AN34 Experiment 18

Neutron Activation Analysis (Fast Neutrons)

Equipment Needed from ORTEC

- 113 Scintillation Preamplifier
- 266 Photomultiplier Tube Base
- 4006 or 4001A/4002D Bin and Power Supply
- 556 High Voltage Power Supply
- 575A Amplifier
- 905-3 2-in. x 2-in. or 905-4 3-in. x 3-in. NaI(Tl) Detector and PM Tube
- Easy-MCA 2k System including a USB cable, a suitable PC and MAESTRO-32 software (other ORTEC MCAs may be substituted)
- Coaxial Cables and Adapters:
  - One C-24-1/2 RG-62A/U 93-Ω coaxial cable with BNC plugs on both ends, 15-cm (1/2-ft) length.
  - One C-24-12 RG-62A/U 93-Ω coaxial cable with BNC plugs on both ends, 3.7-m (12-ft) length.
  - Two C-24-4 RG-62A/U 93-Ω coaxial cables with BNC plugs on both ends, 1.2-m (4-ft) length.
  - One C-36-12 RG-59B/U 75-Ω cable, with SHV female plugs on both ends, 3.7-m (12-ft) length.

Equipment Required from Other Manufacturers

- Oscilloscope (bandwidth ≥100 MHz).
- 1- to 3-Ci Am-Be neutron source.
- ~1 µCi activity ^{137}Cs source and ^{60}Co source for energy calibration; from Source Kit SK-1G (sealed solid-disk gamma-ray sources).
- Sample Set No. 318: 6 samples with high cross sections for fast neutrons: Mg, Na, Si, V, Fe and Cr.
- Small flat-blade screwdriver for tuning screwdriver-adjustable controls, or an equivalent potentiometer adjustment tool.

Purpose

This experiment will demonstrate the principles of element identification using the technique of fast neutron activation.

Introduction

In this experiment the same isotopic neutron source that was used in Experiment 17 will be used after it has been removed from the howitzer. The target samples will be irradiated by being placed in almost direct contact with the neutron source.

The spectrum of fast neutrons that results from an Am-Be isotopic neutron source is similar to that shown in Fig. 16.2 of Experiment 16. From that figure, it is evident that the neutron energies are distributed from approximately 2 to 11 MeV[†] for the unmoderated source (with no paraffin or water moderator). The reaction that produces the neutrons in the source is

$$^{9}\text{Be} + \alpha \rightarrow n + {}^{12}\text{C} + 5.704\text{ MeV} \qquad (1)$$

Where the alpha particles are provided by the radioactive decay of the ^{241}Am source. In Eq. (1) the 5.704-MeV energy is the Q value for the reaction. It is the effective change in mass, Δm, that is converted into energy, where Δm is given by

$$\Delta m = (m_9 + m_\alpha) - (m_n + m_{12}) \qquad (2a)$$

Where m_9 is the mass of ^{9}Be, m_α is the mass of the alpha particle, m_n is the mass of the neutron and m_{12} is the mass of ^{12}C. Hence,

$$Q = \Delta m\, c^2 = 5.704\text{ MeV} \qquad (2b)$$

Where c is the speed of light.

To find the maximum energy for the neutrons produced by Eq. (1), we can postulate no surrounding material to slow down the alpha particle, and consider the case where the neutron travels in the same direction as the incident alpha particle. Those conditions yield the maximum neutron energy.

Most of the alpha-emitting isotopes that can supply the alpha particle for the reaction in Eq. (1) have alpha energies of the order of 5.5 MeV. For ^{241}Am, the average alpha energy is 5.48 MeV, (which is identical to the alpha energy for the ^{238}Pu-Be source that generated the spectrum in Fig. 16.2). Conservation of energy for Eq. (1) requires

$$\begin{aligned} E_\alpha + Q &= 5.48\text{ MeV} + 5.70\text{ MeV} \qquad (3)\\ &= 11.18\text{ MeV}\\ &= E_n + E_{12} \end{aligned}$$

Where E_α is the incident energy of the alpha particle, E_n is the energy of the neutron, and E_{12} is the kinetic energy of the ^{12}C atom.

