An Introduction to Ion-Optics

Series of Five Lectures
JINA, University of Notre Dame
Sept. 30 – Dec. 9, 2005

Georg P. Berg
1st Lecture: 9/30/05, 2:00 pm: Definitions, Formalism, Examples

2nd Lecture: 10/7/05, 2:00 pm: Ion-optical elements, properties & design

3rd Lecture: 10/14/05, 2:00 pm: Real World Ion-optical Systems

4th Lecture: 12/2/05, 2:00 pm: Separator Systems

5th Lecture: 12/9/05, 2:00 pm: Demonstration of Codes (TRANSPORT, COSY, MagNet)
3rd Lecture: 10/14/05, 2:00 pm:
Real World Ion-optical Systems

- Ion-optical systems: e.g. dispersive, achromatic, telescopic sections
- Spectrometers, beam lines
- Matching of phase space, dispersion matching

- Spectrometers and their properties (4 - 10)
- Achromatic system (11 - 12)
- Beam lines and their functions (13 - 18)
- Dispersion Matching (19 -23)
- Scattering angle reconstruction (24 – 26)
- Results of Dispersion Matching (27)
The Browne-Buechner, a Historic Spectrograph
built at MIT (1951-1954)

THE REVIEW OF SCIENTIFIC INSTRUMENTS

VOLUME 27, NUMBER 11 NOVEMBER, 1956

Broad-Range Magnetic Spectrograph*

C. P. Browne† and W. W. Buechner
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge 39, Massachusetts
(Received August 8, 1956)

A broad-range magnetic spectrograph for precise measurement of the energies and intensities of charged particles from nuclear reactions is described. A uniform magnetic field with a circular boundary focuses particles from a source outside the field along a hyperbolic focal surface. Particles with energies varying by as much as a factor of 2.5 may be simultaneously recorded on nuclear-track plates. Under routine operating conditions, an energy resolution of better than 1000 is obtained over the length of the focal surface. The design, construction, testing, and operation of the spectrograph are described, and plots of dispersion, magnification, aberration, and calibration are given.

Spectrograph refers to an instrument with a photographic plate (historic!) in the focal plane.

Spectrometer refers to an electrical detection system in the focal plane, e.g. a position sensitive wire chamber.
The present Notre Dame Spectrometer

A modified Browne-Buechner spectrometer

DESIGN AND PERFORMANCE OF A NEW MAGNETIC SPECTROGRAPH FOR ACCURATE ENERGY MEASUREMENTS

J. D. GOSS, A. A. ROLLEFSON and C. P. BROWNE

Department of Physics, University of Notre Dame*, Notre Dame, Indiana 46556, U.S.A.

Received 16 January 1973

A large broad-range magnetic spectrograph of a new design is described. The primary requirement of accuracy is achieved with a single dipole magnet, fixed focal surface and high dispersion. A large energy range of $E_{\text{min}}/E_{\text{max}} = 3.7$, a solid angle up to 2.8 msr in the normal mode, and an energy resolution greater than 3000 over much of the range make it an excellent instrument for reaction energy measurements. The design, construction and testing are described.
Spectrometer Design

(1st Order Resolving Power)

Spectrometer Transfer
Matrix S

Dispersion: \( S_{16} = \frac{dx}{dp/p} = D \)
Magnification: \( S_{11} = \frac{dx(\text{f.p.})}{dx(\text{tgt})} = M \)
Beam size: \( 2x_0 \) (target, dispersive direction, monochromatic)
Resolving Power: \( R_p = \frac{p}{\Delta p} = \frac{D}{M \times 2x_0} \) \(^{(22)}\)

Note: \( R_p \) depends on \( x_0 \), if not given here \( x_0 = 1 \text{ mm} \)

Note: **Resolving Power** is the “best possible 1st order resolution a spectrometer can provide.

