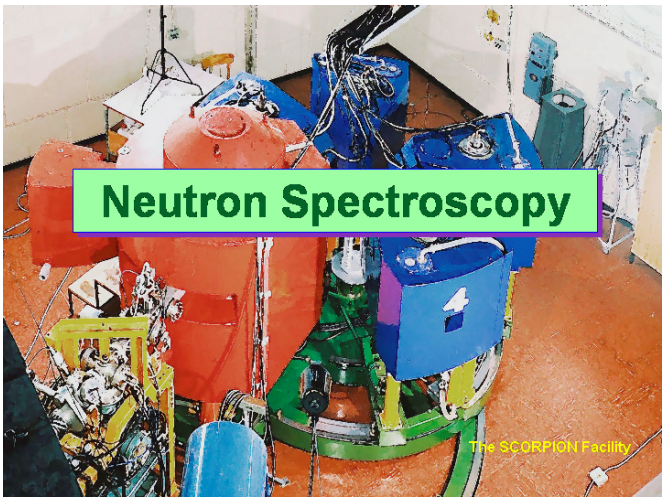
1. Provide plots of calibration spectra, the three-dimensional coincidence spectrum in isometric and contour display form; choose a proper color code for the third dimension; show both single spectra; verify the resolution of both detectors

2. Evaluate a table with all coincidence peaks (energies, intensities)

3. Evaluate the decay scheme using the coincidence peak table, show the evaluation path

E. Example Questions

14 Neutron Spectroscopy



Location: room Jordan 305 and 305a

A. Short Description

In this experiment the so-called proton-recoil spectrometer technique can be studied. Fast neutrons from an AmBe source are scattered elastically off the hydrogen nuclei of an organic scintillator. The proton spectra can be measured and calibrated by the use of standard γ calibration sources, because the scintillation detector (stilbene or liquid NE 213, now BC 501A) is sensitive to both, gamma's and neutrons. The light output is given in so-called light units. From the Compton edge of a single line Compton spectrum one derives the detector resolution. The light output of BC 501A has different rise times or pulse shapes for electrons and for protons because of the different excitation density along the path length. The electronic pulse shape discrimination technique allows the separation of neutron and gamma events. The proton recoil spectra are continuous and need to be unfolded by use of appropriate codes for the response matrix and the unfolding procedure itself.

B. About the AmBe-neutron source and its shielding

The AmBe-neutron source is sitting inside a shielding cylinder providing about 60 cm of paraffin shield in either direction. Under the surface of the cylinder there is a thick layer of boron-carbide which absorbs the thermalized neutrons but produces only little gamma radiation in comparison for example with cadmium. The channel on top of the source is closed by a polyethylene plug which can be exchanged with a polyethylene collimator to let a beam of fast neutrons enter the neutron detector.

The measured radiation levels are the following:

Neutron dose rate in μSv/h :

at the middle of the cylinder mantle: 0.07
at the center of cylinder top when closed with the plug: 0.016
at the center of cylinder top using the collimator: 14.0
at the center of cylinder top using the collimator and the additional cap: 0.09

Gamma dose rate in μSv/h :

at the middle of the cylinder mantle, directly at the surface: < 0.35

So it is safe to work near the neutron source the whole day, which is not necessary because the electronics of the neutron experiment are outside this room 305A.

C. Necessary Knowledge

Physics :

- Spectroscopy methods for fast neutrons in comparison
- Proton recoil spectroscopy, elastic n-p-scattering, kinematics
- Physics of organic scintillators with pulse shape discrimination properties
- Some important neutron producing reactions, especially (α,n) reactions; the ^{9}Be(α,n)^{12}C reaction
- Physics of an AmBe neutron source
- Light output functions

Measuring Technique :

- Design and function of proton recoil spectrometers using NE 213 (now BC 501A)
- Shielding of neutron sources
- Compton spectra obtained with an organic scintillator
- Electronic pulse shape discrimination technique
- Unfolding techniques for continuous spectra: Matrix inversion, stability problems, maximum likelihood
- Calculation of the so-called response matrix

Mathematics : Method of least squares, unfolding techniques, matrix inversion

References

[1]	**Eisele, Wolfgang :** Praktikumsversuch zur Neutronenspektroskopie mit Hilfe eines Protonenrückstoß-Spektrometers Thesis of high school teachers, University of Stuttgart 1998	Original thesis on this teaching lab experiment
[2]	**Hammer, J.W., G. Bulski, W. Grum, W. Kratschmer, H. Postner and G. Schleussner :** SCORPION, the Stuttgart Scattering Facility for Fast Polarized Neutrons Nucl. Instr. Meth. **A 244**, 455 (1986)	Comprehensive article on measurement techniques for fast neutrons with references
[3]	**Cierjacks, S. and H. Barshall :** Neutron Sources for Basic Physics and Applications Pergamon Press, Oxford 1983	Compilation on different, mostly accelerator based neutron sources
[4]	**Dietze, G. and H. Klein :** Gamma-Calibration of NE 213 scintillation counters Nucl. Instr. and Meth. **193**, 549 (1981)	Method to use radioactive γ-source to calibrate organic scintillators with a Compton edge
[5]	**Etzel, R. :** Entfaltungsmethoden bei Neutronenspektren Diploma thesis, University of Stuttgart 1991	Unfolding of proton recoil spectra
[6]	**Marion, J.B. and J.L. Fowler :** Fast Neutron Physics Interscience Publishers, New York, 1960	Standard work on fast neutron physics
[7]	**Geiger, K.W. and L. van der Zwan :** Radioactive Neutron Source Spectra from ^{9}Be$(\alpha, n)^{12}$C cross section data Nucl. Instr. and Meth. **131**, 315 (1975)	Examples of neutron spectra
[8]	**Vijaya, A.D. and A. Kumar :** The neutron spectrum of Am-Be neutron sources Nucl. Instr. and Meth. **111**, 435 (1973)	Examples of neutron spectra
[9]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard work on detectors
[10]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics
[11]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data

Experimental Tasks

- Set-up of one of the fast neutron detectors; for the small stilbene detector HV = - 1900 V
- Watch signals on a fast oscilloscope
- First test with the detector facing a ^{22}Na source, two Compton edges visible
- Put the detector (HV off) on top of the neutron collimator

- Study the function of the pulse shape discrimination circuit with the oscilloscope

- Get help for the variation of parameters at the special DDL amplifier

- Measure the TAC spectrum showing neutrons and gammas well separated using the Multiport II MCA (512 channels); the gamma peak from the TAC should have exactly an amplitude of 8 Volts

- Set the discrimination to gammas (SCA: LL = 700; UL = 900); measure the Compton spectra of ^{22}Na, ^{60}Co, ^{137}Cs; the detector is removed from the neutron collimator); measure the gammas coming from the neutron source: np-fusion gammas at 2.2 MeV and the 4.4 MeV gammas from ^{12}C*.

- Set the discrimination to neutrons (SCA LL = 030; UL = 650) and measure the neutron spectrum (= proton recoil) from the AmBe neutron source

- At present the unfolding codes for unfolding the p-recoil spectra (FANTI and NRESP) are not available

- Alternatively use a detector with a liquid scintillator (NE 213); same procedures as above

WARNINGS

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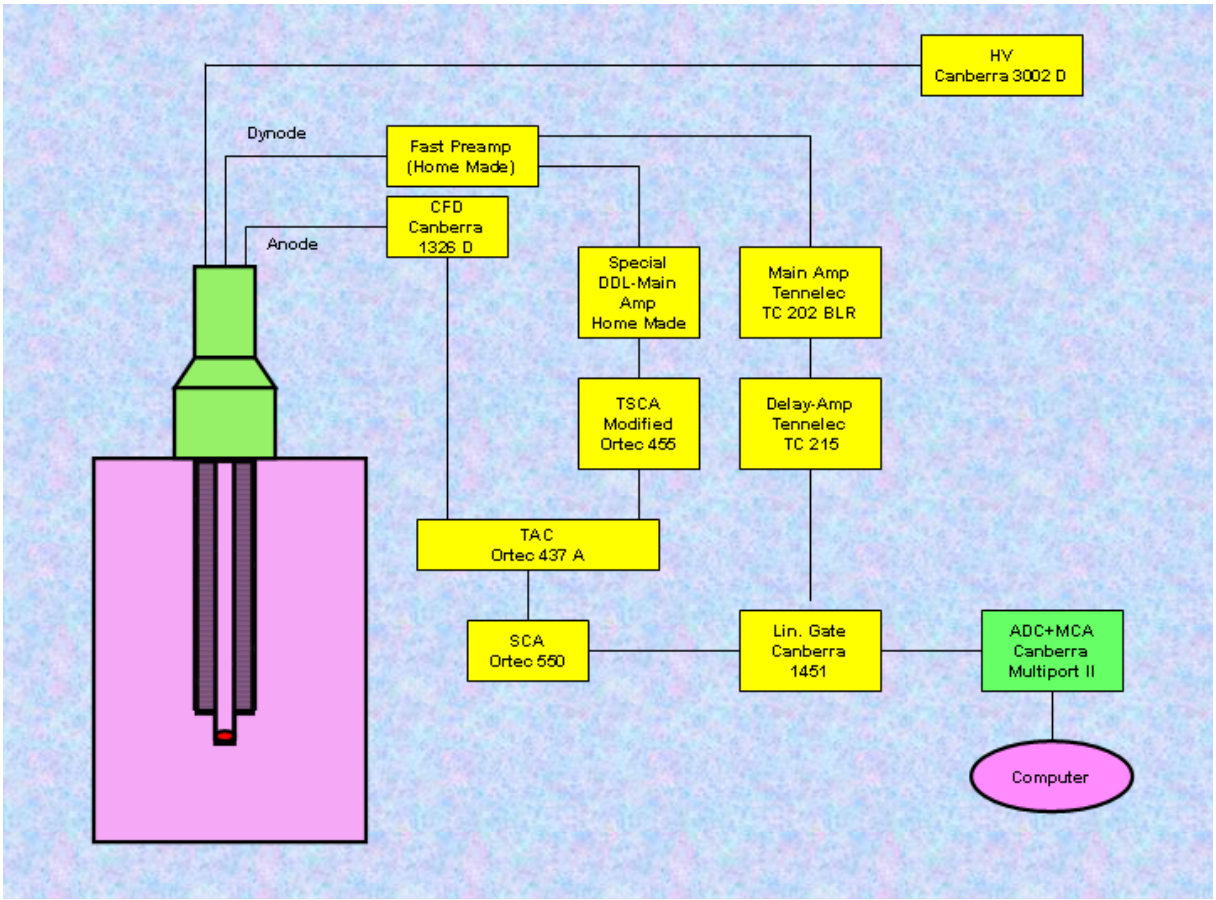
-

D. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

Detector : 3 organic scintillation detectors are available:
A. A small stilbene crystal, 1" dia x 1" length, best n-γ separation properties
B. NE 213 fluid cell 4" dia x 1" length
C. NE 213 fluid cell 3" dia x 1" length

HV : High voltage power supply for the detectors, Canberra # 3002D

CFD : Canberra # 1328 constant fraction discriminator, to derive a timing signal from the anode pulse at about 10 % fraction of the anode pulses

Pre-amp :	Pre-amplifier (home-made) for obtaining fast signals at low impedance from the dynode pulses
DDL :	Special fast DDL shaping amplifier (home-made) to obtain bipolar pulses at a fraction of about 80 - 85 %
TSA :	Modified timing single channel analyzer (Ortec #455) unit to derive a time signal with minimum walk from zero crossing of the DDL amp pulse
TAC :	TAC (Ortec # 437A) to measure the rise time of each individual pulse between 10 % and 85 % fraction
Amp :	Amp Tennelec # TC 202 BLR; slow signal circuit to treat the linear (energy) signal of the proton recoil detector
SCA :	Ortec single channel analyzer # 550 to select neutron or γ events from the TAC output
DelAmp :	Delay amplifier Tennelec # TC 215 to accommodate the timing for the ADC
LinGate :	Linear Gate Tennelec # TC 1451 to select either the neutron or the gamma events
MCA :	Canberra Multiport II MCA, connected via USB to a PC, software GENIE 2000 with dongle

Information about the radioactive neutron source

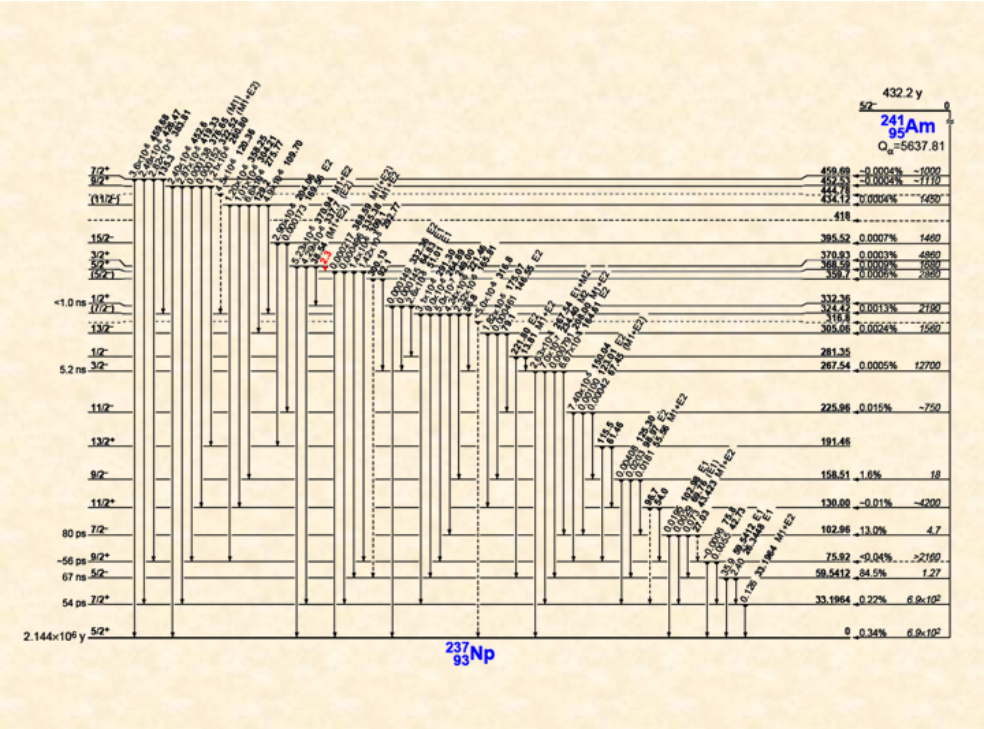


Figure 52: Decay scheme of ^{241}Am from [11].

For the decay schemes of the γ calibration sources see under experiment 08 "Gamma Spectroscopy".

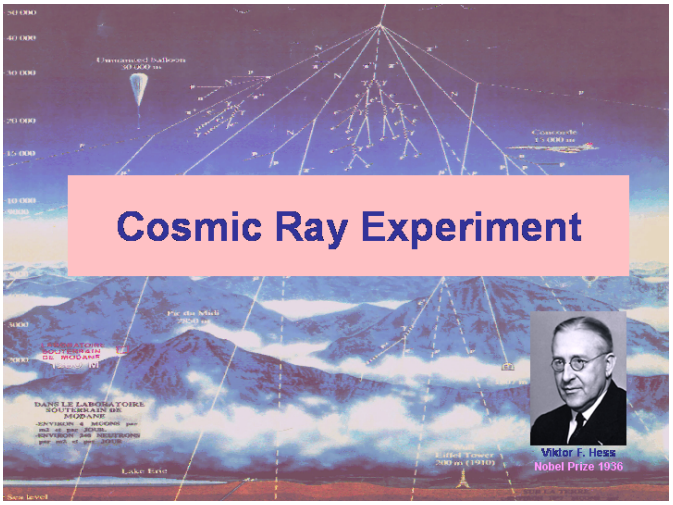
E. Discussion of Results

- Provide
-
-

F. Example Questions

-
-

15 Cosmic Ray Experiment



Location: room Jordan 308

A. Short Description

The flux of cosmic rays consists at the surface of the earth mainly of positive and negative muons $\mu^{\pm}$, the strong component and fast electrons, the weak component and in addition some γ-rays. The muons are created through the decay of pions which themselves are created mainly by the interaction of very fast protons with the nuclei of the earth atmosphere, causing huge "air showers" of secondary particles. So all strong interacting particles are transformed in the outer atmosphere and only weak interacting particles reach the earth's surface, in the case of muons due to the relativistic time dilatation effect. The muon, a lepton, is the heavy "brother" of the electron with a mass $m_\mu = 206.7\, m_e$ ($105.7\,\mathrm{MeV/c^2}$). It interacts only by the weak interaction (and the coulomb force) and has therefore a relative long lifetime of $2.197\,\mu$s. In the cosmic ray flux it has an average energy of about 2 GeV. About 10^4 muons reach 1 square meter of the earth's surface every minute.

The flux of secondary cosmic rays, mainly the muons, shows a strong zenith angle dependence ($\cos^2\theta$; θ = zenith angle; θ=0 zenith) and which differs slightly when measured in the North-South or in the East-West direction. The muon flux intensity is measured in this experiment by using a counter telescope, made of three thin plastic scintillator plates coupled each to a 2" photomultiplier. A cosmic particle is releasing a triple coincidence when its direction corresponds to the direction of the telescope. The effect is mainly caused by the atmosphere of the earth where an inclined infall causes the secondary particles to cross a thicker layer of air. Another effect is caused by the magnetic field of the earth.

The polar angle dependence is measured in north-south and in east-west direction.

B. Necessary Knowledge

Physics :

- Basics of cosmic rays, chain of interactions, showers, phenomena
- Basic principles of elementary particles
- Muon physics, lifetime, decay, energy spectrum
- The standard model of elementary particles
- Basic interactions: Strong, weak and electromagnetic interaction
- Conservation laws in particle physics
- The interaction with the earth's atmosphere

Measuring Technique :

- Detection techniques of cosmic rays and elementary particles
- Plastic scintillators and detector telescopes
- Fast coincidence techniques; basic electronic circuits, constant fraction discriminators, coincidence circuits, time-to-amplitude converters, electronic counters etc.
- Energy loss of cosmic rays

Mathematics : Method of least squares for arbitrary functions

References

[1]	**Grieder, P. K. F. :** Cosmic Rays at Earth: Researcher's Reference Manual and Data Book Elsevier, 2001. ISBN 0444507108	Reference Manual
[2]	**Hillas, A. M. :** Cosmic Rays Pergamon Press, Oxford, 1972, ISBN 0080167241	A good overview of the history and science of cosmic ray research including reprints of seminal papers by Hess, Anderson, Auger and others
[3]	**Perkins, D. :** Particle Astrophysics Oxford University Press, 2003, ISBN 0198509510	Very interesting and well written book
[4]	**Melissinos, A. C. and Napolitano J.:** Experiments in Modern Physics Academic Press, Amsterdam etc. 2003	Textbook on Modern Physics Experiments
[5]	**Gaisser, T. K. :** Cosmic Rays and Particle Physics Cambridge University Press, 1990. ISBN 0521326672	Standard textbook

[6] **Heath, G. L. and R.G. Helmer:** Gamma Ray Spectrum Catalogue, Fourth Edition, 1998
Idaho National Engineering and Environmental Laboratory
Comprehensive collection of gamma spectra of the isotopes together with decay schemes and tables

Experimental Tasks

- In this experiment the properties of cosmic rays should be studied with aim on the following
  1. The fraction of cosmic rays which are electrons/muons
  2. The ratio of gamma rays to charged particles in cosmic rays
  3. The zenith angle distribution of muons
  4. The zenith angle distribution of electrons
  5. As a possible extension: measure the muon energy distribution by using up to four layers of lead bricks in region "B"
- Set-up of the detectors: high voltage negative HV = - 1300 Volts for all three detectors, which determines their gain
- Set the threshold of the three constant fraction discriminators very carefully, to obtain a good signal/background ratio; there are only the two parameters: high voltage versus the CFD-threshold, try 10 – 50 mV threshold
- Make yourself familiar with the operation of the counter telescope, all the signals and settings, there is a region for the HV and threshold setting where the count-rate shows some kind of plateau e.g. the coincidence count rate is independent of gain and threshold; if the gain is too low, counts are lost, if it is too high, accidental counts rise rapidly.
- Set the timing of the three signals entering the triple coincidence unit very carefully to obtain optimal overlapping by the use of both tracks of the oscilloscope. The matching of the timing is achieved by inserting appropriate delay cables RG 58. One can measure a coincidence resolution curve by this way, or borrow a TAC-unit and get the coincidence timing curve from the TAC spectrum. Counts outside the coincidence peak are accidental or chance coincidences and should be subtracted to obtain the true rate.
- One can fill the gap between detector 2 and 3 with three rows of lead bricks to slow down the muons or absorb the electrons, also a thin layer of lead can be put on top of detector 1 to discriminate the different constituents of cosmic rays. There are about seven choices for the absorbing layer:

1. no absorbers
2. 2" or 50mm of lead between detector 2 and 3 (region B)
3. 4" or 100mm of lead in region B
4. 6" or 150mm of lead in region B
5. 8" or 200mm of lead in region B
6. 1/16" or 1.5mm of lead on top of detector 1 (region A)
7. 1/16" or 1.5mm of lead in region B

One should verify the following:

- The efficiency for γ-rays is nearly zero for the detector telescope, it can be risen by applying the lead sheet in region A where the cosmic gamma rays interact by creating electron/positron pairs, which can be detected.
- The charged particles with sufficient energy are detected with intrinsic efficiency = 1
- Cosmic ray electrons lose energy by bremsstrahlung characterized by an exponential energy loss with characteristic length L_{rad} which is 42.4 cm for a plastic scintillator and 0.52 cm for lead.
- Cosmic muons lose energy by ionization (bremsstrahlung is suppressed relative to electrons by$(m_e/m_\mu)^2$). This process is characterized by approximately constant ionization energy loss per unit length, dE/dx, which is 2.09 MeV/gcm^{-2} for plastic scintillator and 1.13 MeV/g cm^{-2} for lead.