By combining conservation of momentum with conservation of energy from Eq. (3), the neutrons emitted in the forward direction are predicted to have an energy E_n = 11.0 MeV, i.e., 98.6% of the available energy E_α + Q. Of course, the neutron energy decreases from this maximum as the neutron's angle of departure increases relative to the original direction of the incident alpha particle. The minimum neutron energy, 6.78 MeV, occurs when the neutron is emitted in the direction opposite to the incident alpha particle. It is therefore possible to produce neutrons with an upper energy value of 11 MeV. The neutron energies in Fig. 16.2 are distributed over a wide range of energies for the following reasons:

1. Varying amounts of energy are lost via ionization as the alpha particle travels through the source material before the reaction in Eq. (1) occurs. Consequently, the incident alpha-particle energy effectively varies from 5.48 MeV down to zero. For zero alpha energy, the calculated neutron energy would be 5.26 MeV.
2. ^{12}C can be left in one of its excited states (e.g. 4.43 MeV, or

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[†] Note that the ^{3}He (n, p) ^{3}H reaction inherent in the operation of the ^{3}He neutron spectrometer used to measure the neutron spectrum in Fig. 16.2 adds Q = 764 keV to the energy recorded in the spectrum. Q is the kinetic energy derived from a change in the total rest-mass energy of the constituents before the nuclear reaction to the total rest-mass energy of the products after the reaction. The fact that the neutron energy spectrum in Fig. 16.2 has an upper end-point at 11 MeV, indicates that the spectrum has been corrected for the Q = 764 keV added by the ^{3}He spectrometer. See Ref. 11 for further details on the 3He semiconductor sandwich detector for neutron spectrometry, and for more information on neutron sources.

7.66 MeV). This lowers the effective Q of the reaction.

3. Neutron energies vary with the reaction angles involved.

OPTIONAL EXERCISE

Using the equations for conservation of energy and conservation of momentum, derive the expression for the neutron energy as a function of Q and E_α for the case where the neutron emission direction is along the line defined by the incident alpha-particle direction. Confirm the neutron energies for the three special cases outlined above.

Typical Slow-Neutron Reactions: The activation in Experiment 17 was produced by slow neutrons. The spectrum of the neutrons from the isotopic source was thermalized by a paraffin moderator. The moderation could also have been produced by water. Slow neutron reactions are usually of the type

$$\mathrm{A}\ (n,\gamma)\ \mathrm{B} \qquad (4)$$

Where A is the target nucleus. The product nucleus B has the same atomic number as A, but contains one additional neutron. Usually, B decays by β^- emission followed by gamma radiation (see examples in Experiment 17).

Typical Fast-Neutron Reactions: For fast neutrons there are three types of reactions that predominate:

$$\mathrm{A}\ (n,p)\ \mathrm{B} \qquad (5)$$

$$\mathrm{A}\ (n,\alpha)\ \mathrm{B} \qquad (6)$$

$$\mathrm{A}\ (n,2n)\ \mathrm{B} \qquad (7)$$

The reactions produced by Eq. (5) generally have neutron thresholds in the range of 1 to 3 MeV, and therefore cannot be produced with thermal neutrons. The thresholds for Eqs. (6) and (7) are even higher, and are usually in the range of 10 to 20 MeV. Consequently, an unmoderated Am-Be neutron source is effective in producing only (n,p) reactions. Typically, the product B is radioactive, and emits gamma-rays that can be used to identify the isotope. Subsequently, one can identify the element A present in the sample, given the identification of B and the knowledge of the reaction type.

QUESTIONS: A and B are generic place-holders for the actual isotope symbols in Eqs. (5), (6) and (7). How do the atomic numbers and atomic masses change in the transition from A to B for the three reaction types?

General Instructions for Fast-Neutron Activation

***SAFETY WARNING**: Handle the Am-Be source cautiously. One Curie (1 Ci) of this material produces in excess of 10^6 neutrons/s. Minimize your exposure time, and maintain as much distance as possible between the source and any part of your body. Do not physically contact the isotopic source at any time. Choose the location for the source to minimize exposure to other people in the laboratory, or people passing by outside the laboratory. Access to the immediate area of the source should be restricted with a radiation boundary rope barrier, with radiation warning signs posted. When the source is outside of its shielded enclosure, it can be positioned by handling it with tongs at least 3-ft long, or by a long string. Instructions for the safe handling of the neutron source are supplied by the manufacturer of the source. These instructions should be read carefully before using the source.*

For the experiment, the neutron source is usually removed from its storage container with tongs, or by a string, that will prevent the handler from getting any part of his body within 3 ft. (0.9 m) of the source. The neutron source is then placed in the center of a table that has been roped off and identified as a radiation hazard to ensure personnel isolation. Subsequently, the sample to be activated can be placed adjacent to the neutron source using 3-ft tongs. This process ensures that the sample will be exposed to fast neutrons, with minimal activation by moderated (slow) neutrons. Obviously, the amount of hydrogen-rich material in close proximity to the source on the table should be minimized to avoid creating thermal neutrons.