**Resolution** is what is measured in the Focal Plane.

**Resolution** is also effected (deteriorated) by:
Aberrations, target effects, detector resolution

Note: “**Resolution**” in Energy \( R_E = \frac{E}{\Delta E} = 0.5 \times R_p \)
because \( E = \frac{p^2}{m} \) (non-relativistic)

Peaks are “resolved” when \( \Delta x = \text{FWHM} \)
Specifications of the Browne-Buechner Spectrometer

**MIT version**
- Bending radius: $\rho_0 = 0.5 \text{ m}$
- Resolving power: $p/\Delta p = 2000$
- $B_{\text{max}} = 1.2 \text{ T}$
- Gap = 1.27 cm
- Weight = 6.5 tons (iron)
- Large range: $E_{\text{min}}/E_{\text{max}} = 2.5$

**ND version**
- Bending radius: $\rho_0 = 1.0 \text{ m}$
- Resolving power: $p/\Delta p = 6000 - 10000$
- $B_{\text{max}} = 1.2 \text{ T}$
- Gap = 5.0 cm
- Weight = 35 tons (iron)
- Large range: $E_{\text{min}}/E_{\text{max}} = 3.7$

Compare weights
Gap is expensiv!
Bending radius $\rho_0 = 2.0$ m
$B_{\text{max}} = 1.7$ T
Gap = 5 cm (D1), 6cm (D2)
Weight = ~ 30 tons (D1)
    ~ 45 tons (D2)

Medium Dispersion: $B(D1) = B(D2)$
Resolving power: $p/\Delta p = 20000$
Dispersion = 12 cm/% ( = 12 m)
Magnification $M_x = 0.41$
Large range: $E_{\text{min}} / E_{\text{max}} = 1.14$

Kinematic correction: K coil
Hexapole correction: H coil

The K600 is shown in 0° Transmission mode
High Dispersion Plane
$B(D1) > B(D2)$
BIG KARL Spectrometer (Juelich, KFZ)

Bending radius $\rho_0 = 1.98$ m
$B_{\text{max}} = 1.7$ T
Gap = 6cm
Weight = $\sim 50$ tons (D1)
$\sim 70$ tons (D2)

Resolv. power: $p/\Delta p = 0 - 20600$
Dispersion = -2.0 to 26 cm/%
Magnification $M_x = 0.63 - 1.26$
Magnification $M_y = 25.4 - 1.94$
Large range: $E_{\text{min}} / E_{\text{max}} = 1.14$
Solid angle: $< 12.5$ msr

Fig. 9. Arrangement of the magnetic elements of the QQDDQ spectrometer BIG KARL. The central ray (optical axis) is shown as dashed curve. The outermost rays with the extreme radial distances are drawn as full lines. Four channels in the inner yokes allow NMR probes to be moved into the gaps of the dipoles for radial field measurements. The multipole element between Q1 and Q2 allows the correlation of vertical aberration.
Fig. 4. Spectra of $^{58}$Ni(p, p') measured for different dispersions $D = 26$, 16, 6.3, 3, 1.5, 0.25, and 0.2 cm/s. The spectrometer was optimized for $D = 16$ cm/s.

Fig. 19. High resolution spectrum of the (p, d) neutron pick up reaction on $^{109}$Ag at 25 MeV incident energy and a solid angle of 1.2 mrad. The resolution was 4 keV.
Fig. 9.6. Two double sector field arrangements that both cause achromatic beam deflections. Note that there are opposite signs for the radii of deflection in (a) and opposite signs for the area $A_\alpha$ in (b).
Fig. 9.7. An achromatic beam deflector consisting of two sector fields preceded and followed by quadrupole doublets. Note that the areas $A_{\alpha 1}$ and $-A_{\alpha 1}$ are of equal size. The quadrupole in the middle between the sector fields can be adjusted so that the overall system is not only dispersion free $(x|\delta_K) = (x|\delta_m) = 0$ but achromatic $(a|\delta_K) = (a|\delta_m) = 0$; i.e., particles of different rigidities ($\delta_K \neq 0$) are parallel in the middle of the center quadrupole and coincide at the end of the systems if they coincided at the beginning.