- Verify the response to those different settings with absorbers: cosmic ray electrons should be stopped almost completely by 2" of lead, while successive layers of 2" of lead will stop increasing fractions of cosmic ray muons according to their energy distribution and respective ranges in lead. The coincidence count rates in 6) and 7) will both be decreased from 1) due to stopping some fraction of electrons and muons. However, the rate in 6) will also be increased by conversion of some fraction of γ's to $e^{\pm}$ pairs in the thin layer of lead. A rough estimate of the conversion efficiency assumes that every pair production event leads to an extra coincidence count, i.e. that none of the $e^{\pm}$ pairs so produced are stopped in the thin layer of lead. As a result, the difference in coincidence count rates in 6) and 7) can be used to estimate the gamma ray flux with energies above the pair production threshold energy.

- Measure triple coincidences for a preset time (about 5 min) and polar angles between 90° and 0° for the East–West and the North–South direction, setting the angle every 5° by the use of the threaded rod and the steering wheel and the attached angle meter – use some lubricating oil. Do this measurement in configuration 2) and 1) with respect to the absorbers.

- Consider the acceptance angle of the detector telescope which folds with the azimuthal distribution

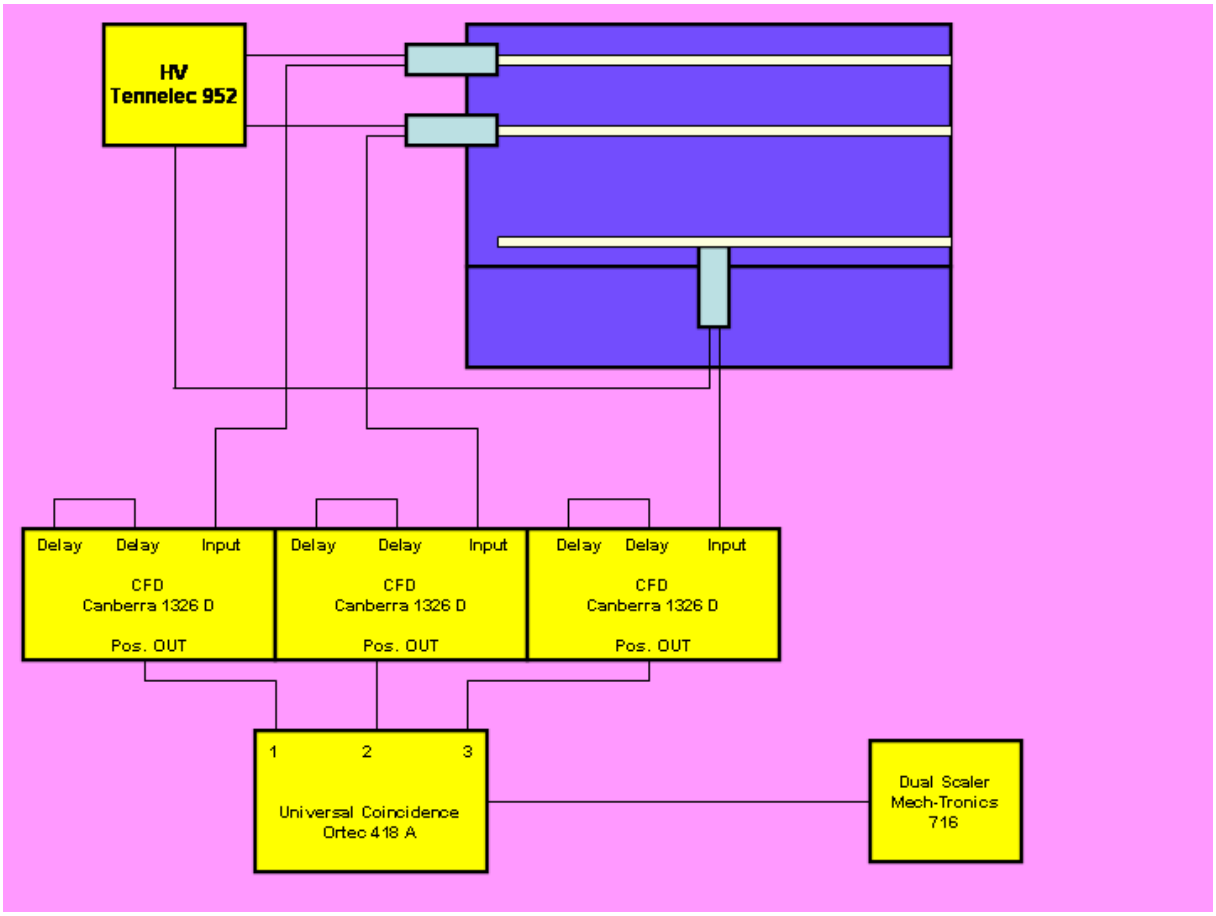
WARNINGS

- The wooden box has some taped connections to achieve light-tightness, from time to time this has to be controlled by using a flashlight. If room light can enter the box it can happen that the detector is blocked by that leaky current.

- Don't touch the photomultiplier connectors, they are fragile

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

detectors :	Detector telescope made of three plastic scintillator sheets BC 400, each 20 x 120 x 1.27 cm's, attached photomultipliers: Hamamatsu # R 878, photomultiplier voltage dividers (bases) Hamamatsu # E 1198-03, magnetic shields Hamamatsu # E 989-05
CFD :	Constant fraction discriminators Canberra # 1326D, external delay about 50 cm of RG 58, threshold about 050
HV :	High Voltage for the Detectors, Tennelec # TC 952, set to HV = - 1300 Volts, never exceed 1500 Volts
Coinc :	Universal Coincidence Unit Ortec # 418

Scaler : Mech-Tronics Dual Scaler # 716

lead : The gap between detector 2 and 3 (region B) can be filled with layers of lead bricks (2", 4", 6", 8", 1.5mm - sheet) to get information on the other constituents of cosmic rays. In addition one can put a layer of lead on top of the first detector (region A) when there is no tilt chosen, layer thickness about 1.5 mm

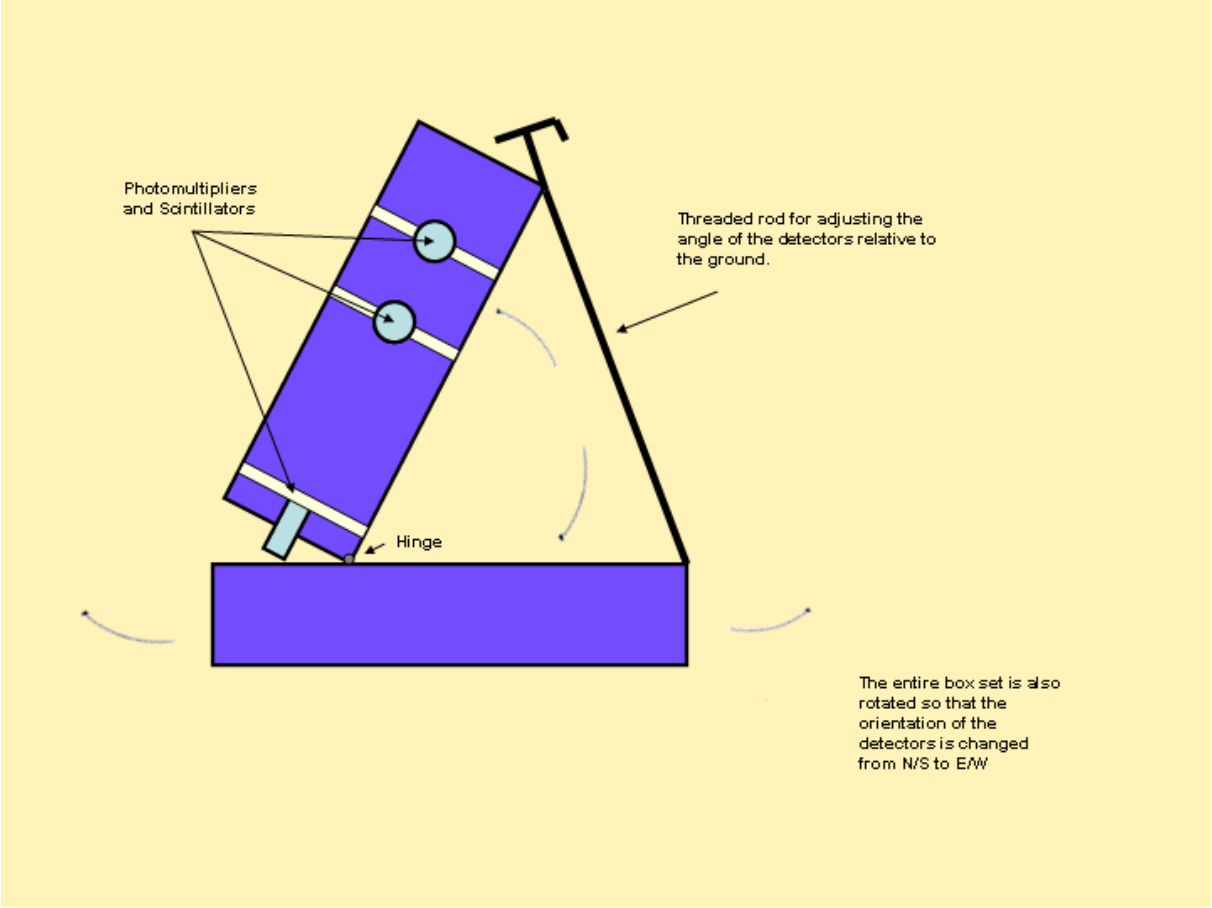


Figure 53: Cross section of the tiltable counter telescope for cosmic rays.

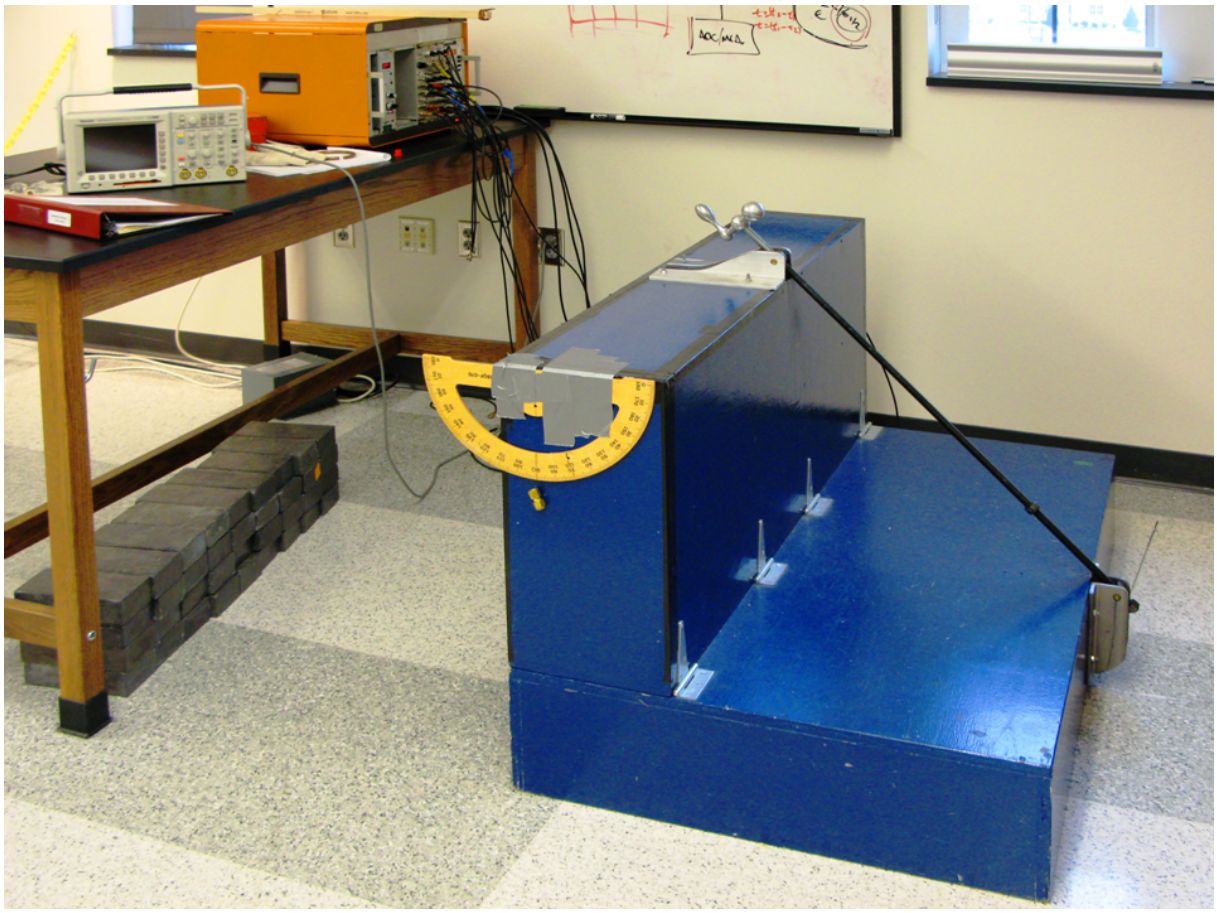


Figure 54: Photo of the tiltable counter telescope.

Information on used calibration sources

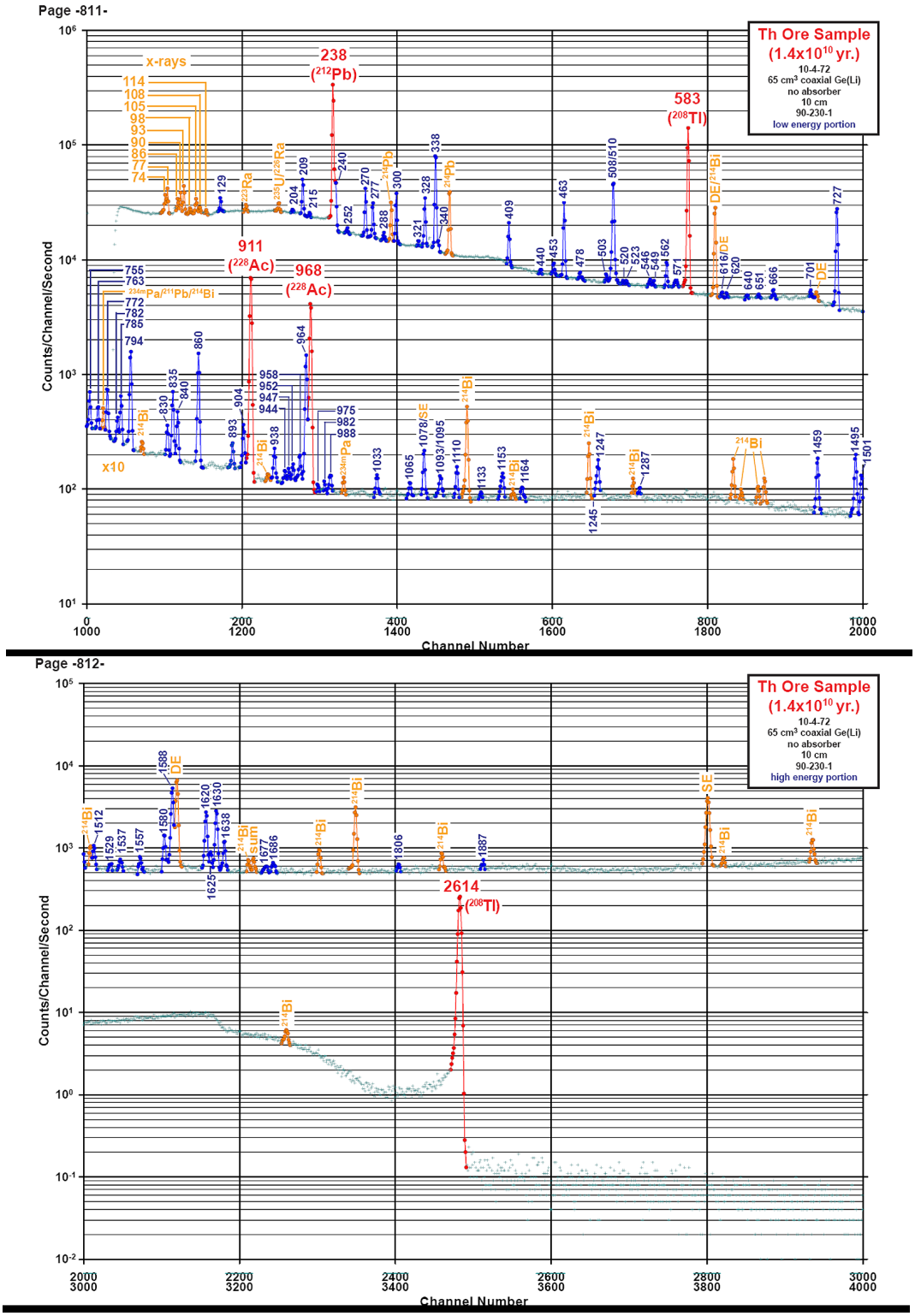


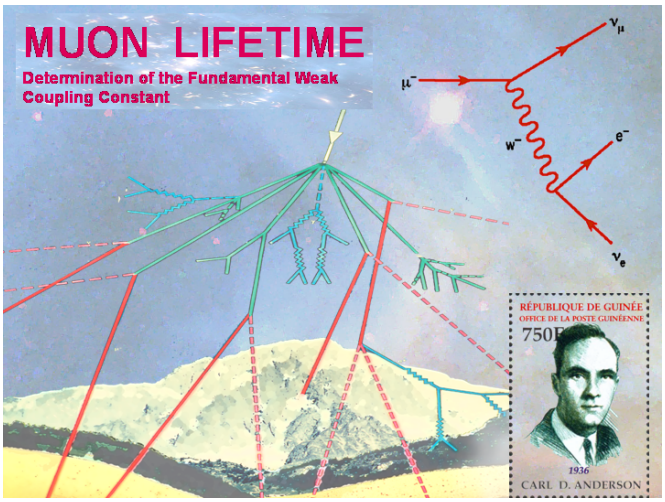
Figure 55: Gamma spectrum (two pages) of a natural thorium ore sample from [6].

D. Discussion of Results

- Provide in the analysis the count rates due to each type of cosmic ray: N_e, N_μ, N_γ
- Calculate E^{μ}_{mean}, the approximate mean muon energy, assuming that the energy dependence you observe at low energies can be extrapolated linearly.
- Determine the cosmic muonic flux in dependence from the polar angle in the East-West and North-South direction and present it in appropriate diagrams with a model fit assuming a $(\cos\theta)^n$ - behaviour, n = 1,2 or 3. Try to fold out the rather large angular acceptance of the detector telescope.
- Repeat this procedure without the 2" lead absorber in region B. Subtract the results from the rates obtained in the procedure before to find the angular dependence for the electron component of the cosmic flux. Again fit the distribution and try to correct for the acceptance angle.

E. Example Questions

16 Muon Lifetime Experiment – Determination of the Fundamental Weak Coupling Constant



Location: room Jordan 305

A. Short Description

Muons are produced in the outer atmosphere mainly by reactions of cosmic protons with air, yielding pions and kaons which decay into muons μ^-, antimuons μ^+ and related neutrinos. Because of their high speed and the involved time dilatation muons reach the earth's surface despite of their short lifetime of about 2.2 μs and can be detected in a scintillation detector. The energy loss and the decay of the muon can be measured in the same detector as two well separated events and the time interval between both is the individual decay time. Collecting the decay of many muons leads to the decay curve and the nominal decay time τ. The decay of negative muons is enhanced in matter because a further decay channel opens up depending strongly on the Z of the material. In an organic scintillator as used in this experiment this effect is small. From the decay time τ and the muon mass the Fermi coupling constant G_F of the weak interaction can be derived . Furthermore for valid decays the energy spectrum can be measured and compared with theory.

Some formulae

The Muon is unstable and decays into an electron, a neutrino and an antineutrino:

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

The lifetime of the muon is of order 2.2 μs and its mass is $m_\mu = 105.65\,\mathrm{MeV/c^2}$. The neutrinos

from the muon-decay are not detected, only the electron or positron; the maximum energy is observed when the two neutrinos recoil against the electron, the corresponding energy being:

$$E_e(max) \quad = \quad \frac{1}{2}\, m_\mu\, c^2 \quad = \quad 53\, MeV$$

The energy spectrum of the decay-electrons is shown in the next slide; it is difficult to separate from all other events in the big detector used. The spectrum is continuous because the decay involves 3 resp. 4 'bodies'. Because of the high energy deposit one has to work with low amplification and therefore the high voltage is set to only -1300 Volts. Important are also the threshold settings of the two constant fraction discriminators, scale 250 for the start signal and 050 for the stop. Because the start and the stop signal are derived from the same detector and signal line one has to make sure that no stop pulse will be on the stop line when the start arrives; for this purpose the start signal is delayed by about 60 ns using a delay cable. The TAC is set to the 10 μms range and it has to be calibrated by using the Ortec time calibrator. Random coincidences are determined from a fit to the background line and have to be subtracted from all channels.