As in Experiment 17, each sample is normally activated for at least one half-life.

EXPERIMENT 18.1

Gammas and Half-Lives from (n,p) Reactions

Procedure

1. Set up the electronics as shown in Fig. 18.1. The details for cable connections and instrument settings are:
   - a. Ensure the NIM bin power and the HV Power Supply are turned off.
   - b. Connect the ANODE output of the 266 PMT Base to the INPUT of the 113 Scintillation Preamplifier using the 15-cm C-24-1/2 RG-62A/U 93-Ω cable. Set the INPUT CAPacitance switch on the 113 to zero.

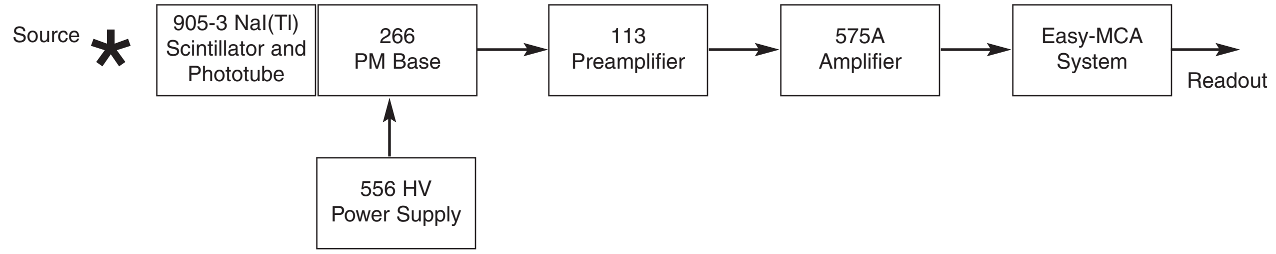

Fig. 18.1 Instrumentation and Interconnections for Experiment 18.

c. Connect the 113 Preamplifier power cable to the PREAMP POWER connector on the rear panel of the 575A Amplifier. Check that the time constant switches accessible through the side panel of the 575A Amplifier are all set to 0.5 µs.

d. Insert the 575A Amplifier and the 556 HV Power Supply in the NIM bin.

e. Connect the 113 Preamplifier OUTPUT to the 575A Amplifier INPUT using the 3.7-m C-24-12 RG-62A/U 93-Ω cable. Set the amplifier input polarity to NEGative.

f. Using the 3.7-m C-36-12 RG-59B/U 75-Ω cable with two SHV female plugs, connect the OUTPUT of the 556 HV Power Supply to the POS HV input of the 266 PMT Base. Check that the POLARITY switch on the rear panel of the 556 is set to POSitive. Set the front-panel voltage controls on the 556 to their minimum values.

g. Connect the Bipolar output of the 575A Amplifier to the analog INPUT of the Easy-MCA using the 1.2-m C-24-4 RG-62A/U 93-Ω cable.

h. Turn on power to the NIM bin and the computer that supports the Easy MCA.

2. Position a ^{60}Co radioactive source from the source kit in front of the NaI(Tl) detector.

3. Adjust the controls on the instruments as follows:

a. Set the 556 high voltage to the value that is recommended for the scintillation detector. Turn on the 556 HV POWER.

b. Set the amplifier gain for a bipolar output amplitude of approximately +6 V, as observed on the 1-MΩ input of the oscilloscope. Check that the FOCUS control on the related 266 PMT base has been adjusted to maximize the above pulse height. Reconnect the 575A BIpolar OUTput to the analog INPUT of the Easy-MCA.

4. Connect the UNipolar OUTput of the 575A Amplifier to the 1-MΩ input of the oscilloscope. Set the horizontal scale of the oscilloscope to 50 µs/cm and the vertical scale to 100 mV/cm. With a small, flat-blade screwdriver, adjust the PZ ADJ on the 575A Amplifier to make the pulses on the UNIpolar OUTput return to baseline as quickly as possible without undershooting the baseline between pulses. For further guidance on the Pole-Zero Cancellation adjustment, consult the instruction manual for the amplifier, or the introduction to the amplifier product family on the ORTEC web site at www.ortec-online.com.