$R_{16} = R_{26} = 0$
Dispersion matched beam line WS to the high resolution spectrometer Grand Raiden
**Grand Raiden High Resolution Spectrometer**

Max. Magn. Rigidity: 5.1 Tm
Bending Radius $\rho_0$: 3.0 m
Solid Angle: 3 msr
Resolv. Power $p/dp$: 37000

Beam Line/Spectrometer fully matched

- Dipole for in-plane spin component
- Faraday cup for $(^3\text{He},t)$
  
  $B_p(t) \sim 2B_p(^3\text{He})$

Focal Plane Detector

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**Diagram Details**

- Magnetic Spectrometer
- Target Point
- Focusing Q section
- Grand-analyzer Focus
- Q-lens for Angular Dispersion Matching
- Grand-analyzer section
- Intermediate Focus
- Pre-analyzer Focus
- Source Point (SP)
Functions of the MPRI Beam Line
The PT Eye line

AMD Proton Therapy Beamline
Indiana University Cyclotron Facility
Sept. 1997

(AMD = Age-related Macular Degeneration)
Matching between beam line and spectrometer

First Order TRANSPORT Matrix Description:

Dispersion Matching

High resolution experiments
Secondary beam (large dp/p)
The transformation (without assuming $s_{16} = -s_{16f}$) in the bending plane from the cyclotron exit to the focal plane is given as:

$$x_{f.p.} = x_0 \left( s_{11} b_{11} T + s_{12} b_{21} \right)$$

$$\Theta_0 \left( s_{11} b_{11} T + s_{12} b_{22} \right) \rightarrow \text{kin. defoc. equ. (1)}$$

$$\delta_0 \left( s_{11} b_{11} T + s_{12} b_{26} + s_{16c} \right) \rightarrow \text{disp. matching}$$

$$\Theta \left( s_{12} + s_{16f} \right) \rightarrow \text{kin. correction (kin. dipoles)}$$

$$\Theta_{f.p.} = x_0 \left( s_{21} b_{11} T + s_{22} b_{21} \right)$$

$$\Theta_0 \left( s_{21} b_{12} T + s_{22} b_{22} \right) \rightarrow \text{kin. defoc. equ. (2)}$$

$$\delta_0 \left( s_{21} b_{16} T + s_{22} b_{26} + s_{26c} \right) \rightarrow \text{angular disp. matching}$$

$$\Theta \left( s_{22} + s_{26f} \right)$$

$$\delta_{f.p.} = k \cdot \Theta + \zeta \delta_0$$

For details see: Y. Fujita et al., NIM B 126 (1997) 274

Hendrie, Dispersion Matching

$$b_{16} = -\frac{D}{M} \ast \frac{C}{T} \quad (23')$$

D = $s_{16}$ = Spectrometer dispersion

M = $s_{11}$ = Spectrometer magnification

Solution of first order Transport and Complete Matching

Complete Matching

For best Resolution in the focal plane, minimize the coefficients of all terms in the expression of $x_{f.p.}$

For best Angle Resolution

Minimize Coefficients of $\delta_0$ in expression of $\Upsilon_{f.p}$.

Note: Also the beam focus $b_{12}$ on target is important ($b_{12} = 0$ for kinem. $k = 0$)

Spacial Dispersion Matching:

D.L. Hendrie In: J. Cerny, Editor,

*Nuclear Spectroscopy and Reactions, Part A*,

Spacial and Angular Dispersion Matching

Solutions for \( b_{16} \) and \( b_{26} \) under conditions that both \( \delta_0 \)-coefficients = 0 in (23) and (23)

\[
\begin{align*}
    s_{11} b_{16} T + s_{12} b_{26} + s_{16} C &= 0 \\
    s_{21} b_{16} T + s_{22} b_{26} + s_{26} C &= 0
\end{align*}
\]

Solutions:

\[
\begin{align*}
    b_{16} &= \frac{-s_{16}}{s_{11}} \left( 1 + s_{11} s_{26} K - s_{21} s_{16} K \right) \frac{C}{T} \\
    b_{26} &= (s_{21} s_{16} + s_{11} s_{26}) C \\
    b_{12} &= \frac{-s_{12} b_{22}}{s_{11} T} = \frac{s_{16} b_{22} K}{s_{11} T}
\end{align*}
\]