The Fermi Weak Interaction Constant G_F

The decay of the muon proceeds through the weak interaction, only leptons being involved in this process. Therefore one can calculate the weak interaction constant G_F, one of the fundamental constants, from the measured muon lifetime:

$$\frac{1}{\tau} \quad = \quad \frac{1}{\hbar} \quad \frac{G_F^2}{(\hbar\, c)^6} \quad \frac{(m_\mu\, c^2)^5}{192\, \pi^3}$$

The measured lifetime has to be corrected for a small effect: When negative muons are stopped in matter they can be captured by protons of a nucleus opening thus a further decay channel, which shortens the lifetime of negative muons to some extent:

$$\mu^- + Z \quad \longrightarrow \quad (Z-1)^* + \nu_\mu$$

The effective mean life τ_e for negative muons becomes:

$$\frac{1}{\tau_e} \quad = \quad \frac{1}{\tau_\mu} + \frac{1}{\tau_e}$$

where $1/\tau_\mu$ and $1/\tau_C$ are the rates for decay and capture, respectively. For a plastic scintillator (carbon in the hydrocarbon, average Z $\approx$ 5) this effect of shorter lifetime is about 4%.

The measurement of the energy spectrum of the muon decay products is more difficult because one has to consider only events that have shown a decay, e.g. one selects after a true coincidence the second event with its amplitude. The selection is made by a single channel analyzer (SCA) after the TAC, choosing the range of about $1 - 6\,\mu$s. The other difficulty is, that the linear pulses have to be quite short to avoid pileup with the first event, the stopping of the muon in the scintillator. Therefore the linear pulses are prepared in a very unconventional manner: The linear signal is prepared in a timing filter amplifier to be very short. But the decision whether it is a valid pulse comes after the sequence of the TAC, e.g. after a few microseconds and therefore the linear pulse has to be delayed before the gate which is opened by a logic pulse after a true decay event. The other problem is the high energy range of the signals of about 50 MeV and their calibration. The highest energies of radioactive sources are in the range of $2 - 3$ MeV and they are therefore nearly invisible in this setup. But γ transitions in the range of $8 - 10$ MeV can be produced by using our Am-Be neutron source and a neutron capture reaction, for example the 7.3 MeV n-capture line of iron.

B. Necessary Knowledge

Physics :

- Basic elementary particle physics
- The Standard Model of elementary particles
- Lepton families
- Lepton number conservation
- Weak interaction
- Neutrinos
- Weak interaction, theory, the Fermi weak coupling conbstant
- Muon decay
- Cosmic rays, showers, energy spectra of Cosmic rays
- Relativistic time dilatation
- Decay characteristics of the muon

Measuring Technique :

- Scintillation detectors
- Properties of fast plastic detectors
- Fast photomultipliers

- Fast time measurement techniques, fast signals
- Basic nuclear electronics; fast NIM electronics
- Multichannel analyzer
- Neutron capture and γ-transition production
- Problems to isolate the right muon decay events and to measure the energy spectrum of decay electrons (or positrons)

Mathematics : Method of least squares for a logarithmic decay curve

References

[1]	**Kane, G.L. :** Modern Elementary Particle Physics Westview Press (1993)	Textbook on Modern Particle Physics
[2]	**Perkins, D.H. :** Introduction to High Energy Physics Cambridge University Press 2000	Textbook on Modern Particle Physics
[3]	**Melissinos, A. C. and J. Napolitano :** Experiments in Modern Physics Academic Press, Amsterdam etc. 2003	Textbook on Modern Physics Experiments
[4]	**Siegbahn, K., Ed. :** Alpha-, Beta-, Gamma-Ray Spectroscopy North Holland, Amsterdam 1965	Detailed textbook on Nuclear Spectroscopy
[5]	**Schatz, G. and A. Weidinger :** Nuclear Condensed Matter Physics John Wiley & Sons, Chichester, New York etc. 1996	Textbook on Nuclear Methods and Applications in Condensed Matter Physics
[6]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[7]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard work on detectors
[8]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics

Experimental Tasks

- Prepare setup for lifetime measurement (block scheme Nr.1)
- HV = -1300 Volts, TAC-range 10μs or 20μs, MCA 1024 or 2048 channels,
- Thresholds of the two CFD's: scale 250 (start) and 050 (stop)
- Use oscilloscope to watch and understand all signals

- Measure lifetime by an overnight or overweekend run

- Calibration of the TAC and the time-axis with Ortec time calibrator

- Prepare set-up for measurement of the energy spectrum according to block scheme Nr. 2

- The linear pulses have to be very short, else one obtains summing up of the incoming muon energy and the decay product energy

- The exact timing of all pulses is very important (use oscilloscope)

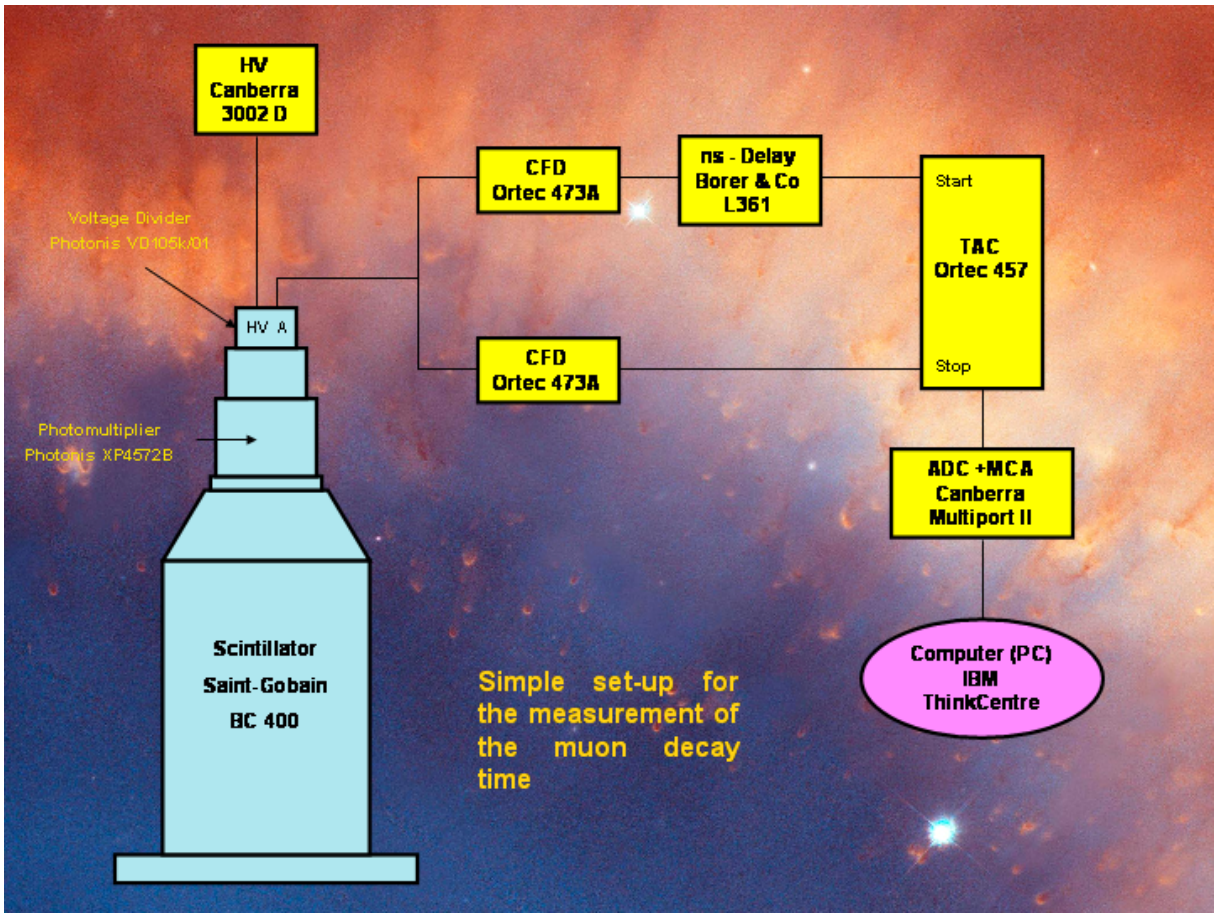
- Calibration of the energy spectrum using n-capture γ-rays, get help with handling of the neutron source

WARNINGS

-

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram Nr. 1 (lifetime measurement)

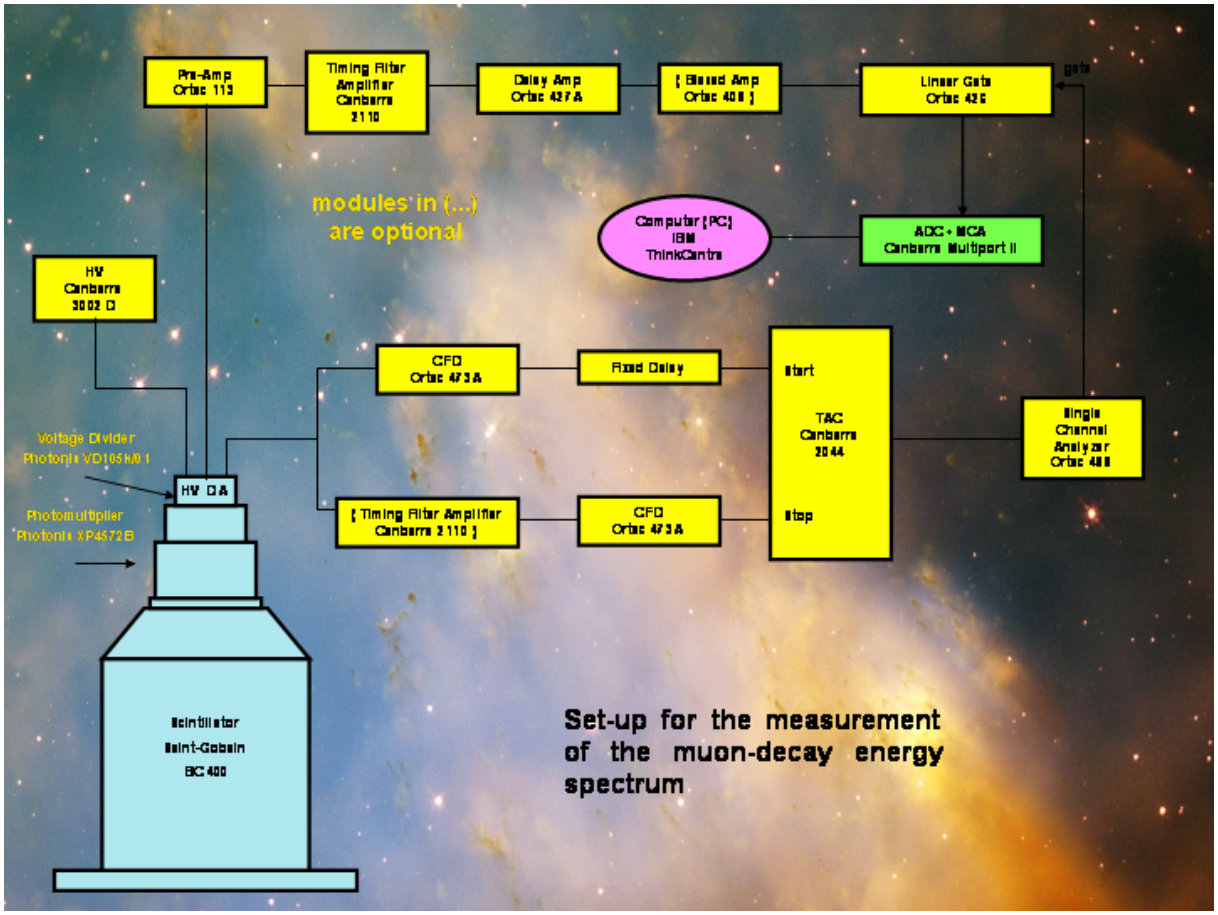


Legend for the simple set-up of the muon-lifetime measurement:

Detector :	Fast plastic detector, Saint Gobain BC 400, 250 mm diameter, 562.5 mm total height with tapered section, cylindrical section 500 mm height, reflector Teflon-sheet as inner layer, aluminum foil as outer layer, fast photomultiplier Photonis XP 4572 B
Div :	Voltage divider Photonis VD 105k/01
HV :	High voltage power supply for the detector, Canberra Mod. # 3002D, set to neg. -1300 V
CFD :	Two constant fraction discriminators, Ortec Mod. # 473 A; threshold start-signal 250 scale-units, stop-signal 050 scale-units

Delay :	Cable delay 60 ns to avoid self-coincidences from the same event, the start is delayed
TAC :	Time-to-amplitude converter Ortec Mod. .... , set to range 10 or 20 μs to cover the decay curve and random coincidences
ADC/MCA :	ADC set to 1024 channels, Aptec MCA-card with 8192 channel ADC, Mod. # 5008, software Canberra Genie 2000 with dongle
PC :	'Industrial' PC with passive backplane and ISA and PCI slots to accommodate measuring cards as the Aptec 5008, 'slot-CPU"

Schematic Drawing, Block Diagram Nr. 2 (energy spectrum measurement)



Legend for the advanced set-up, measurement of the energy spectrum of muon decay :

HV : High Voltage for the Detectors, Canberra 3002D

Information about the used radioactive sources

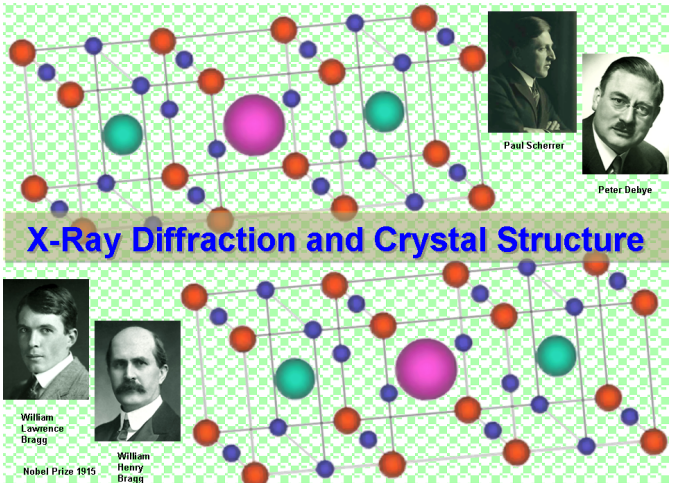
Figure 56: Decay scheme of ^{22}Na from [6].

D. Discussion of Results

1. Provide

E. Example Questions

17 X-Ray Diffraction and Crystal Structure (XRD)



Location: room Jordan 305

A. Short Description

X-ray diffraction (XRD) is one of the most important non-destructive tools to analyze all kinds of matter - ranging from fluids, to powders and crystals. From research to production and engineering, XRD is an indispensable method for structural materials characterization and quality control, typically making use of what is known as the Debye-Scherrer or powder diffraction method. Just as an optical grating diffracts laser light, an atomic grating can be used to diffract significantly shorter wavelength light: X-rays. As the structure of most solids is based on periodic arrangements of atoms, with regular spacings on the order of Angstroms, X-rays can be diffracted through such an atomic or crystalline lattice. If one knows the X-ray wavelength, one can interpret the lattice structure of the solid from the observed diffraction peaks, which is essential to calculating the electronic, thermal, and structural properties of the solid. One can use 'white' X-rays instead of monochromatic X-rays in what is known as the Laue method–however, this is mostly useful only for crystal orientation and not determination of crystal structure.

As any local physical property of a crystal, such as the charge concentration, electron number density, or magnetic moment density is invariant under a fixed length translation, it is convenient to describe lattices in terms of Fourier analysis. This analysis generates a set of vectors related to, but 'reciprocal' to, the coordinate vectors that uniquely describe the arrangement of atoms in a solid–these are the reciprocal lattice vectors. It is these vectors that determine the possible X-ray reflections. Any sets of parallel planes of atoms in a crystal will diffract X-rays when illuminated at the right angle; it is mathematically much simpler to work in reciprocal space than in coordinate space. One could imagine mounting a crystal and rotating an X-ray

beam around it, such that every orientation of lattice planes will be observed. In practice, it is much simpler to rotate the crystal and keep the X-ray source fixed. However, both methods have a drawback–the diffracted X-rays will come off in all directions! X-ray sensitive film, mounted in a loop around the experiment, was used to measure these. The Debye-Scherrer method, or powder diffraction method, removes this technical obstacle. In this the crystal is ground into powder containing micron-scale crystallites, tiny on a physical scale but still huge on an atomic scale. With such a powder, **every** orientation of lattice planes is achieved simultaneously; a 3 dimensional problem is reduced to a 1 dimensional problem. One describes the three dimensional space with reciprocal axes x*, y* and z* or alternatively in spherical coordinates q, $\varphi*$, $\chi*$. The Debye-Scherrer method averages over $\varphi*$ and $\chi*$ and only q remains as an important measurable quantity. To eliminate effects of texturing and to achieve true randomness one rotates the sample orientation. In the socalled diffractogram the diffracted intensity is shown as function either of the scattering angle 2θ or as a function of the scattering vector q which makes it independent of the used X-ray wavelength. The diffractogram is like a unique “fingerprint” of materials.
This method gives laboratories the ability to quickly analyze unknown materials and characterize them in such fields as metallurgy, mineralogy, forensic science, archeology and the biological and pharmaceutical sciences. Identification is performed by comparison of the diffractogram to known standards or to international databases.
In addition, neutron diffraction is also a popular tool for investigation of the physical properties of materials – a coherent beam of thermal neutrons is used instead of X-rays. In addition to structural information via Bragg scattering off of lattice points, there is additional scattering due to the magnetic moment of the neutron interacting with the magnetic moments of atoms or magnetic field lines inside the material.

Related Nobel Prizes in Physics :

- Max von Laue, 1914 "For his discovery of the diffraction of X-rays by crystals."
- W.H. Bragg and W.L. Bragg, 1915 "For their services in the analysis of crystal structure by means of X-rays."
- C.J. Davisson and G.P. Thomson, 1937 "For their experimental discovery of the diffraction of electrons by crystals."
- B. Brockhouse and C.G. Shull, 1994 "For the development of the neutron diffraction technique"

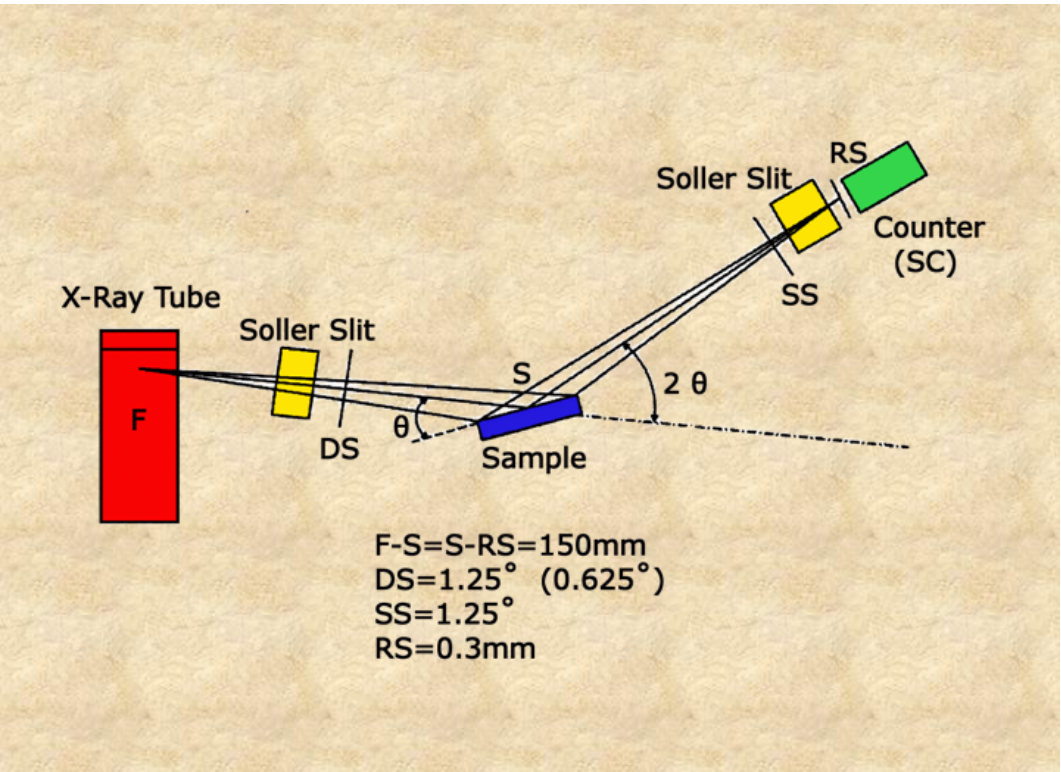


Figure 57: Scheme of X-ray diffraction using the Debye-Scherrer method.

Some additional notes :

X-Ray Diffraction is a tool that can be used to determine the arrangement of atoms in a crystalline structure, as X-ray wavelengths are comparable to interatomic spacing in solids. The RIGAKU software includes a MANUAL MEASUREMENT program, used to rotate which sample is used and adjust the angle of a 6 sample tray. The included STANDARD MEASUREMENT program can be used to setup the angular range and time duration of X-ray exposure. The JUNO 8 program can be used to open the generated .raw data files and includes a peak finder option (See Appendix 1). The goal of this experiment is to allow one to analyze and predict the angles of interference peaks, which requires understanding of crystalline lattices, reciprocal space, and diffraction.