5. Via the Acquire menu and the ADC tab in the MAESTRO-32 software that operates the Easy-MCA, select the Gate Off option, and adjust the Upper Level discriminator to its maximum value. Adjust the Lower Level discriminator as low as possible without causing excessive counting rate on the noise. It may be useful to temporarily turn off the 556 High Voltage for the Lower Level discriminator adjustment. Under the Preset tab, clear all data fields, and do the same for the MDA Preset option (if supported). Clearing those fields will default to manual control for starting and stopping spectrum acquisition. Select the analog-to-digital conversion range to be 1024 channels for a 0 to +10-V input. Familiarize yourself with the software controls for setting up, acquiring and erasing spectra.

6. Adjust the amplifier gain to calibrate the system for full scale on the MCA of ~2 MeV. Use the ^{137}Cs and ^{60}Co gamma sources from the source kit for the calibration. Draw the calibration line (as in Experiment 3 or use the MCA energy calibration feature).

7. Place the aluminum target from Sample Set No. 318 in contact with the Am-Be source for ~30 min. The reaction produced is ^{27}Al(n,p)^{27}Mg and the $T_{1/2}$ of the product will be 9.5 min (Fig 18.2).

8. Transfer the sample to the NaI(Tl) detector and count for a period of time long enough to define the gamma groups for the reaction.

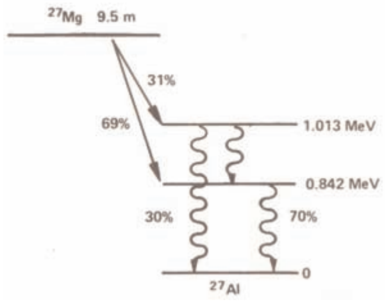

Fig. 18.2 Decay Scheme for the Product of the ^{27}Al(n,p)^{27}Mg Reaction.

EXERCISE

a. Measure the gamma energies. Do they agree with those shown for this reaction in Fig. 18.2?

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9. Set the ROI of the MCA so that it brackets the 1.013-MeV gamma for the reaction. Preset for a counting time of 40 s. Take a 40-s count every 2 min until enough data have been obtained to plot a half-life curve. What is the measured $T_{1/2}$?

10. Figure 18.2 shows that 70% of the gammas are 0.842 MeV and that 30% are 1.013 MeV. Irradiate a second aluminum sample for ~30 min to obtain a sample that will be used to check this ratio.

11. Use the ROI of the MCA to set two regions of interest, one for 0.842 MeV and the other for 1.013 MeV. Transfer the sample to a counting position that is 9.3 cm from the face of the detector. Accumulate a spectrum in the MCA for a period of time long enough to have ~1500 counts under the 1.013-MeV peak.

EXERCISE

b. Correct the sums from both of the gamma-ray peaks by

$$\Sigma(\text{corrected}) = \frac{\Sigma(\text{uncorrected})}{\varepsilon_p} \tag{8}$$

where ε_p is the intrinsic peak efficiency of the detector at that energy level (Fig. 3.6 of Experiment 3). The corrected sums should be in the ratio of 70% to 30% as stated above. Are they?

EXPERIMENT 18.2

Optional (n,p) Reactions that can be Studied

Procedure

Table 18.1 lists six (n,p) reactions from Sample Set No. 318 to be studied in the same manner as the ^{27}Al(n,p)^{27}Mg reaction of Experiment 18.1. All of the samples needed for the experiments outlined in Table 18.1 are contained in Sample Set No. 318.

Table 18.1 Fast Neutron Activation Parameters for the Samples in Sample Set No. 318.

Element	Reaction	σ_{barns}	$T_{1/2}$	Measured γ (keV)	Activation Time	Counting Times(s)
Magnesium	^{24}Mg(n,p)^{24}Na	0.180	14.9 h	1370	4 h	1000
Sodium	^{23}Na(n,p)^{23}Ne	0.034	40.2 s	440	3 min	100
Silicon	^{28}Si(n,p)^{28}Al	0.220	2.3 min	1780	5 min	100
Vanadium	^{51}V(n,p)^{51}Ti	0.027	5.8 min	320, 605	10 min	200
Iron	^{56}Fe(n,p)^{56}Mn	0.110	2.56 h	845, 1810	4 h	1000
Chromium	^{52}Cr(n,p)^{52}V	0.080	3.76 min	1440	10 min	200

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