(25) Spacial Dispersion Matching

(26) Angular Dispersion Matching

(27) Focusing Condition
Spacial and Angular Dispersion Matching

Figure 2.2: Schematic ion trajectories under different matching conditions of a beam line
Grand Raiden High Resolution Spectrometer

Max. Magn. Rigidity: 5.1 Tm
Bending Radius $\rho_0$: 3.0 m
Solid Angle: 3 msr
Resolv. Power $p/dp$: 37000

Beam Line/Spectrometer fully matched

IUCF K600!
Diagnostic of Dispersion Matching

of beam line & spectrometer using a double strip target & multi slit

IUCF K600, 1986

Fig. 4. Scatterplots of horizontal position $x_{fp}$ versus angle $\theta_{fp}$ and projections measured in the focal plane of the K600 using the “multi-slit system”. For details, see text.
Momentum and Angular Resolution

Spacial & Angular Dispersion Matching & Focus Condition allows

Energy Resolution: $\Delta E/E = 4.3 \times 10^{-5}$, $\Delta p/p = 2.5 \times 10^{-5}$, despite beam spread: $\Delta E = 4-6 \times 10^{-4}$

Angular resolution: $\Delta Y_{\text{scatt}} = \sqrt{\Delta Y_{\text{hor}}^2 + \Delta \Phi^2} = 4 - 8 \, \text{msr}$

At angles close to beam (e.g. 0 deg) vert. angle component is needed $\rightarrow$ Overfocus mode, small target dimension, because $(y|y)$ is large,
Limitation: multiple scattering in detector

Data suggest: Use $y_{fp}$ not $\Phi_{fp}$ to calibrate angle!

Over-focus mode (b)

**New ion-optical mode run for R=300 cm**

Projection onto $y_{fp}$ axis

$\Delta \phi_{tgt} = 3 - 5 \text{ mr (}\sigma\text{)}$

Projection onto $\phi_{fp}$ axis

$\Delta \phi_{tgt} = 11 - 14 \text{ mr (}\sigma\text{)}$
Scattering Angle
reconstructed from focal plane measurements using complete dispersion matching techniques

$L=0$ Angular Distributions

Scatt. Angle reconstruction near 0 deg using Overfocus Mode

Figure 4.4: Spectrum of $^{88}$Ni($^3$He,$t$) reaction. The lateral and angular dispersion matching technique and over-focus mode were applied in this experiment for high energy and scattering angle resolution. Energy resolution of about 30 keV (FWHM) was realized.

Figure 4.5: Example of angle dependence in the $^{88}$Ni($^3$He,$t$) spectra near 0°. Three spectra are shown for the angle ranges 0-0.8° (left), 0.8-1.4° (middle) and over 1.4° (right), respectively. The 3.54 MeV state show clearly different angular distribution from the adjacent $1^+$ states which are dominated at forward angle.
Fig. 19. High resolution spectrum of the (p, d) neutron pick up reaction on $^{109}\text{Ag}$ at 25 MeV incident energy and a solid angle of 1.2 msr. The resolution was 4 keV.
Study of Gamow-Teller Resonances

$^{58}\text{Ni}(p,n)^{58}\text{Cu}$

$E_p = 160\text{MeV}$ at $\theta_{\text{lab}} = 0^\circ$

$\Delta E \sim 400\text{ keV}$

J. Rapaport et al.,

$^{58}\text{Ni}(^{3}\text{He},t)^{58}\text{Cu}$

$E_{^{3}\text{He}} = 150\text{MeV/u}$ at $\theta_{\text{lab}} = 0^\circ$

Y. Fujita et al.,

1994, RCNP

Development of Dispersion matching

$^{58}\text{Ni}(^{3}\text{He},t)^{58}\text{Cu}$

$E_{^{3}\text{He}} = 140\text{MeV/u}$, 0-deg

$\Delta E = 35\text{keV}$

2001 RCNP

Where is the limit?
End Lecture 3