B. Necessary Knowledge

Physics :

- Bragg condition for diffraction, $n \cdot \lambda = 2\,d \cdot sin(\theta)$
- Max von Laue and Bragg method
- Debye-Scherrer technique

- Crystal lattices
- Reciprocal space
- Identification of lattice parameters; Miller indices
- Identification of compounds
- Powder Diffraction File (PDF)
- Cambridge Structural Database (CSD)
- Electron density determination

Measuring Technique :

- Generation of monochromatic X-rays
- Principles of a Bragg spectrometer
- X-ray tube and X-ray production
- X-ray optics, slits, Soller slits, X-ray reflexion
- Wavelength discrimination
- X-ray detectors
- Sample preparation
- Compare with Neutron Diffraction
- Application of the XRD method to different other fields

Mathematics :

- Fourier Analysis
- Computer programming to calculate locations of diffraction peaks, can even be done in Mathematica

References

[1]	**von Laue, M. :** Fields of X-ray waves in crystals Sitzungsberichte der Deutschen Akademie der Wissenschaften zu Berlin, Klasse für Mathematik, Physik und Technik, n 1 (1959), 3-26	.....
[2]	**Scherrer, P. :** Crystal Structure of Aluminum Physikalische Zeitschrift, v 19, 15. Jan 1918, 23-27	.....
[3]	**Debye, P. :** Scattering of X-rays Annalen der Physik, v 46, n 6, 30 Mar 1915, 809-823	.....
[4]	**Kittel, Ch. :** Introduction to Solid State Physics (Chapters 1-2) John Wiley & Sons, Inc., New York 2005 (p. 29)	Fundamental textbook on Solid State Physics
[5]	**Wyckoff, R.W.G. :** Crystal Structures, Second Edition. Volumes 1 & 2, (CuO- Vol.1 p140. Y2O3- Vol.2 p4. BaCO3- Vol.3 p366.) John Wiley & Sons, New York 1963	.....
[6]	**Namikawa, Y., M. Egami, S. Koyama, Y. Shiohara, and H. Kutami :** Crystallinity of YBa2Cu3O72x single crystals grown by the pulling method. Journal of MATERIALS RESEARCH 804 J. Mater. Res., Vol. 11, No. 4, Apr 1996 (Received 27 July 1995; accepted 11 December 1995	.....
[7]	**Ashcroft, N., and N. D. Mermin:** Solid State Physics (Chapters 4-7) Brooks/Cole Thomson Learning, Inc., USA 1976	.....
[8]	**Hook, J.R. and H.E. Hall :** Solid State Physics (Chapters 1-2, 12) Wiley & Sons, Inc., New York 2003	.....
[9]	**Serway, R. et.al. :** Modern Physics (Chapter 11) Saunders College Publishing, New York 1989	.....
[10]	**Cullity, B :** Elements of X-Ray Diffraction Addison-Wesley, 1956 (p42 & p471)	.....

Experimental Tasks

- The Group will familiarize themselves with the experimental setup using the **Rigaku MiniFlexII X-Ray Diffractometer**. Please note that the detector arm and sample both move in this device, and the X-ray tube is fixed. For this reason, sample must be thinly packed into the trays, and the maximum angle must be less then 145°.

- Prepare 5 samples, (KCl, NaCl, NaBr, NaF, NaI). This will include grinding the samples into a fine packed powder to reduce clumpiness caused by hydration. The pressurized

hood is to be used when preparing the NaF sample. Sodium salts are very hygroscopic, so grinding the powders prior to use is always necessary.

- Clean sample stages with ethanol (NOT acetone!)
- Neatly pour powder into sample apparatus and load them on to the rotating sample holder, load materials into XRD machine.
- Adjust system for measurement parameters, 10 - 120° is sufficient
- Record data of the 5 samples using the STANDARD MEASUREMENT program. The start angle in the conditions file should be 10° and the final angle should be 100°. The scan speed is listed in degrees/minute. Please note that the angular measurements are in units of 2θ. The wavelength of the copper K_α X-Ray source is $\lambda = 1.5406$.
- Prepare the last 4 samples, (YBCO BaCO3 Y2O3 CuO). Y2O3 and BaCO3 may require grinding. Select this alternate set of chemicals from lab inventory and repeat.
- Record data for these samples.
- This experiment will likely require 2 - 3 lab periods of data acquisition.

Warnings:

- The Rigaku Miniflex II system is designed as a functioning end-user workstation. Maintenance of the instrument should not be required. This means do NOT touch the insides of the machine aside from mounting samples!
- Never touch the Be foil window on the X-ray generator inside the machine!
- Do not attempt to use the Rigaku Miniflex II if the water circulator is not operating
- The Miniflex II is designed with safety in mind. The X-ray beam will be shuttered if the machine is opened or any panels are removed on the machine.

C. Information Regarding the Experimental Procedure

A respirator mask and gloves are available for use while grinding materials. The only health hazard is due to inhaling very small particles, but is very unlikely due to the minimum particle

size generated in grinding.
In the Miniflex II system, to save on physical space, the X-ray generator is kept stationary. The sample stage is rotated, as is the X-ray detector. This is equivalent to rotating the X-ray generator and the X-ray detector while keeping the sample stationary, but makes the engineering significantly simpler as one need not worry about moving the water cooling lines and the high voltage lines.
Remember, the angle measured is actually $2 \cdot \theta$, the angle between arms of the gonimeter, **NOT** θ, the angle from vertical (see scheme of X-ray diffraction)!

D. Information Regarding the Experimental Setup

Detector: ?
X-ray wavelength : 1.5459 , Cu K-alpha line

Schematic Drawing, Block Diagram

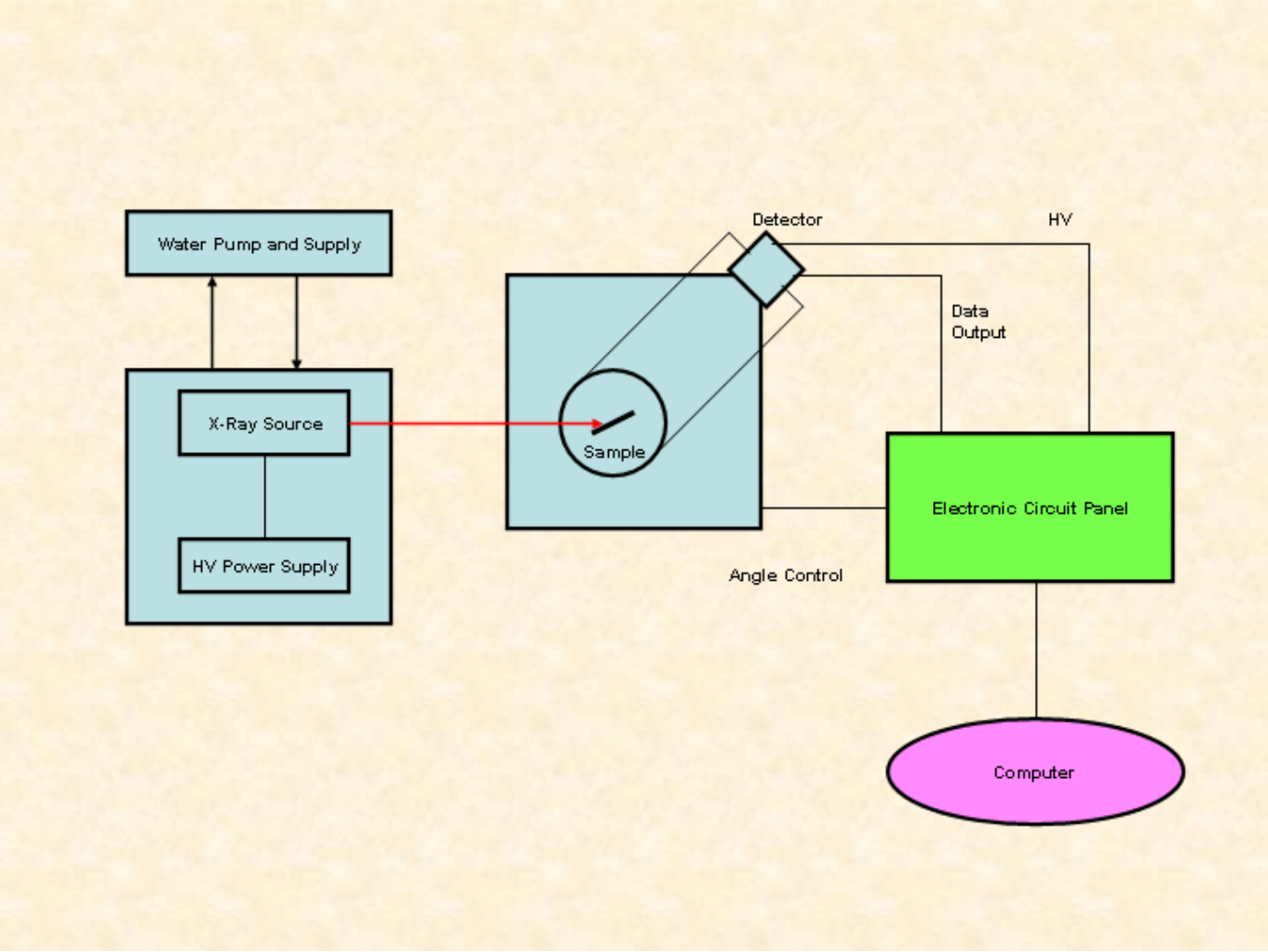


Figure 58: Block scheme of the XRD-experiment with cooling unit, RIGAKU Miniflex II diffractometer, consisting of X-ray source, double angle Bragg difractometer drive (goniometer), detector and electronic control, PC for data taking and evaluation.

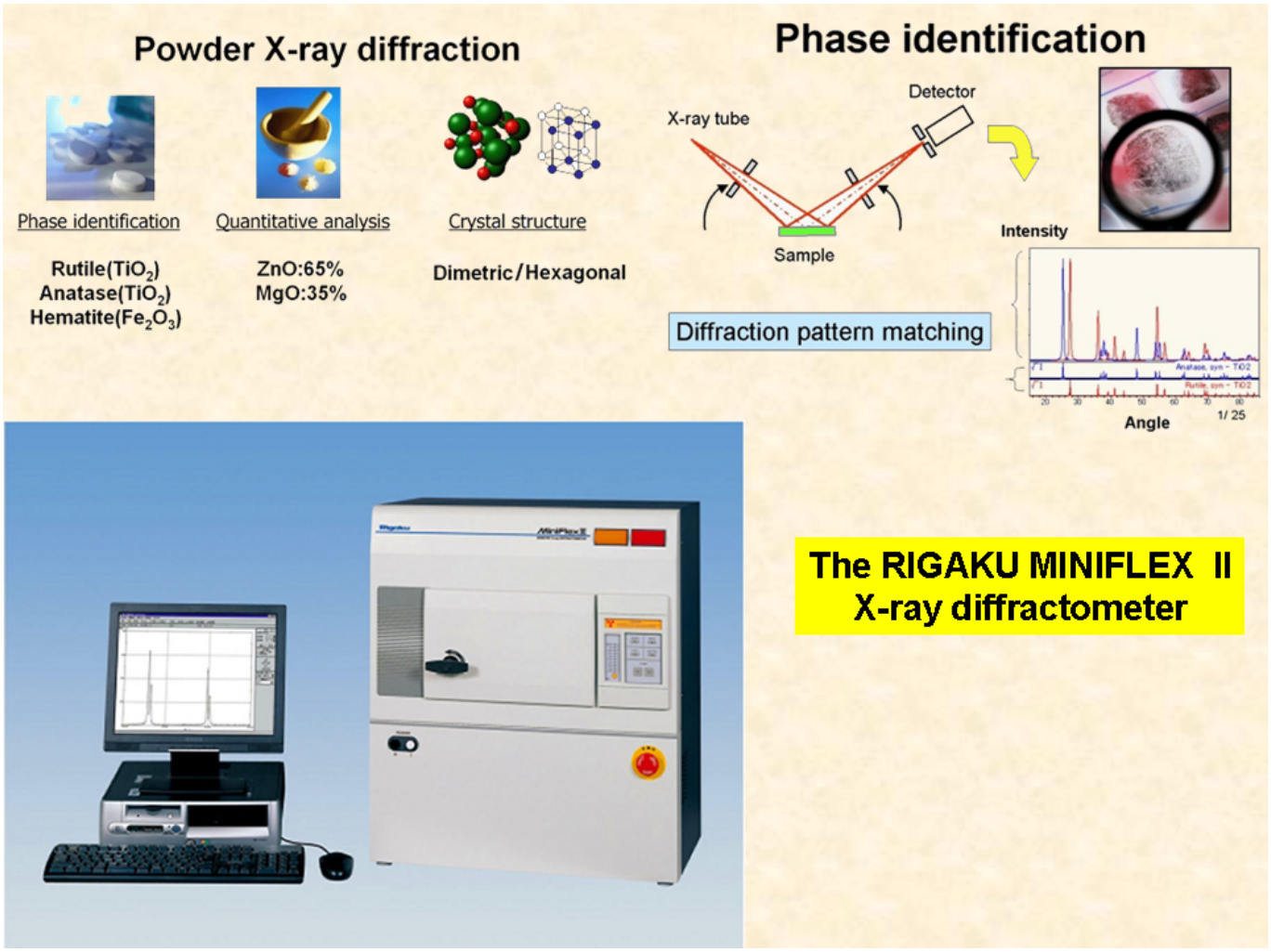


Figure 59: Photo of the RIGAKU Miniflex II with some schematic figures.

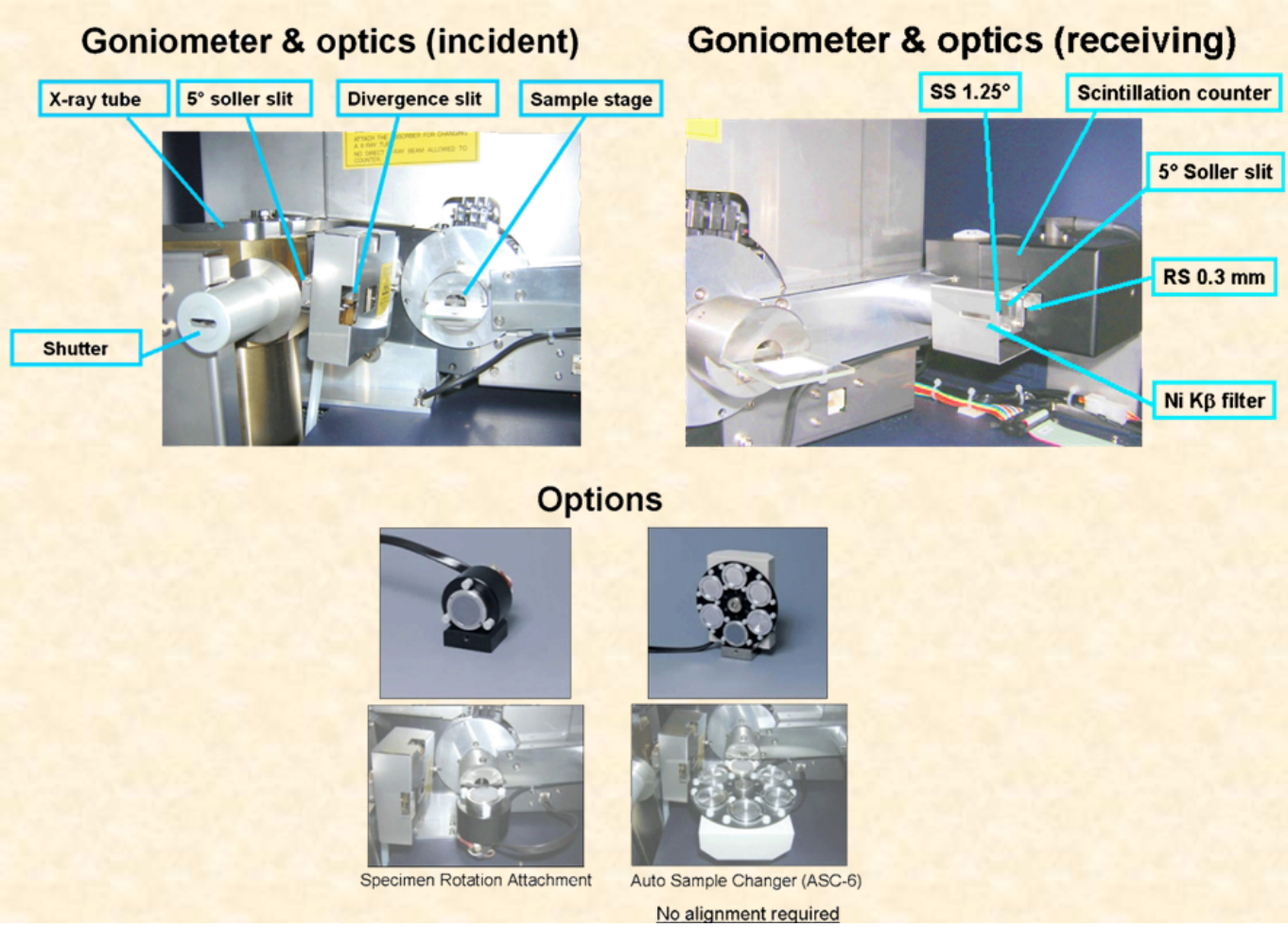


Figure 60: Photo of the interior of the RIGAKU Miniflex II, especially the goniometer, Soller slits, sample holder and changer, and the detector.

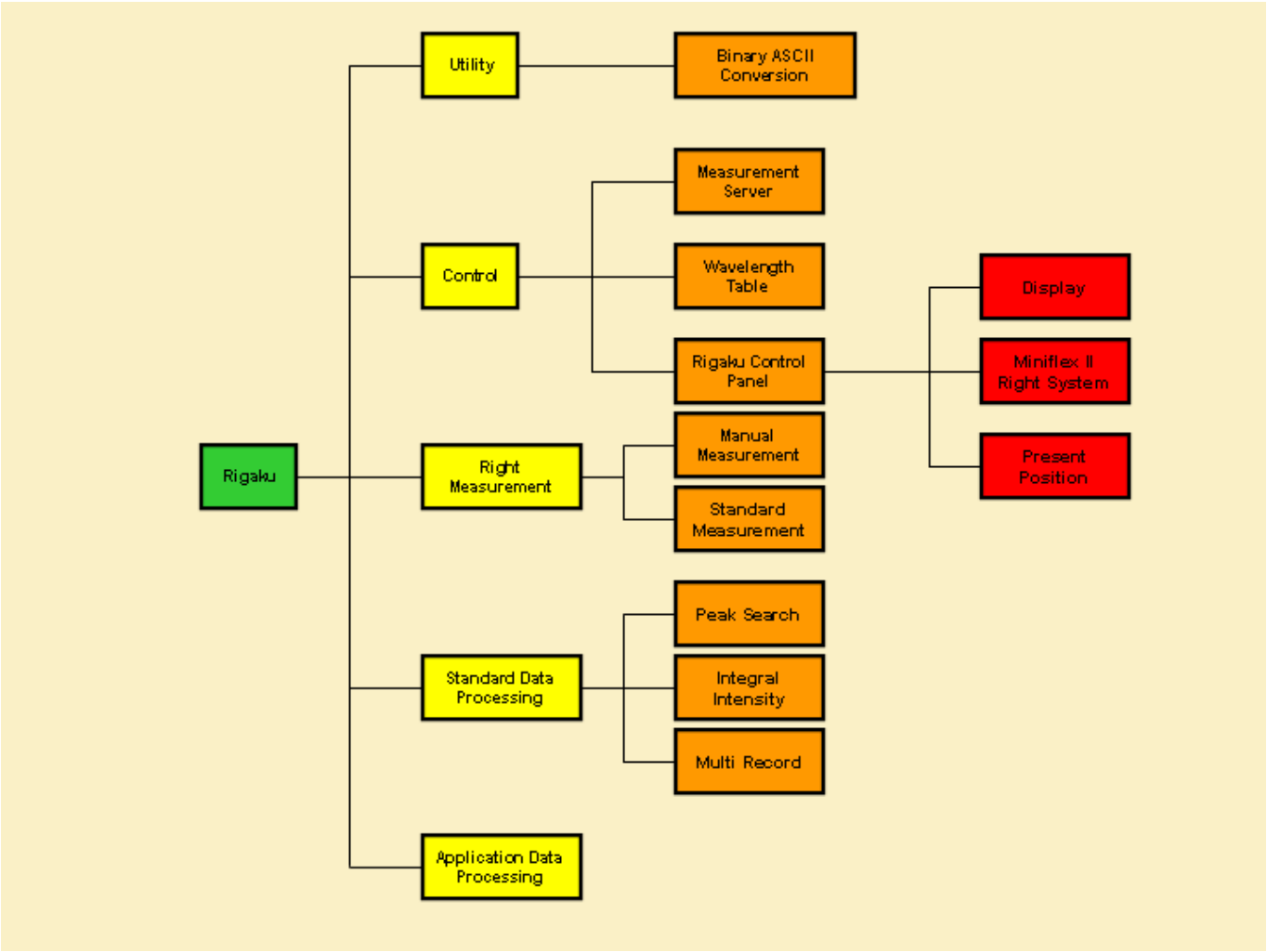


Figure 61: Block scheme of the software for the RIGAKU Miniflex II, including control of the goniometer, data taking, peak evaluation, and analysis procedures.

E. Discussion of Results

- Produce a comparison plot of observed spectra with theoretical prediction of the angular location of peaks as determined using Bragg's Law and the Miller indices of the first 5 samples, this information is in Appendices 2 and 3. Comment on any discrepancies.

  Bragg's Law : n λ = 2 d sin(θ)

  For a Face Centered Cubic, all the lattice parameters are equal. The interplanar spacing is related to the lattice parameter, a, listed in Appendix 2 by the following relation

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

  interplanar lattice spacing

  For any given Miller Index, (h,k,l) and order of diffraction, n, the angle of constructive interference is:

$$\theta_{nhkl} = sin^{-1}\left\{\frac{\lambda\, n\, \sqrt{h^2 + k^2 + l^2}}{2\, a}\right\}$$

  where n = 1,2,3 and h,k,l = 1,2,3...

- Now that the Miller indices have been associated with specific angles we can calculate the lattice parameter for each of the first 5 samples and compare with standards.

$$a = \frac{\lambda\, n\, \sqrt{h^2 + k^2 + l^2}}{sin(\theta_{hkl})}$$

  lattice parameter for each angle and set of indices

- Use Bragg's Law to investigate the compounds used to create YBCO. The groups will determine the Miller Indices of all 3 samples by calculating all possible Miller Indices and identifying which are observed. From this information comment on the shapes and structures of the lattices.

  In General, the interplanar lattice spacing is

$$d = \frac{2\pi}{\left|\vec{G}\right|}$$

The reciprocal lattice vector $\vec{G}$ is comprised of reciprocal basis vectors, $\vec{b_i}$, and Miller indices.

$$\vec{G} = h\vec{b_1} + k\vec{b_2} + l\vec{b_3} \qquad \text{where} \qquad \vec{b_i} = 2\pi \frac{\vec{a_j} \times \vec{a_k}}{\vec{a_i}\,\vec{a_j} \times \vec{a_k}}$$

See Appendix 4 for specifics on the primitive vectors of the crystal lattice, $\vec{a_i}$.

- Then determine the role of each of the 3 compounds in YBCO, by comparing their spectra with that of YBCO. Research the processes for the construction of YBCO. Comment on the production of YBCO and how it will relate to the apparent abundances of BaCO3, Y2O3, and CuO.
- Identify the lattice structures for the Na salts and KCl from the literature. Using this information, calculate via computer program the location of all diffraction peaks, and compare with the observed diffraction data. The calculation can be done in Mathematica or Maple, or in whatever computer language you are comfortable in. Doing the calculation by hand is extremely tedious as the calculation will be repeated up to 1000 times in order to match the observed data.
- From the diffraction data on the Na salts, and the information in item X above, estimate the ionic radii of the halogen ions. What systematic effect is there, and does this match your expectations from the literature?
- The structural calculations for the halide salts is simple due to their easy basis vectors. Repeat the calculations for your additional materials and explain any discrepancies.

F. Appendix

1. Example of data for NaCl on Jade 8 with Peak Search window open.

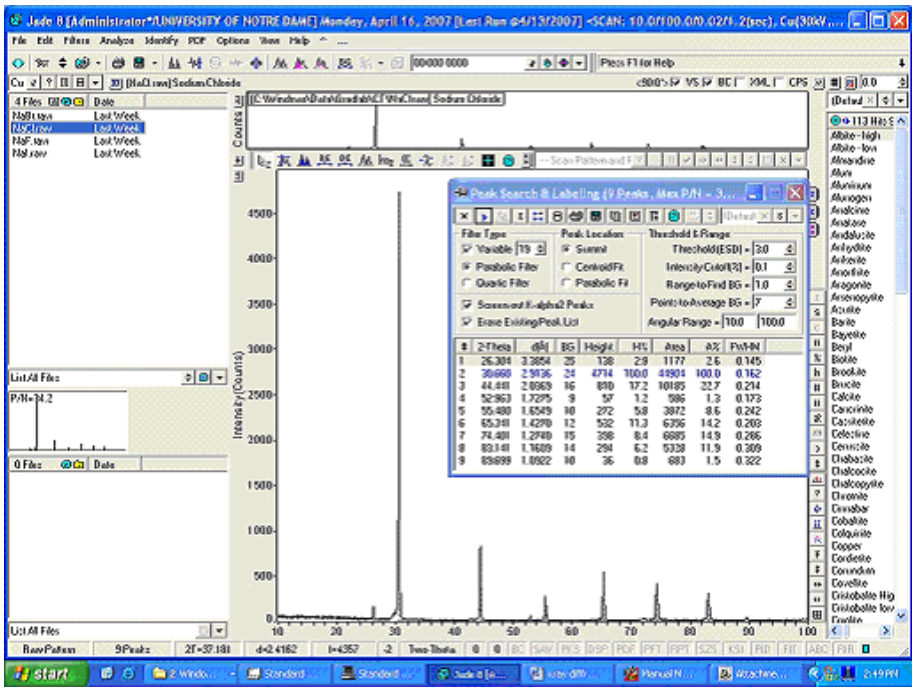


Figure 62: Example of data for NaCl on Jade 8 with Peak Search window open.

2. Abbreviated from Table 4.5 pg 80 of Ashcroft & Mermin's 'Solid State Physics' For Face Centered Cubic Packing Lattice Parameters for compounds with structure similar to Sodium Chloride [1].

Name	Lattice parameter a (Å)
NaF	4.62
NaCl	5.64
NaBr	5.97
NaI	6.47

3. Abbreviated from Appendix 6 p 471 of 'Elements of X-Ray Diffraction' Table Quadratic Form of Miller Indices [2].

$h^2+k^2+l^2$	Face Centered (h,k,l)
2	1,1,0
4	2,0,0
8	2,2,0
11	3,1,1
12	2,2,2
16	4,0,0
19	3,3,1
20	4,2,0
24	4,2,2
27	5,1,1 and 3,3,3
32	4,4,0
35	5,3,1
36	6,0,0 and 4,4,2
40	6,2,0
43	5,3,3
44	6,2,2
48	4,4,4

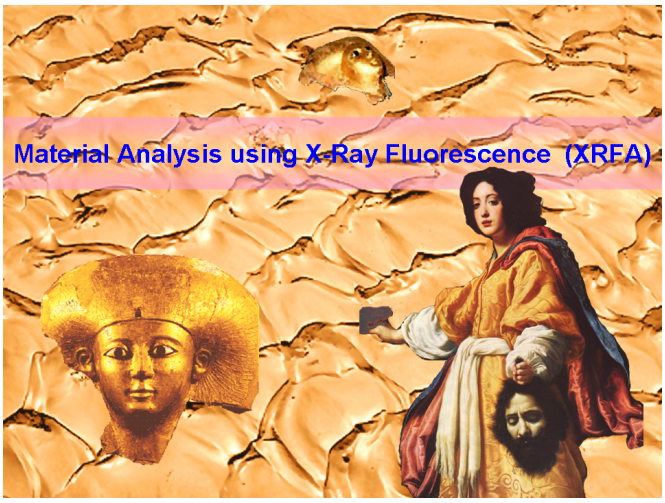
4. Table comprised of information gathered from Wyckoff's Crystal Structures Volumes 1 & 2 [4]. β is the angle of the third lattice vector, such that $\vec{a_3} = c_0\,[cos(\beta)\,\hat{y} + sin(\beta)\,\hat{x}\,]$. All other angles are 90° so the principle vectors are orthogonal. Specifically, $\vec{a_1} = a_0\,\hat{x}$, $\vec{a_2} = b_0\,\hat{y}$.

Name	**Description of Shape**	$\mathbf{a}_0$ **(Å)**	$\mathbf{b}_0$ **(Å)**	$\mathbf{c}_0$ **Å)**	β
CuO	Monoclinic	4.653	3.410	5.108	99° 29'
$BaCO_3$	Othorhombic	8.8345	6.5490	5.2556	90°
Y_2O_3	Cubic Bixbyite	10.604	10.604	10.604	90°

G. Example Questions

- How is the X-ray beam generated and wavelength-selected?
- How do scientists classify lattices, and how does the mathematical description of lattices work?
- What do reciprocal vectors actually mean?
- Demonstrate how one determines whether a set of Miller indices describing a plane results in constructive interference.
- How is the amplitude of X-ray diffraction peaks determined?
- How would one determine the structure of an unknown material from an X-ray diffraction pattern?
- How would one identify the existence of impurities in a material by X-ray (or neutron) diffraction?

18 Material Analysis using X-ray Fluorescence (XRFA)



Location: room Jordan 305

A. Short Description

The excitation of characteristic X-rays in a sample of material is the preferred method of material analysis. It is based on the pioneering work of H.G.J. Moseley, who explored the systematics of characteristic X-rays.
In this experiment a radioactive γ-source (^{241}Am) or an X-ray tube is used for the excitation depending on the energy range or Z-region of interest. A high resolution Si-X-ray detector and a multichannel analyzer enables us to distinguish neighbor elements which differ only by one unit in the proton number (Z). The X-ray fluorescence is an efficient and quick method. It doesn't harm the investigated sample. Several examples are given below. The XRFA-method is complimented by the method of proton induced X-ray measurement (PIXE) which requires higher expenditures, shown in the example of the mask of Queen Sat-Djehuti.

B. Necessary Knowledge

Physics :

- Basic atomic physics of inner shells, concepts and terms, characteristic numbers, Roentgen fluorescence yield, binding energy in the shell model of the atom, Auger electron emission
- Production of X-rays
- Bremsstrahlung; Synchrotron radiation
- Characteristic X-rays, selection rules, K- and L-series

- Absorption and scattering of X-rays
- Applications of characteristic X-ray spectroscopy
- Some quantitative considerations

Measuring Technique :

- Principles of X-ray detectors, especially silicon detectors
- Classical method of X-ray wavelength determination
- Function of the specific ^{241}Am source
- Function of an X-ray tube
- Required electronic units and function
- Multichannel-Analyzer and function of an ADC

Mathematics : Method of least squares, peak evaluation, background subtraction

References

[1]	**Deslattes, R.D., E.G. Kessler Jr., P Indelicato, L. de Billy, E. Lindroth and J. Anton :** X-ray transition energies : new approach to a comprehensive evaluation Re. Mod. Phys. **75**, 35 (2003)	Most recent review article on all X-ray transitions of the elements
[2]	**Beckhoff, B. (Ed.), KanngieSSer, B. (Ed.), Langhoff, N. (Ed.), Wedell, R. (Ed.),and H. Wolff (Ed.) :** Handbook of Practical X-Ray Fluorescence Analysis Springer; 1. edition (July 28, 2006)	Comprehensive handbook
[3]	**Jenkins, R. :** X-Ray Fluorescence Spectrometry (Chemical Analysis: A Series of Monographs on Analytical Chemistry and Its Applications) Wiley-Interscience; 2 edition (June 18, 1999)	Good introduction into the field
[4]	**Van Grieken, R. (Ed.), and A. Markowicz (Ed.) :** Handbook of X-Ray Spectrometry Revised and Expanded (Practical Spectroscopy, V. 29) John Wiley & Sons New York 1996	Current reference for nuclear data
[5]	**Jenkins, R., Gould, R. W., and D. Gedcke :** Quantitative X-ray Spectrometry (Practical Spectroscopy) Marcel Dekker; 2 edition (April 26, 1995)	Valuable compendium
[6]	**Janssens, K.H.A., Adams, F.C.V., and Anders Rindby (Eds.) :** Microscopic X-Ray Fluorescence Analysis Wiley; 1 edition (May 12, 2000)	.....

[7]	**Van Grieken, R.,and K. Janssens :** Cultural Heritage Conservation and Environmental Impact Assessment by Non-Destructive Testing and Micro-Analysis Taylor & Francis (August 15, 2004)	.....
[8]	**Janssens, K., and R. Van Grieken (Eds.) :** Non-destructive Micro Analysis of Cultural Heritage Materials, Volume 42 (Comprehensive Analytical Chemistry) Elsevier Science; 1 edition (January 26, 2005)	.....
[9]	**Uda, M., Demortier, G., and I. Nakai (Eds.) :** X-rays for Archaeology Springer; 1 edition (September 27, 2005)	.....
[10]	**Sven A. E. Johansson (Editor), John L. Campbell (Editor), Klas G. Malmqvist (Editor) :** Particle-Induced X-Ray Emission Spectrometry (PIXE) (Chemical Analysis: A Series of Monographs on Analytical Chemistry and Its Applications) Wiley-Interscience; 1 edition (August 4, 1995)	.....
[11]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[12]	**Knoll H. G. :** Radiation Detection and Measurements Kap. 10, John Wiley & Sons, New York 1989	Standard work on detectors

Experimental Tasks

- Get the X-ray tube or the variable X-ray source from the TA; get help with the set-up
- Turn on first the NIM power, then turn on very slowly the high voltage bias of the detector (- 500 Volts) and watch the signals from the main amplifier. In case they are not regular stop and ask.
- Important: Check the main settings of the main amplifier to obtain good resolution. Time constant of 3μs will work best. Amplification set that the 59.5 keV line of ^{241}Am has an amplitude of nearly 8 Volts.
- Set MCA to 2048 channels (both channel select and conversion gain)
- Check pole zero cancellation very carefully with the oscilloscope, the baseline must be absolutely flat and quiet
- Calibration of the detector using three lines Cu K_α, Ba K_α and 59.5 keV ^{241}Am line, you can also use the Cs-137, the Mn-54 and the Co-57 source

- Determine detector resolution in keV for at least two lines (iron K_α and 122 keV line of ^{57}Co)
- Determine about 10 unknown samples (ask TA which ones), about 30 samples are available
- Alternative task: Measure several L-spectra for various elements and explain them
- In addition, you can determine some more elements than six, which have appropriate K lines
- Alternative experiment: use X-ray tube instead of the ^{241}Am source. There are two settings for the tube: the applied high voltage and the tube current. The high voltage affects the X-ray spectrum shape (more soft or more hard) and the current affects the intensity. In most cases a few μA's are sufficient!
- The X-ray tube is more appropriate and efficient for elements in the range $20 < Z < 40$. Consider also the use of the L-series.

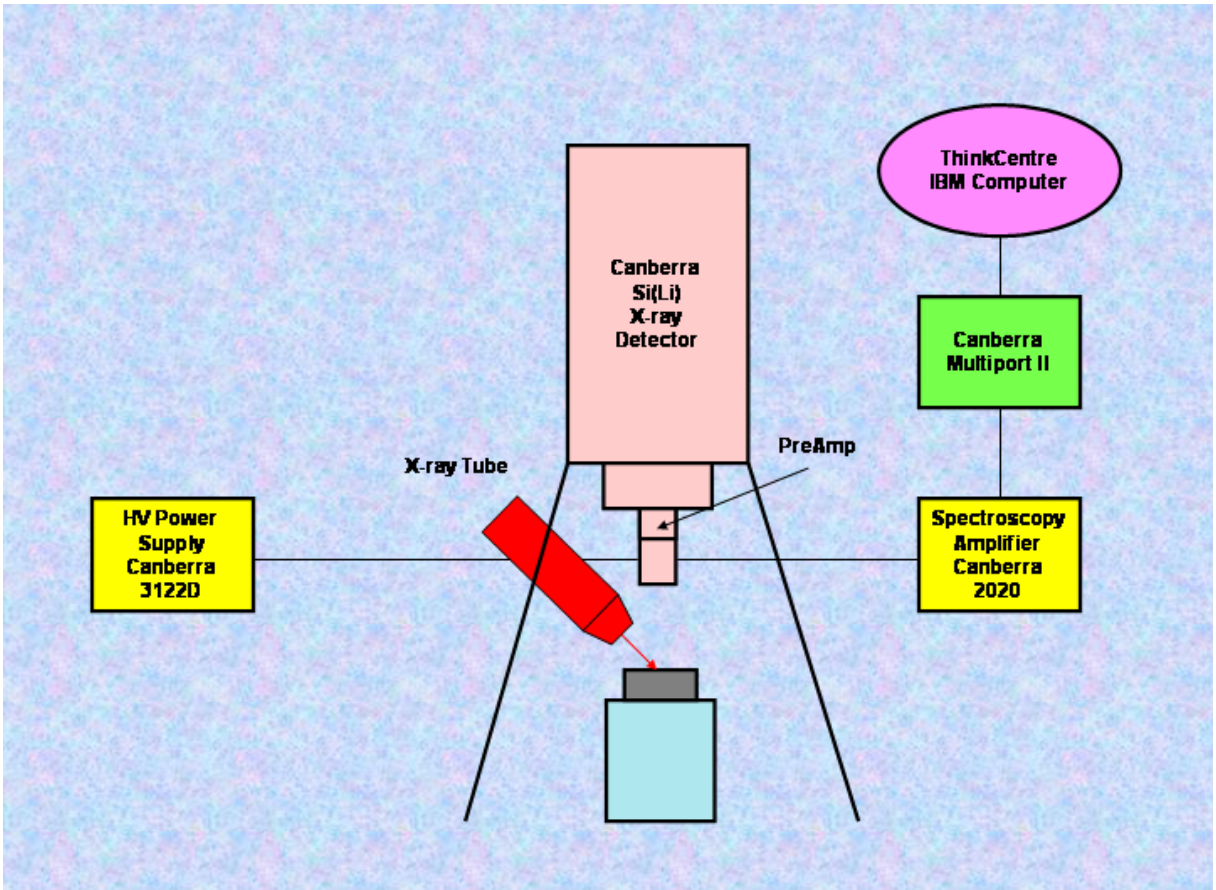
WARNINGS

- Make sure that the detector was cold for 3 hours or more prior to HV application
- No HV without preamp power on! Internal FET can die!
- HV turn on and off very slowly. No abrupt switch off!
- Remove protective cap from detector before starting measuring
- Never touch the ultra thin Be window of the detector
- Watch count rates ! Too high count rate can latch up preamp or deteriorate resolution
- Be careful with the use of the ^{241}Am source, it is strong and under special regulations (transuranium element).
- No measurement of spectra during LN_2 filling.
- The X-ray tube can deliver very high intensities of X-radiation, several precautions are necessary: use always a brass collimator with the tube, start working with low currents (1 - 2 μA) and watch the detector signals, use sufficient shielding around the irradiated area. Let the TA or the professor check your set-up before switching on the X-ray tube.

- Never touch the extremely thin and expensive Be-window of the X-ray tube.

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

X-ray :	Excitation source for fluorescent X-rays: X-ray tube Eclipse IV from Oxford Instruments or AmpTek, with a Rd-anode; max. voltage: 45 kV; max current : 50 μA. Usual setting about 30 kV and 1 – 4 μA. Alternatively : ^{241}Am source using the 59.5 keV γ transition
Detector :	Si(Li)–Semiconductor Detector Canberra EURISYS Mod. ESLX 30-150-ER No 0251 (year 2002) Crystal dimensions : useful surface 30 mm^2; external diameter 6.2 mm; length 5.5 mm; volume 0.15 cm^3;

	dead layer $\simeq 0.2\,\mu$m/Si; distance from cap 3 mm Energy resolution 150 eV at 5.9 keV
Bias :	Canberra HV 2122 D, neg. -500 Volts
Preamp :	Preamplifier PSC 854
SpecAmp :	Main spectroscopy amplifier CANBERRA 2020
MCA,ADC :	Canberra multiport II (ADC and MCA)
Computer :	Computer IBM think centre; CANBERRA MCA software Genie 2000 (dongle)

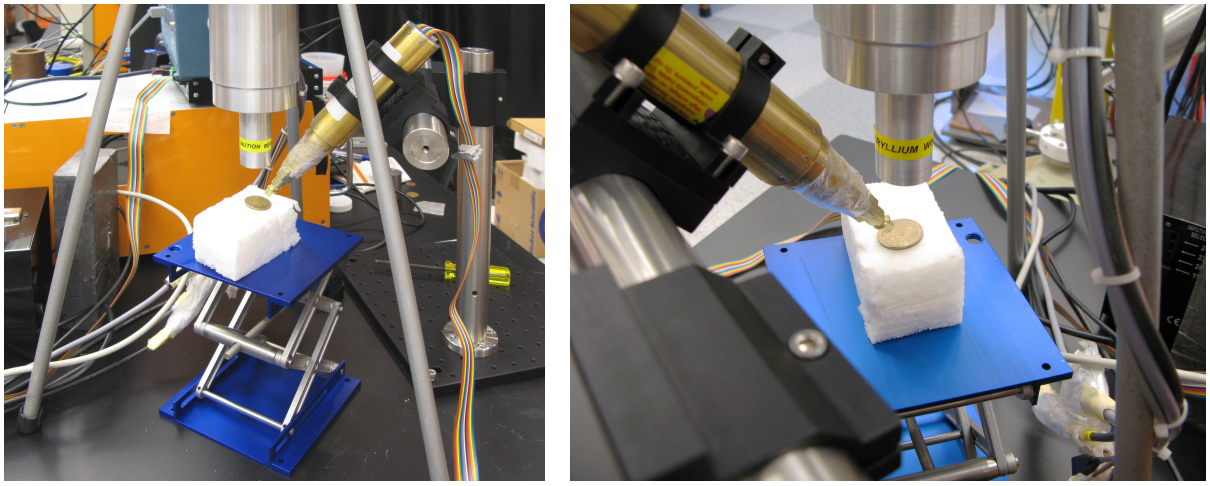


Figure 63: XRFA-set-up using the X-ray tube Eclipse IV from Oxford Instruments aiming on a coin. The indispensable X-ray collimator is a provisional one in this picture. The characteristic X-rays are detected with a Canberra SiLi-X-ray detector.

About the preamplifier and the main amplifier

The preamplifier works with a so-called optical feedback, which means that the feedback resistor is over most of the time nearly infinite, but after reaching a certain level of amplitude of the output signal it is switched to a low value by a flash of a light emitting diode. The main amplifier has to deal with these strong negative switching signals and only a few have this property, the Canberra 2020 being one of them. The advantage is better resolution and higher count rates. The proper settings for pole zero cancellation and base line recovery are very important. With an inappropriate main amp one can produce so-called "ghost-lines", electronic artifacts.

Tables of the X-ray lines

Those tables are already given in experiment No 5 "X-ray Spectroscopy". Here are only the data for the L-series displayed.

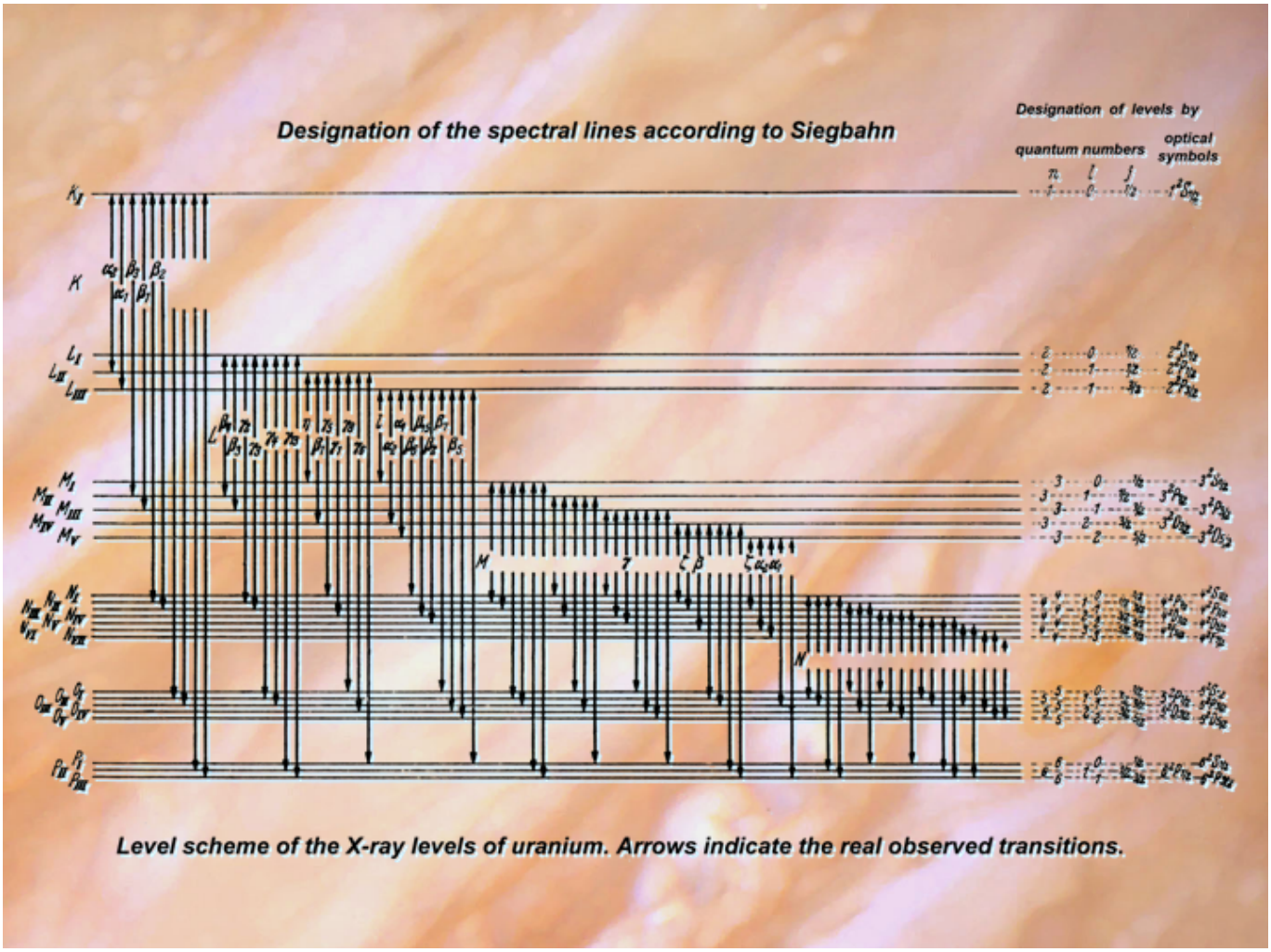


Figure 64: X-ray transitions for the L-series in uranium. The designation of the observed lines is according to Siegbahn.

Most intense L-X-ray lines of some heavy elements

Element Symbol (Z)	Tantalum Ta (73)	Tungsten W (74)	Platinum Pt (78)	Gold Au (79)	Mercury Hg (80)	Lead Pb (82)	Thorium Th (90)	Uranium U (92)
Line*	**Energies in electron-volts [eV]**							
α_1 (L_3M_5)	8146.17	8398.242	9442.39	9713.44	9988.91	10551.6	12967.937	13614.87
α_2 (L_3M_4)	8087.93	8335.34	9361.96	9628.05	9897.68	10449.59	12809.49	13438.97
β_1 (L_2M_4)	9343.19	9672.575	11070.84	11442.45	11822.7	12613.8	16201.556	17220.15
β_2 (L_3N_5)	9651.89	9964.133	11250.66	11584.75	11924.2	12622.8	16024.6	16428.44
β_3 (L_1M_3)	9487.62	9818.91	11230.89	11610.5	11995.4	12793.4	16423.855	17455.17
β_4 (L_1M_2)	9212.47	9525.23	10854.41	11204.81	11563.1	12305.9	15639.54	16575.51
γ_1 (L_2N_4)	10895	11286	12942	13381	139830	14764	18978	20167
γ_2 (L_1N_2)	11217	11610	13270	13709	14162.3	15218.2	19302	20484
γ_3 (L_1N_3)	11277.68	11680.49	13361.5	13809.1	14264.8	15218.2	19503	20712.95
γ_5 (L_2N_1)	10570	10948	12552	12974	13410	14307	18364	19506
l (L_3M_1)	7173.2	7387.8	8268.2	8494.03	8721.32	9184.56	11118.06	11618.41
η (L_2M_1)	8428.09	8724.42	9975.2	10308.41	10651.4	11349.4	14510.327	15399.81

* Siegbahn notation (modern notation)

Information on the used radioactive sources

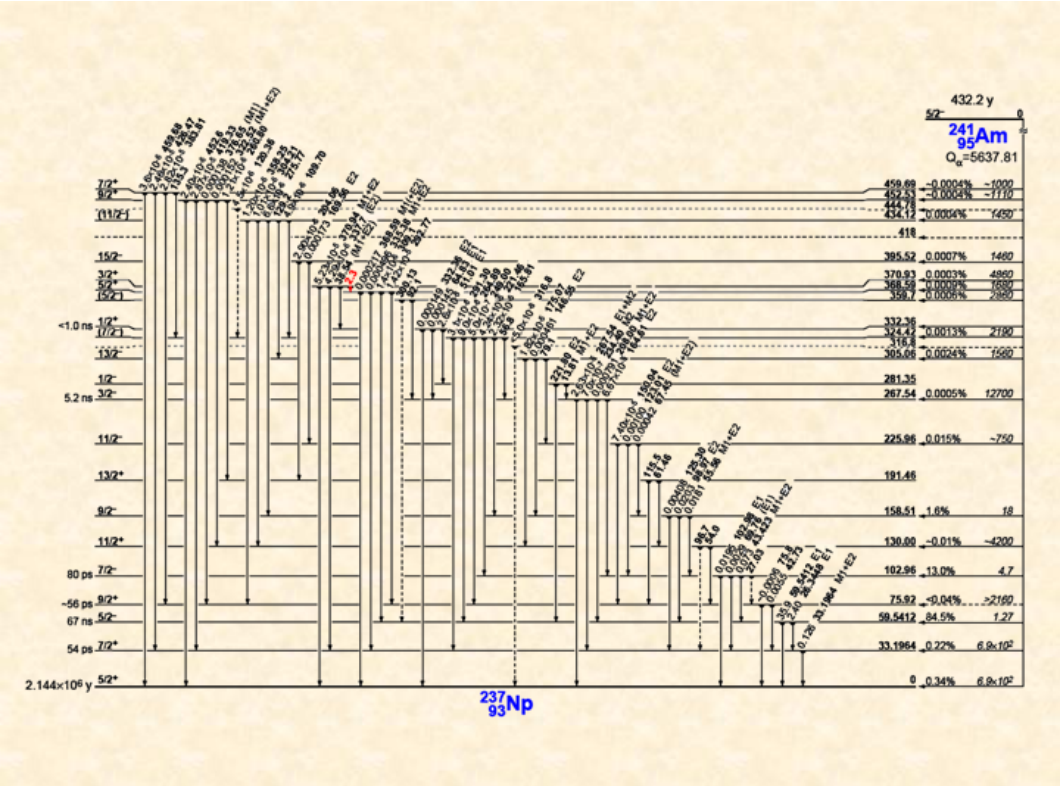


Figure 65: Decay scheme of ^{241}Am from [11].

D. Examples

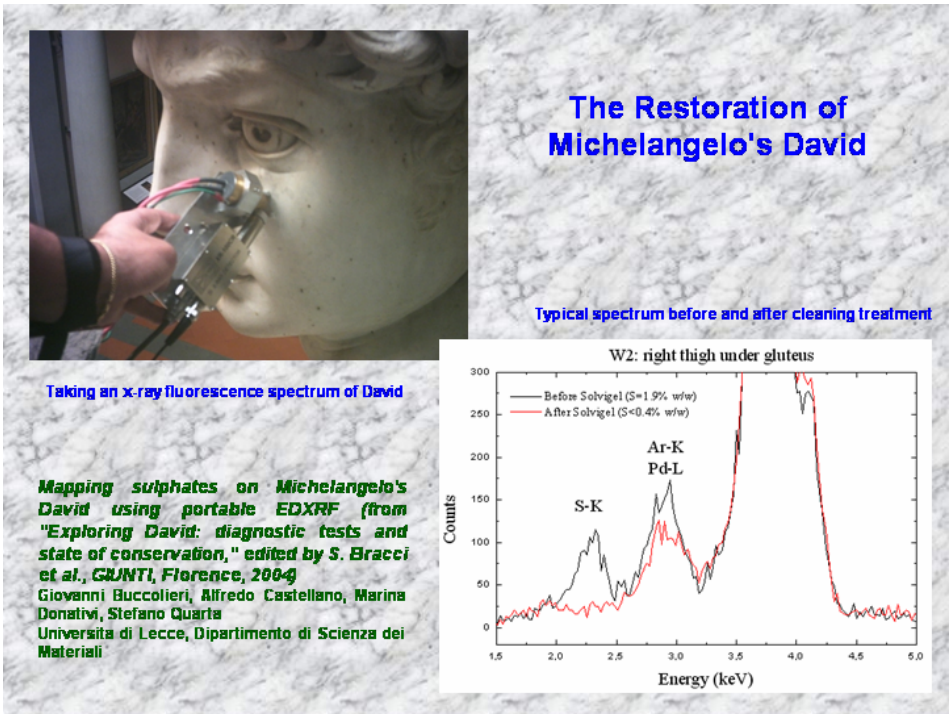


Figure 66: Restoration of the surface of Michelangelo's *David*; remove of sulphates.

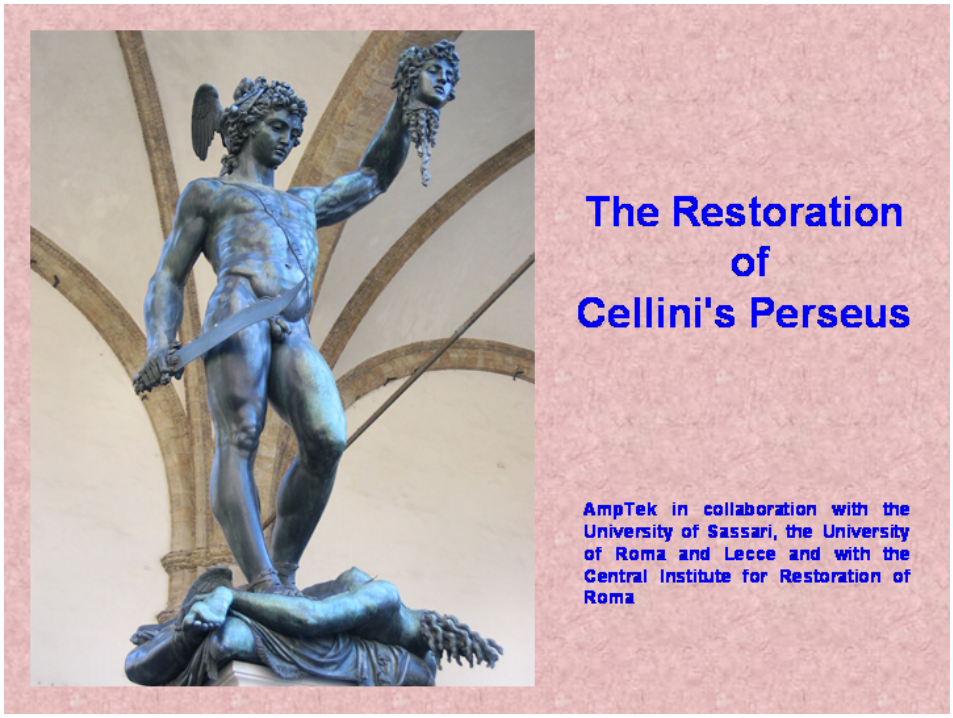


Figure 67: Restoration of Cellini's bronce statue *Perseus*; investigation of the patina.

Figure 68: Rare found: the *Gold Ibex* from Santorini; the body is cast gold, the legs are soldered.

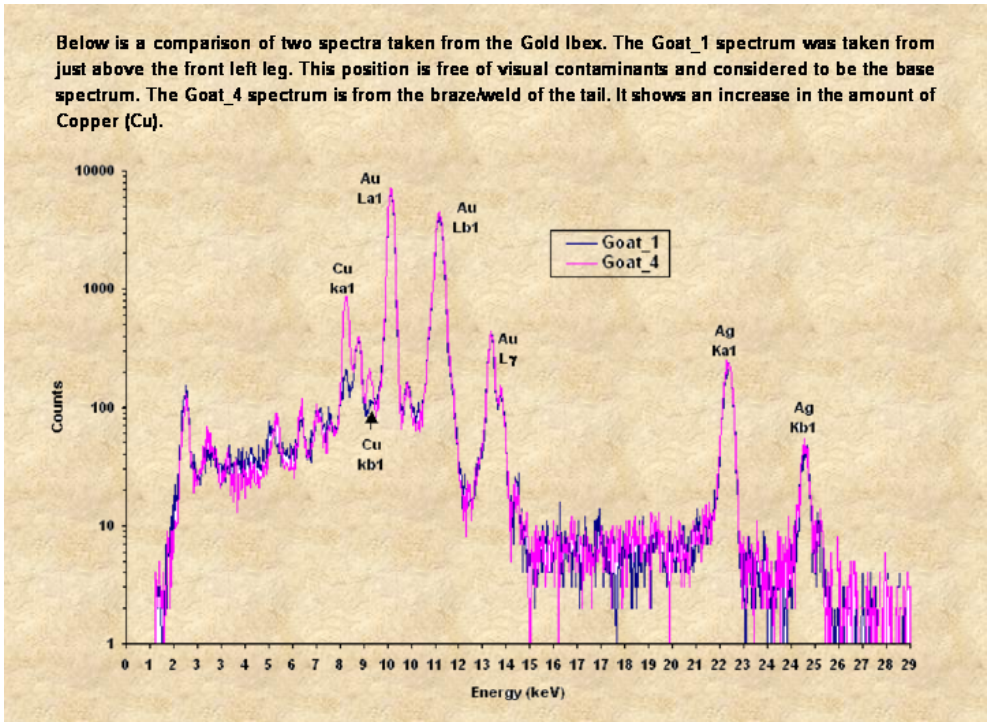


Figure 69: Investigation of the 'make' of the *Gold Ibex*.

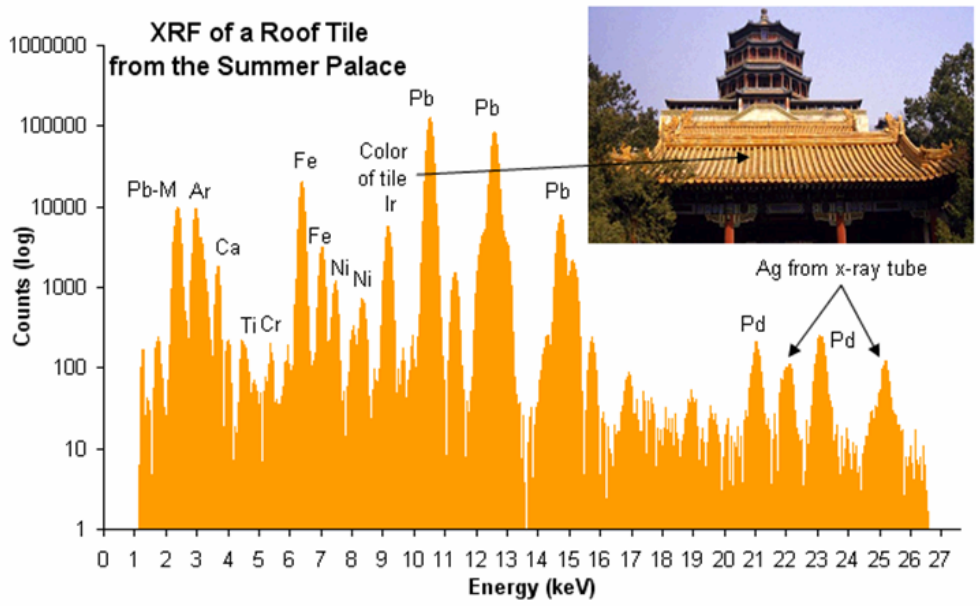


Figure 70: Investigation of the elementary composition of roof tiles from the famous summer palace.

Figure 71: PIXE investigation of the gold plated funeral mask of *Queen Sat Djehuti* at the HMI Berlin.

E. Discussion of Results

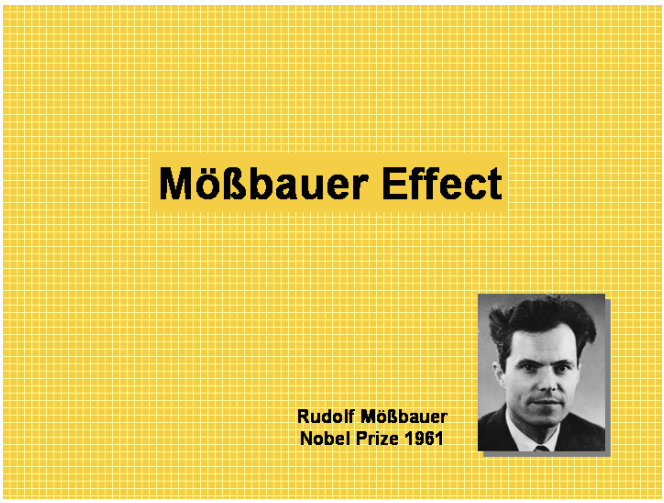
- Provide

F. Example Questions

- How are X-rays created?
- What is the difference between X-rays and γ-rays?
- What is the Auger effect?
- What is a fluorescence yield?
- Explain Moseley's formula
- How is the material analysis performed?
- Why has the silicon-detector to be cooled?

- Which other methods of X-ray spectroscopy are known?
- Can you explain whether one can distinguish all chemical elements in an X-ray analysis or not? Is it possible to distinguish isotopes? Explain.
- What is the purpose of a so-called "main spectroscopy amplifier"?

19 Mößbauer Effect



Location: room Jordan 305

A. Short Description

In the Mößbauer-experiment one makes use of the recoilless resonant absorption or fluorescence of specific γ-transitions in nuclei embedded in a lattice of solid matter. These lines have a relative and natural line width in the order of 10^{-13}.....10^{-17} ("sharpest line of the world") and they can be used to measure extreme small energy shifts or splittings and to determine internal fields in solid matter. One famous example was the measurement of the gravitational redshift of photons at Harvard by Pound and Rebka, testing and proving general relativity at a 10^{-15}-level. To make use of these sharp lines one has to make them quasi Doppler-free. In a lattice the absorption and reemission of γ's happens to a certain portion recoilless – no exchange of phonons – and the portion is given by the theory of the Debye-Waller factor. The energy shift is achieved by moving the source and applying the controlled Doppler effect. In this experiment the hyperfine splitting, quadrupole splitting and isomeric shift can be determined in specific probes.

Pound and Rebka, *Phys. Rev. Lett.* **4**, 337 (1960)

B. Necessary Knowledge

Physics :

- Natural line width of γ-lines; Heisenberg uncertainty principle
- Doppler effect, recoil of nuclei
- Resonance fluorescence

- Nuclei in solid matter lattice, Debye-Waller factor
- Mößbauer effect, "sharpest line of the world"
- Mößbauer isotopes and sources

Measuring Technique :

- Mößbauer drives
- What can be measured with the Mößbauer effect
- Energy shift, line splittings, internal fields
- Pound-Rebka experiment
- γ-laser
- Proportional counter
- Nuclear electronics
- Principles of a multiscaler
- Mößbauer data software
- Evaluation software

Mathematics : Method of least squares

References

[1]	**Stückel, B.:** Der Mößbauer-Effekt im Praktikum Thesis of high school teachers, University of Stuttgart 1998	Original thesis on this teaching lab experiment
[2]	**Schatz, G. and A. Weidinger:** Nuclear Condensed Matter Physics John Wiley and Sons, Chichester, New York etc. 1996	Standard textbook on nuclear methods in solid state physics
[3]	**Gibb, T.C. :** Mössbauer Effect: Principles and Applications Halsted, New York, 1976	Fundamental textbook
[4]	**Gonser, U., Ed. :** Mössbauer Spectroscopy Topics in Applied Physics, Vol.5 Springer-Verlag, Berlin 1975	Expert textbook with collected articles
[5]	**Gonser, U., Ed.:** Mössbauer Spectroscopy II, The Exotic Side of the Methods Topics in Applied Physics, Vol. 26 Nr. 1, Springer-Verlag, Berlin 1981	Expert textbook with collected articles
[6]	**Krane, K. S. :** Introductory Nuclear Physics John Wiley and Sons New York 1988	Standard textbook for Nuclear Physics
[7]	**Firestone R. B. :** Table of Isotopes CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data

Experimental Tasks

- Switch on NIM-power
- Set HV for proportional counter to + 2020 Volts (Scale 3400)
- Remove brass plug from the source and insert lead aperture
- Watch pulses of main amp on the oscilloscope, get appropriate count rate by choosing right source-detector distance
- Set single channel analyzer exactly on the 14.4 keV line
- Set Mößbauer drive controller to sinus mode and max. velocity to 7 mm/s at 1024 channels
- Insert pure iron absorber to get first hyperfine splitting
- Start multiscaler, lines should show up after about 10 minutes, take longer run

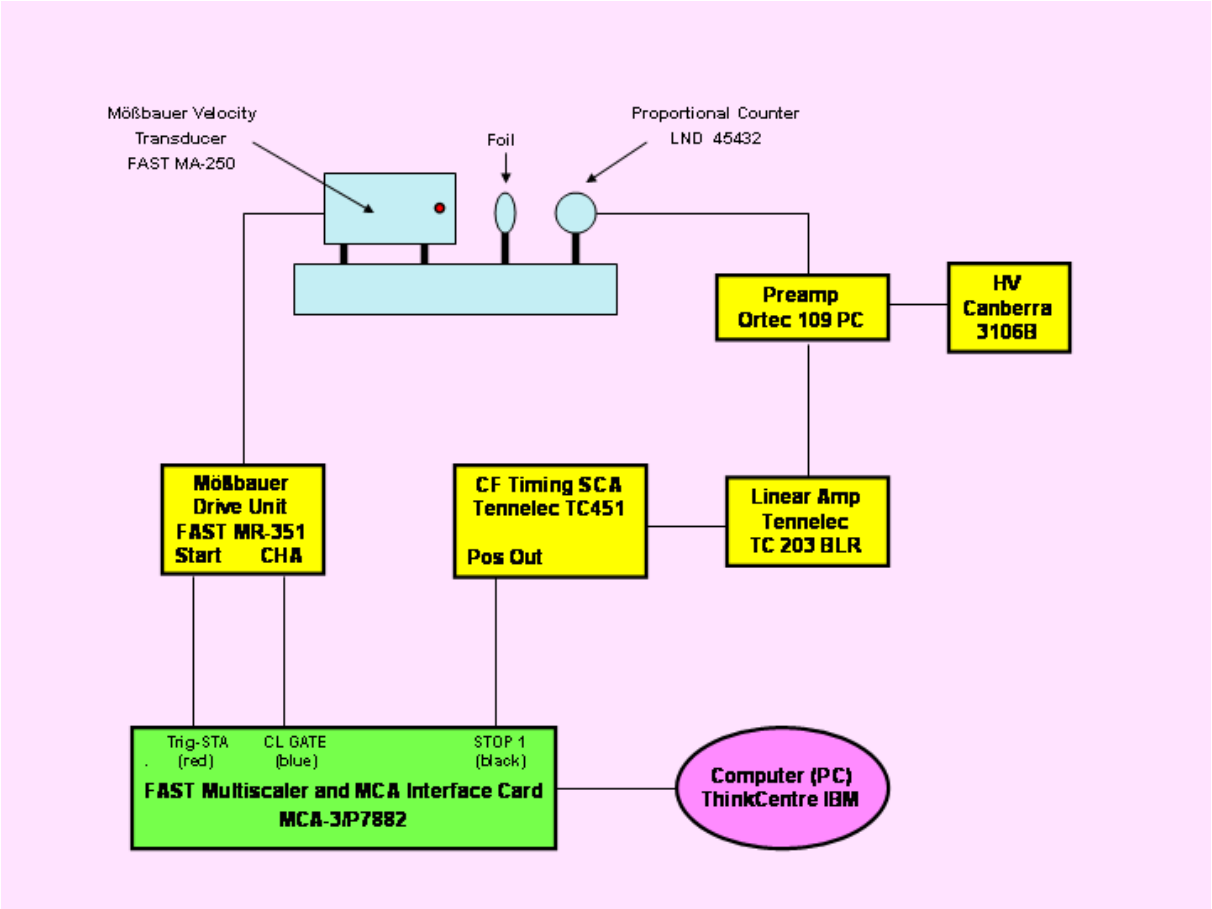
- Determine quadrupole splitting and isomeric shift by a similar procedure, max. velocity 5 mm/s resp. 3 mm/s
- Measure energy spectrum of the Mößbauer source using the ADC of the FAST MCA-3 card (see Manual)
- Evaluate the Mößbauer spectra with the software, determine field etc.
- Alternative tasks : measure hyperfine splitting with an applied transversal and/or longitudinal magnetic field to the iron foil, the occupation probabilities of the sublevels will change!

WARNINGS

- After finishing the measurement, turn down HV of the proportional counter
- Insert plug into the collimator of velocity transducer to stop the radiation from the source
- Put all the absorbers back to the box

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

MBdrive :	Mößbauer drive (motion transducer) FAST-ComTec # MA-250, closed loop loudspeaker system with calibrated precise velocity scan, attached to the drive is the Mößbauer source ^{57}Co, 50 mC at delivery date,
Controller :	Mößbauer electronic drive controller FAST-ComTec # MR-351, use the sinusoidal-mode of the drive because of the analysis software (PC-MOS II), minimize the movement errors
Foil :	Absorber foil; choice of natural iron, enriched natural iron (?), stainless steel, $FeSO_4$, $Fe_4CN_6xH_2O$, etc.

Det :	Detector: proportional counter tube from LND Inc., Oceanside, NY, filled with xenon, LND # 45432, required high voltage + 2020 Volts
HV :	High voltage power supply for the proportional counter, Canberra # 3106B
preamp :	Pre-amplifier for proportional counters, Ortec # 109 PC
mainamp :	Main spectroscopy amplifier, Tennelec # TC 203 BLR
SCA :	CF-timing single channel analyzer, Tennelec # TC 451
MSC-MCA :	FAST-ComTec Dual Multiscaler # 7882 and MCA interface card # MCA 3FADC with an ultrafast ADC; this card runs with the MCDWIN software under Windows XP
PC :	PC : industrial PC (DCM-computer?, check) with slot-computer card and passive backplane to accommodate ISA and PCI measuring cards
soft :	Evaluation software for Mößbauer effect PC-MOS II for the final analysis, requires data taken in sinusoidal mode

Information about the sources

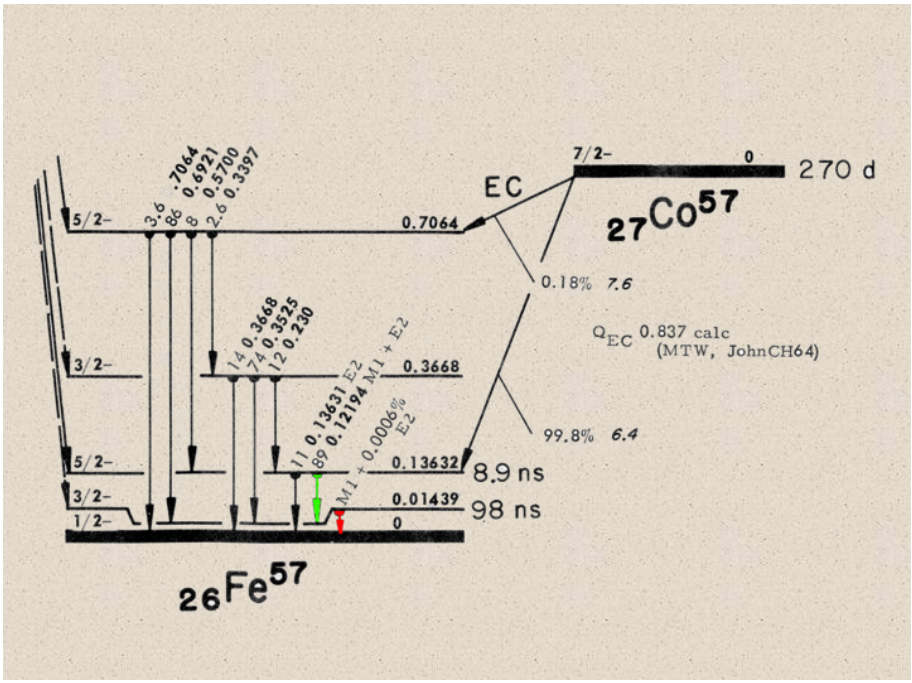


Figure 72: Decay scheme of ^{57}Co from [7].

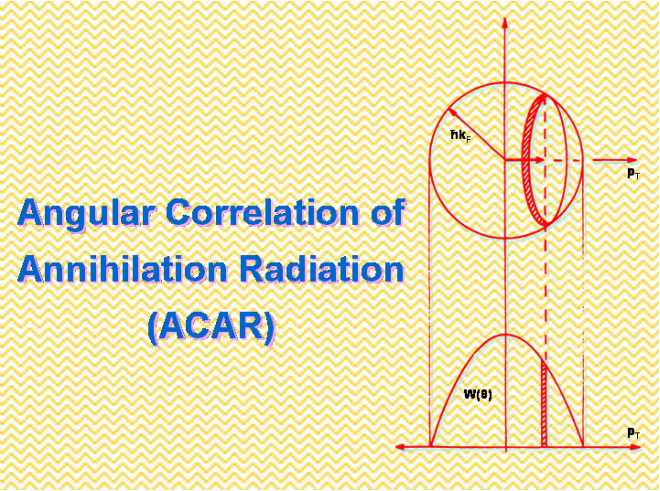
D. Discussion of Results

1. Provide graphs of the ^{57}Co spectrum, the three Mößbauer spectra for hyperfine splitting, quadrupole splitting and isomer shift (or chemical shift)
2. Evaluate the Mößbauer spectra with respect to line shifts and line splittings
3. Use the analysis software PC-MOS II to determine the internal fields or field gradients

E. Example Questions

- What is the Mößbauer effect?
- What are the preconditions for observing that effect?
- Which experimental preconditions have to be fulfilled?

20 Angular Correlation of Annihilation Radiation (ACAR)



Location: room Jordan 308

A. Short Description

Positrons are slowed down in matter to thermal energies before they can form positronium with the electrons and finally annihilate. In case the solid matter is a metal the annihilation proceeds mostly with the electrons of the free electron gas. Only a very small portion annihilates with the so-called core electrons. Electrons of the free electron gas carry a momentum which corresponds to one for this metal characteristic Fermi-momentum and therefore also the electron-positron pairs have a characteristic momentum distribution. This momentum causes a small modification of the angular correlation of the two annihilation quanta which would be emitted at exactly 180° to each other if the positronium was at rest. This modification is expressed by the angular deviation θ from 180° and it is caused by the transverse momentum of the conduction electrons. In a free electron gas (T = 0) all states with momentum below the Fermi momentum are occupied and all higher states are empty. The momentum distribution is a filled sphere with uniform density and radius $\hbar\, k_F$. The count rate per momentum interval Δp_T of the γ-rays with correlation $180° \pm \theta$ is therefore proportional to the volume of the slice of the Fermi sphere for which $p_T = m_e\, c\, \theta$. Therefore the angular distribution has a parabolic dependence on θ and the coincidence rate vanishes for angles larger than the maximum angle θ_{max} which is related to the Fermi momentum via $\theta_{max} = \hbar\, k_F / m_e\, c$. Therefore this method allows an accurate determination of the Fermi momentum or the Fermi energy in metals. The angles θ to be measured are rather small because the Fermi energies are small in relation to the electron's rest mass; they are in the range of a few millirads or a few angular minutes.

For an **ACAR**-experiment (**A**ngular **C**orrelation of **A**nnihilation **R**adiation) one needs a small, high concentrated strong positron source, strongly collimated beams, fast γ-detectors, one on

a fixed bench the other on a movable arm with extreme fine movement control. In the present case two fast BaF_2 detectors coupled to fast UV-sensitive photomultipliers (Photonis # 2020/Q) are used. The coincidence circuit consists of two fast constant fraction discriminators and a time-to-amplitude converter (TAC), achieving an overall time resolution of about 340 picoseconds. The coincidence events are registered in a multichannel analyzer. Optional one can add a slow circuit for the energy selection in both channels and gating of the TAC by the logic pulses derived from the energy discrimination. In the present case the positrons are slowed down in a pure aluminum sample, which gives the highest effect, aluminum having with 11.7 eV the highest Fermi energy of all metals.

Element	**n** (10^{22}/cm^3)	$\mathbf{E_F}$ (eV)	$\mathbf{T_F}$ (10^4 K)	$\mathbf{k_F}$ (10^8 cm^{-1})
Li	4.70	4.74	5.51	1.12
Na	2.65	3.24	3.77	0.92
Cu	8.47	7.00	8.16	1.36
Ag	5.86	5.49	6.38	1.20
Au	5.90	5.53	6.42	1.21
Mg	8.61	7.08	8.23	1.36
Ca	4.61	4.69	5.44	1.11
Nb	5.56	5.32	6.18	1.18
Fe	17.0	11.1	13.0	1.71
Cd	9.27	7.47	8.68	1.40
Hg	8.65	7.13	8.29	1.37
Al	18.1	11.7	13.6	1.75
In	11.5	8.63	10.0	1.51
Ti	10.5	8.15	9.46	1.46
Sn	14.8	10.2	11.8	1.64
Pb	13.2	9.47	11.0	1.58

Table 3: Density of conduction electrons, Fermi energy E_F, Fermi temperature T_F, and Fermi wave vector k_F for several metals (after Frederikse, 1981).

B. Necessary Knowledge

Physics :

- The positron, particle properties
- Formation of positronium in solids, positronium physics

- Free electrons in metals and free electron gas model, Fermi-Dirac statistics, formalism of Fermi-sphere and Fermi-surface, metal physics
- Angular correlation of annihilation radiation, applied to positronium-formation in metals
- Derivation of the Fermi-energy from an ACAR experiment

Measuring Technique :

- Set up of an ACAR experiment
- Detector–source–collimator geometry
- How to align properly four collimators with a source using a) a thread or b) an alignment laser
- Very fast detectors for very high time resolution
- BaF_2 detectors yielding two scintillation light components in the UV and the visible regime
- Fast NIM electronic modules, especially constant fraction discriminators, time-to-amplitude converters, time calibration, handling of ns-signals etc.
- Fine mechanical angular drive, handling

Mathematics : Method of least squares

References

[1]	**Maier, Jens :** Aufbau und Erprobung von Praktikumsversuchen zur Positronenvernichtung Thesis of high school teachers, University of Stuttgart 1998	Original thesis on this teaching lab experiment
[2]	**Schatz, G. and A. Weidinger:** Nuclear Condensed Matter Physics John Wiley and Sons, Chichester, New York etc. 1996	Standard textbook on nuclear methods in solid state physics
[3]	**Vesely, Charles J. :** A Comparison of Methods Used for Angular Correlation of Annihilation Radiation by Slit Geometry, report and master's thesis, University of Texas, 1963 `http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=AD407994&Location=U2&doc=GetTRDoc.pdf`	Report on design criteria for an ACAR experiment

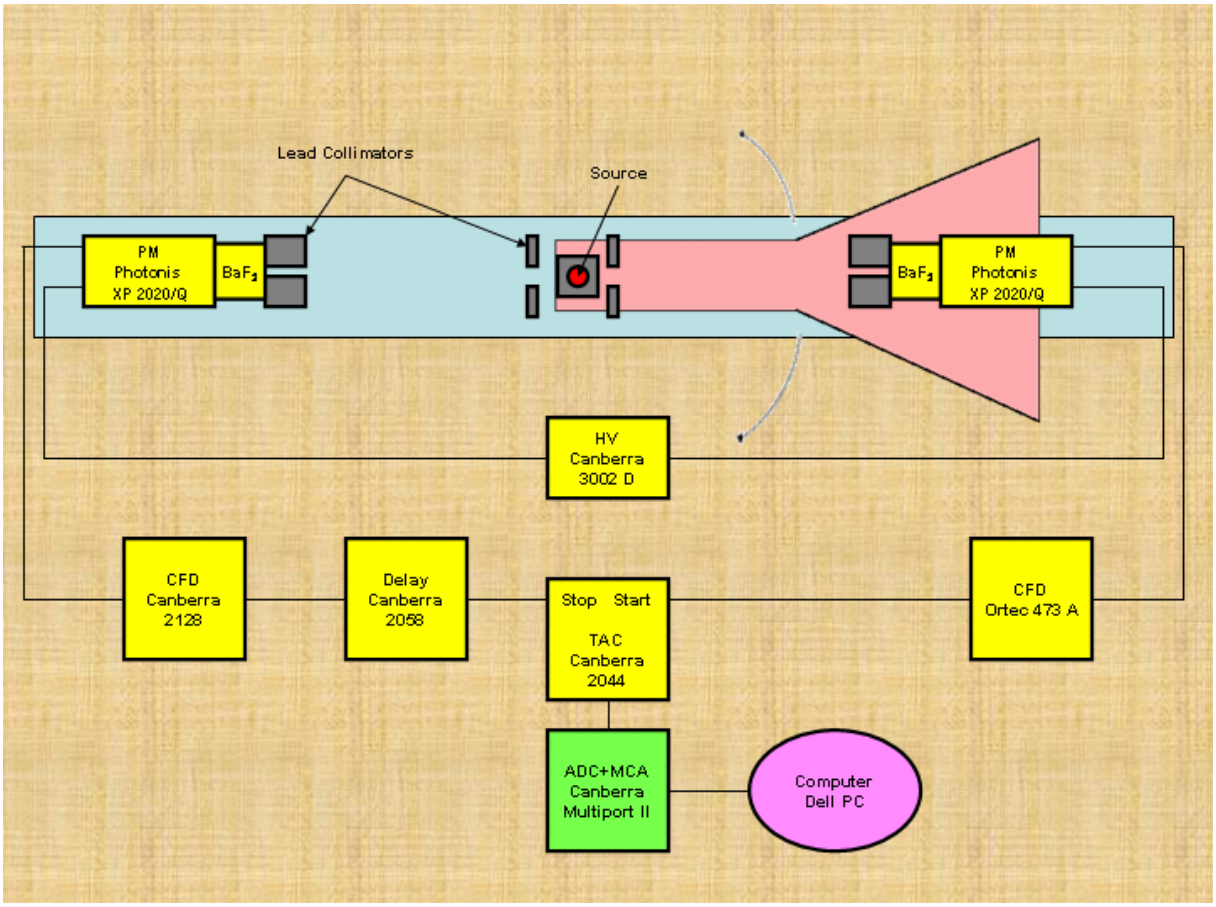
[4]	**Firestone R. B. :** Table of Isotopes, CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data
[5]	**Knoll H. G. :** Radiation Detection and Measurements John Wiley & Sons, New York 1989	Standard work on detectors

Experimental Tasks

- Set-up of
- WARNINGS
-

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram



Legend:

detectors :	BaF_2 detectors, 40 mm dia, 25 mm thick connected to UV-sensitive photomultipliers Photonis # 2020/Q to access the so-called fast UV-scintillation component.
collimators :	Two pairs of lead collimators close to the positron source and close to the detectors to achieve a sharp angular acceptance, collimator width can be adjusted to 0.5 – 3.5 mm, recommended 1.0 – 1.5 mm
source :	^{22}Na source in a pure aluminum capsule; the present source needs to be replaced by a stronger one with capsule diameter of only 4 mm to obtain a good angular response function (To-do-list!)

drive : Ultrafine mechanical angular drive (obtained from an old machine), one scale corresponds to 2 angular seconds $\cong$ 19 μrad, one full turn corresponds to 240 scale-units $\cong$ 480 arc-seconds $\cong$ 2.3 mrad; the unit should only be used turning the screw always in one direction; there is a loaded spring to keep the arm close to the drive, but the spring is too weak for the weight of the arm, therefore one needs to make sure the arm is in contact with the drive

HV : High voltage power supply for the detectors, Canberra # 3002D

CFD : Two constant fraction discriminators to derive uniform time signals; Canberra # 2128 and Ortec # 473A

delay : Switchable ns-cable delay to bring zero time difference at the TAC output to a signal of about 4 V $\cong$ middle of the dynamic range

TAC : Time-to-amplitude converter (TAC) Canberra # 2044, time measuring, used in the 50 ns range

MCA : Multichannel analyzer and ADC, Canberra Multiport II, USB-connected to a PC, software GENIE 2000 with dongle

PC : Standard PC with USB-ports

Information on the used radioactive sources

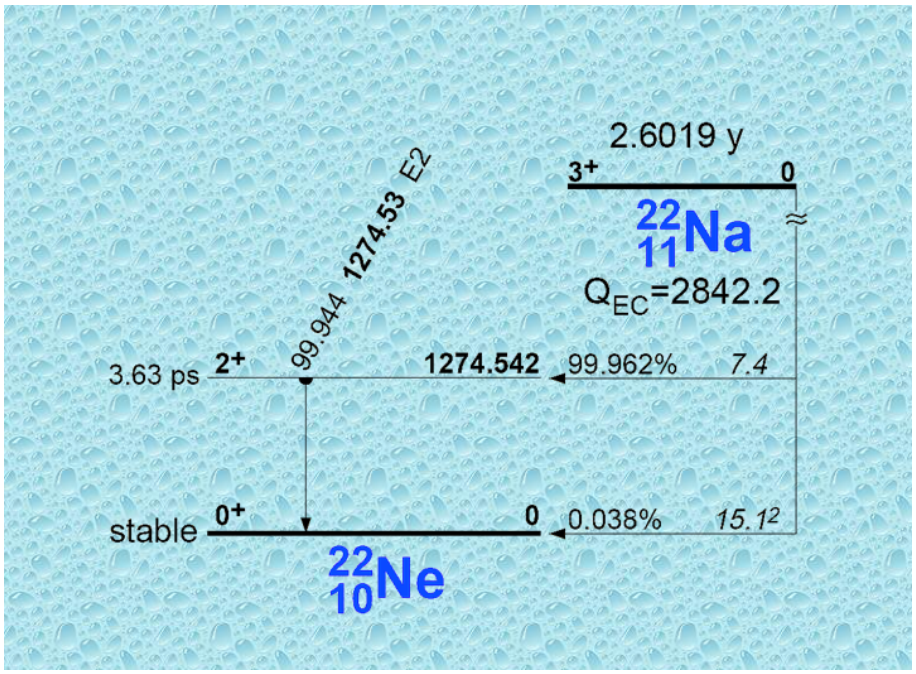


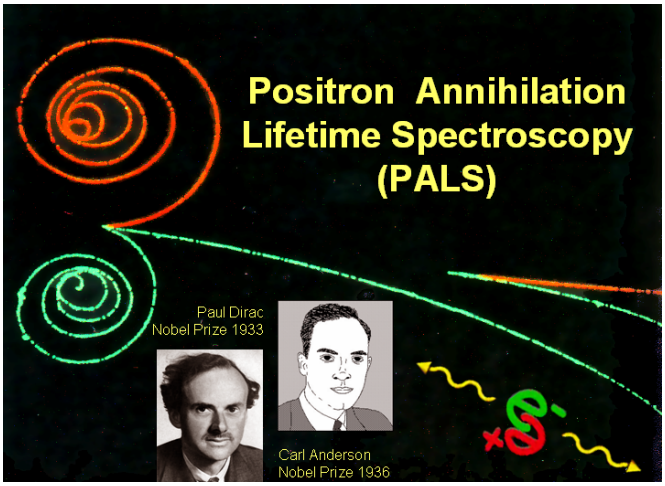
Figure 73: Decay scheme of ^{22}Na from [4].

D. Discussion of Results

- Provide

E. Example Questions

21 Positron Annihilation Lifetime Spectroscopy (PALS)



Location: room Jordan 308

A. Short Description

The positron e^+ is the only antiparticle which is available without major efforts from radioactive β-decay. Positrons were discovered in 1932 by Carl D. Anderson, who gave the positron its name. The discovery was made by passing cosmic rays through a cloud chamber which was equipped with a strong magnet to determine the momentum (and charge) of the particles. The existence of positrons was first postulated theoretically in 1928 by Paul Dirac as a consequence of the Dirac equation.

The positron annihilates with electrons under emission of γ-quanta. The lifetime of positrons in solid matter depends on the specific electron density which can be determined by this method. Positronium is formed in two different states: Ortho-Positronium ($\uparrow\uparrow$; triplet state $^3S_1$) and Para-Positronium ($\uparrow\downarrow$; singlet state $^1S_0$) which differ in lifetime by a factor of 1120; the singlet state having a mean lifetime of 125 ps, and the triplet state 142 ns. In metals the conduction electrons behave like an electron gas and the annihilation takes place as with free electrons because no bound state is possible and the positron is effectively screened by the conduction electrons. In isolators the positron lifetime is prolongated because of the much lower electron density. In this experiment the lifetime in aluminum (or copper) and Teflon is determined by applying fast timing methods. The γ-decay of 1.27 MeV from a ^{22}Na positronium source can be used as a timing signal to start the time-to-amplitude-converter (TAC) for the decay time measurement. The lifetimes to be measured are in the range of 100 picoseconds up to several nanoseconds and therefore ultrafast time measurement methods have to be applied.

B. Necessary Knowledge

Physics :

- Theory of β-decay
- Annihilation of positrons
- Positronium formation in solids
- Positronium lifetime and electron density determination
- Positrons in metals and isolators
- Properties of annihilation radiation

Measuring Technique :

- Physics of fast and ultrafast γ-detectors, emission characteristics
- Construction of BaF_2-detectors
- Fast photomultiplier tubes
- Constant fraction discriminators
- Time-to-amplitude converters (TAC)
- Fast-slow-method: fast circuit for timing; slow circuit for energy selection
- Multichannel analyzer (MCA)
- Preparation of positronium sources

Mathematics : Method of least squares and fitting procedures

References

[1]	**Becker, Johannes :** Praktikumsversuch zur Positronenvernichtung in Festkörpern Thesis of high school teachers, University of Stuttgart 1998	Original thesis on this teaching lab experiment with many references
[2]	**Dlubek, G., K. Saarinen and H.M. Fretwell :** Positron states in polyethylene and polytetrafluoroethylene : A positron lifetime and Doppler broadening study Nucl. Instr. Meth. in Phys. Res. B **142**, 139 (1998)	Special article on the subject
[3]	**Hautojärvi, P. :** Positrons in solids Springer-Verlag, Berlin, 1979	Standard textbook on positrons in solids
[4]	**Ferrell, R.A. :** Theory of positron annihilation in solids Rev. Mod. Phys. **28**, 308 (1956)	Fundamental article on the subject
[5]	**Seeger, A. and F. Banhart :** On the systematics of positron lifetimes in metals Phys. Stat. Sol. A **102**, 171 (1987)	Systematic article on the subject
[6]	**Seeger, A. :** The study of defects in crystals by positron annihilation Appl. Phys. **4**, 183 (1974)	Systematic article on the subject
[7]	**Frank, W. and A. Seeger :** Theoretical foundation and extension of the trapping model Appl. Phys. **3**, 61 (1974)	Article on the so-called 'Trapping Model'
[8]	**Kendall H.W., and M. Deutsch:** Annihilation of positrons in flight Phys. Rev. **93**, 932 (1954) and Phys. Rev. **101**, 20 (1956)	Fundamental article on annihilation of positrons, references
[9]	**Dirac, Paul A.M. :** Theory of Electrons and Positrons `http://nobelprize.org/nobel_prizes/physics/laureates/1933/dirac-lecture.html`	Dirac Nobel Lecture, Dec. 12^{th} 1933
[10]	**Anderson, C.D. :** The Positive Electron Phys. Rev. **43**, 491 (1933)	Fundamental article on the discovery of the positron
[11]	**Schatz, G. and A. Weidinger:** Nuclear Condensed Matter Physics John Wiley and Sons, Chichester, New York etc. 1996	Standard textbook on nuclear methods in solid state physics
[12]	**Laval, M. et al. :** Barium fluoride – Inorganic scintillator for subnanosecond timing Nucl. Instr. Meth. **206**, 169 (1983)	Article on the BaF_2 detectors
[13]	**Wisshak, K. and F. Käppeler :** Large barium fluoride detectors Nucl. Instr. Meth. **227**, 91 (1984)	Article on a crystal ball made of BaF_2 detectors
[14]	**Firestone R. B. :** Table of Isotopes, CD-ROM John Wiley & Sons New York 1996	Current reference for nuclear data

Experimental Tasks

- Set-up of the detectors, HV = - 2100 Volts (negative!)
- Set-up of the NIM electronics, check all important signals with oscilloscope, separate NIM units and crate for positron lifetime, don't mix with speed of light
- Measurement of the energy spectrum of the radioactive ^{22}Na-source
- Setting of the CFD's and SCA's on the 1275 keV resp. the annihilation line (511 keV); these signals provide the Start and Stop for the TAC
- Calibration of the TAC using the Ortec Time Calibrator unit, determine the calibration curve
- Measurement of the lifetime curve for teflon and for one metal (aluminum or copper), run-time about 24 hours
- Evaluation of the decay-time curves

WARNINGS

- First provide NIM crate power before turning on the high voltage for the detectors
- Use close geometry, e.g. short source–detector distance, but watch chance coincidences

C. Information Regarding the Experimental Setup

Schematic Drawing, Block Diagram

Legend:

HV :	High Voltage for the Detectors, Canberra 3002D

Information about the used radioactive sources

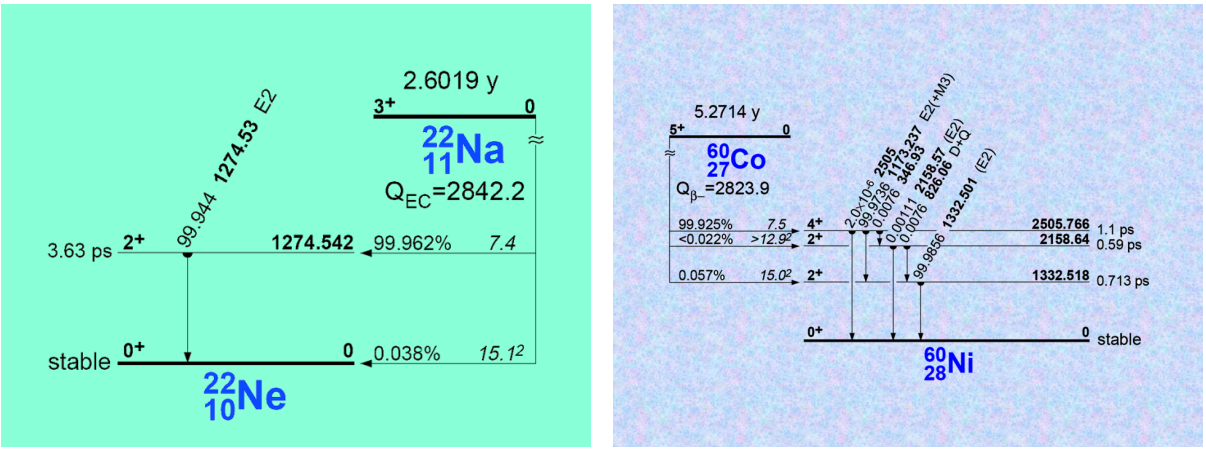


Figure 74: Decay scheme of ^{22}Na and ^{60}Co from [14].

D. Discussion of Results

- Explain the energy spectrum of the ^{22}Na source
- Produce a time calibration curve for the TAC, graphical representation of the calibration
- Determine the standard time resolution of the whole set-up using a ^{60}Co source
- Graphical presentation of the measured lifetime curves; show fits
- Determine the different lifetimes of the positrons
- Determine the experimental uncertainties (statistical and systematic).

E. Example Questions

III. APPENDIX

22 Tables of Important Constants, Units and Conversion Factors

Important Physics Constants

General Constants

Speed of Light in Vacuum	c	299 792 458 (Def.)	ms^{-1}
Permeability in Vacuum	μ_0	$4\pi \times 10^{-7}$ $= 12.566370614$	NA^{-2} $10^{-7}\,\mathrm{NA}^{-2}$
Permittivity in Vacuum, $1/\mu_0 c^2$	ϵ_0	8.854 187 817	$10^{-12}\,\mathrm{Fm}^{-1}$
Gravitational Constant	G	6.672 59(85)	$10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$
Planck's Contant	h	6.626 075 5(40)	10^{-34} Js
in eV, h/$\{e\}$		4.135 669 2(12)	10^{-15} eVs
h/2π	$\hbar$	1.054 572 66(63)	10^{-34} Js
in eV, $\hbar$/$\{e\}$		6.582 122 0(20)	10^{-16} eVs

Electromagnetic Constants

Elementary Charge	e	1.602 177 33(49)	$10^{-19}\,\mathrm{C}$
Bohr Magneton, $e\hbar/2m_e$	μ_B	9.274 015 4(31)	$10^{-24}\,\mathrm{JT}^{-1}$
in eV, $\mu_B/\{e\}$		5.788 382 63(52)	$10^{-5}\,\mathrm{eVT}^{-1}$
in Hertz μ_B/h		1.399 624 18(42)	$10^{10}\,\mathrm{HzT}^{-1}$
in Wavelenghts, μ_B/hc		46.686 437(14)	$\mathrm{m}^{-1}\,\mathrm{T}^{-1}$
in Kelvin, μ_B/k		0.671 709 9(57)	KT^{-1}
Nuclear Magneton, $e\hbar/2m_p$	μ_N	5.050 786 6(17)	$10^{-27}\,\mathrm{JT}^{-1}$
in eV, $\mu_N/\{e\}$		3.152 451 66(28)	$10^{-8}\,\mathrm{eVT}^{-1}$
in Hertz, μ_N/h		7.622 591 4(23)	MHzT^{-1}
in Wavelengths, μ_N/hc		2.542 622 81(77)	$10^{-2}\,\mathrm{m}^{-1}\,\mathrm{T}^{-1}$
in Kelvin, μ_N/k		3.658 246(31)	$10^{-4}\,\mathrm{KT}^{-1}$

Atomic Constants

Fine Structure Constant, $\mu_0 ce^2/2h$	α	7.297 353 08(33)	10^{-3}
	α^{-1}	137.035 989 5(61)	
Rydberg Constant, $m_e c\alpha^2/2h$	R_∞	10 973 731.534(13)	m^{-1}
in Hertz, $R_\infty\, c$		3.289 841 949 9(39)	$10^{15}\,\mathrm{Hz}$
in Joule, $R_\infty\, hc$		2.179 874 1(13)	$10^{-18}\,\mathrm{J}$
in eV, $R_\infty\, hc/\{e\}$		13.605 698 1(40)	eV
Bohr's Radius, $\alpha/4\pi R_\infty$	a_0	0.529 177 249(24)	$10^{-10}\,\mathrm{m}$
Hartree Energy, $e^2/4\pi\epsilon_0 a_0 = 2R_\infty hc$	E_h	4.359 748 2(26)	$10^{-18}\,\mathrm{J}$
in eV, $E_h/\{e\}$		27.211 396 1(81)	eV

Electron

Electron Mass	m_e	9.109 389 7(54)	10^{-31} kg
		5.485 799 03(13)	10^{-4} u
in eV, $m_e c^2/\{e\}$		0.510 999 06(15)	MeV
Compton Wavelength, $h/m_e c$	λ_c	2.426 310 58(22)	10^{-12} m
$\lambda c/2\pi = \alpha\, a_0 = \alpha^2/4\pi R_\infty$	$\bar{\lambda}_c$	3.861 593 23(25)	10^{-13} m
Classic Electron Radius, $\alpha^2 a_0$	r_e	2.817 940 92(38)	10^{-15} m
Thomson Cross Section,			
$(8\pi/3)r_e^2$	σ_e	0.665 246 16(18)	$10^{-28}\,\mathrm{m}^2$
Magnetic Moment of the Electron	μ_e	928.477 01(31)	$10^{-26}\,\mathrm{JT}^{-1}$
in Bohr Magneton	μ_e/μ_b	1.001 159 652 193(10)	
Magnetic Moment of the Electron			
Anomaly, μ_e/μ_B-1	a_e	1.159 652 193(10)	10^{-3}
g-Factor, $2\,(1 + a_e)$	g_e	2.002 319 304 386 (20)	

Muon

Muon Mass	m_μ	1.883 532 7(11)	10^{-28} kg
		0.113 428 913(17)	u
in eV, $m_\mu c^2/\{e\}$		105.658 389(34)	MeV
Muon-Electron Mass Ratio	m_μ/m_e	206.768 262(30)	
Magnetic Moment	μ_μ	4.490 451 4(15)	$10^{-26}\,\mathrm{JT}^{-1}$
Anomaly, $[\mu_\mu/(e\hbar/2m_\mu)]$-1	a_μ	1.165 923 0(84)	10^{-3}
g-Faktor, $2(1 + a_\mu)$	g_μ	2.002 331 846(17)	
Life time (free)	τ_μ	2,19703 $\pm$ 0,00004	10^{-6} s
Half Life	$t_{1/2} = \tau ln2$	1,52287 $\pm$ 0,00003	10^{-6} s

Proton

Proton Mass	m_p	1.672 623 1(10)	10^{-27} kg
		1.007 276 470(12)	u
in eV, $m_p c^2/\{e\}$		938.272 31(28)	MeV
Proton-Electron Mass Ratio	m_p/m_e	1 836.152 701(37)	
Proton-Muon Mass Ratio	m_p/m_μ	8.880 244 4(13)	
Magnetic Moment	μ_p	1.410 607 61(47)	10^{-26} JT^{-1}
in Bohr Magnetons	μ_p/μ_b	1.521 032 202(15)	10^{-3}
in Nuclear Magnetons	μ_p/μ_N	2.792 847 386(63)	
Life Time	τ_p	$> 10^{33}$	a

Neutron

Neutron Mass	m_n	1.674 928 6(10)	10^{-27} kg
		1.008 664 904(14)	u
in eV, $m_n c^2/\{e\}$		939.565 63(28)	MeV
Neutron-Electron Mass Ratio	m_n/m_e	1 838.683 662(40)	
Neutron-Proton Mass Ratio	m_n/m_p	1.001 378 404(9)	
Magnetic Moment	μ_n	0.966 237 07(40)	10^{-26} JT^{-1}
in Bohr Magnetons	μ_n/μ_B	1.041 875 63(25)	10^{-3}
in Nuclear Magnetons	μ_n/μ_N	1.913 042 75(45)	
Lifetime	τ_n	888,6 $\pm$ 3,5	s
Halflife	$t_{1/2} = \tau ln2$	615,9 $\pm$ 2,4	s

Physical-Chemistry Constants

Avogadro Constant	N_A, L	6.022 136 7(36)	$10^{23}\,\mathrm{mol}^{-1}$
Atomic Mass Units,			
m_u = $\frac{1}{12}$ m(^{12}C)	m_u	1.660 540 2(19)	$10^{-27}\,\mathrm{kg}$
in eV, $m_u c^2/\{e\}$		931.494 32(28)	MeV
Faraday Constant, $N_A e$	F	96 485.309(29)	$\mathrm{C\ mol}^{-1}$
Molar Gas Constant	R	8.314 510(70)	$\mathrm{Jmol}^{-1}\,\mathrm{K}^{-1}$
Boltzmann Constant, R/N_A	k	1.380 658(12)	$10^{-23}\,\mathrm{JK}{-1}$
in eV, $k/\{e\}$		8.617 385(73)	$10^{-5}\,\mathrm{eVK}^{-1}$
in Hertz, k/h		2.083 674(18)	$10^{10}\,\mathrm{HzK}^{-1}$
in Wavelengths, k/hc		69.503 87(59)	$\mathrm{m}^{-1}\,\mathrm{K}^{-1}$
Stefan-Boltzmann Constant,			
$(\pi^2/60)k^4/\hbar^3c^2$	σ	5.670 51(19)	$10^{-8}\,\mathrm{Wm}^{-2}\,\mathrm{K}^{-4}$
Wien's Constant,			
$b = \lambda_{max}T$	b	2.897 756(24)	$10^{-3}\,\mathrm{m\,K}$

Source: Atomic Data and Nuclear Data Tables,
Volume 70, Number 1, Sept.'98.

23 Units, Abbreviations, and Conversion Formulas

Primary SI Units

Meter	m	Newton	N
Kilogram	kg	Farad	F
Second	s	Joule	J
Ampere	A	Coulomb	C
Kelvin	K	Tesla	T
Mol	mol	Hertz	Hz
Candela	cd	Watt	W

Prefixes for SI Units

10	10^2	10^3	10^6	10^9	10^{12}	10^{15}	10^{18}
Deca	Hecto	Kilo	Mega	Giga	Tera	Peta	Exa
da	h	k	M	G	T	P	E
10^{-1}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}
Deci	Centi	Milli	Micro	Nano	Pico	Femto	Atto
d	c	m	μ	n	p	f	a

Conversion Factors

1 u =	$m_u = \frac{1}{12}m(^{12}C)$	1 T =	10^4 G
1 eV =	1.602 177 33(49)$\times 10^{-19}$ J	1 Ci =	3.7$\times 10^{10}\,s^{-1}$
1 J =	10^7 erg	1 Å =	10^{-10} m = 10^{-8} cm
1 C =	10^{-1} e.m.u.	1 fm =	10^{-15} m = 10^{-13} cm
=	2.997 924 58$\times 10^9$ e.s.u.	1 b =	$10^{-28}\,m^{-2} = 10^{-24}\,cm^{-2}$