Progress in Recoil Spectrometers for Separation
of Fast-Nuclear-Reaction Products

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Abstract

A review is presented of electromagnetic instruments used for detection and separation of heavy nuclear species emitted from or recoiling from targets in fusion, spallation or fission processes. In the case of fusion reactions, the nuclei, called evaporation residues, are emitted in a narrow cone about zero degree and hence have to be separated from the beam. The beam separation process is a major function of the apparatus.

1. Introduction

This paper discusses a type of instrument that is used for separating and analyzing heavy nuclear reaction products. The reaction may be a heavy-ion induced reaction, e.g., fusion, a spallation reaction induced by a high-energy beam, or induced fission. In all cases we are interested in determining the element number Z , the mass number A , possibly also the kinetic energy E_k and, optimistically, the actual mass m . Except for fully stripped ions, Z can not be determined by electric or magnetic deflection, but modern detectors go a long way towards the goal of determining Z to one unit. We shall leave Z out of the further discussion here. The ion parameters that determines the ion's path in an electromagnetic field are charge, $Q=qe$, velocity v , and mass m . In an electric field, perpendicular to v , the radius of curvature of the orbit is proportional to E_k/q , in a magnetic field to mv/q . In a velocity selector (Wien filter) set for a velocity $v_0 = E/B$ the deflection is to first order proportional to $\Delta v = v - v_0$. Since m and q in the formulas always appear together as m/q , we can reduce the three parameters to two, for instance m/q and v . In a fusion reaction, depending upon the cross section of the reaction, the intensity of the beam might easily be a factor of 10^{12} higher than the intensity of the desired recoil nuclei. A primary function of the apparatus

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becomes to dump the beam so that a very small portion if any, reaches the detector or collector. A second function of the apparatus is to separate the recoil nuclei according to the masses.

Aside from the problem of beam dumping, which is a characteristic of the fusion reaction only, there are for the apparatus designer other very substantial differences between heavy-ion recoils and heavy species produced in an ion source. The recoil nuclei have energies in the multi-MeV range, and even in the case of the fusion reaction the angular distribution is substantially wider than in a conventional isotope separator.

The velocity spread is several percent and the ions are multiply charged with a distribution centered about a mean charge state of, typically, $q=20-40$ for the heavy species. The intensity of the principal charge state is usually about 20 percent of the total. The instrument therefore has to be designed to collect more than one charge state or one has to suffer a substantial reduction in intensity. Figure 1 shows as an example¹ of a spectrum of evaporation residues recoiling from a ^{58}Ni target bombarded with ^{25}S . The compound nucleus has mass 90 and we see mass numbers $A=84, 86$, and 87 and charge states $q=16$ to 21 . The velocity distribution of the recoils was typically $\Delta v/v \approx \pm 15$ percent at half maximum and the angular distribution approximately 0 to 5 degrees (half maximum). These distributions are relatively wide because the particles evaporated in this reaction are protons and alpha particles.

2. Ion Optics

Collection efficiency is always of utmost importance. In general, one therefore needs an instrument that has a large velocity range, a large m/q range and a large solid angle, several milliradians, if possible. Several second-order aberration coefficients then have to be dealt with and possibly also higher-order aberrations. Fig. 2 shows a box diagram representing a general ion-optical transfer system. The angles θ and ϕ define the direction of a given ray from the target. The intersection of this ray with the image plane can be expressed as a power series

$$x_2 = \sum_i (x/\alpha_i) \alpha_i + \sum_{ij} (x/\alpha_i \alpha_j) \alpha_i \alpha_j + \sum_{ijk} (x/\alpha_i \alpha_j \alpha_k) \alpha_i \alpha_j \alpha_k + \dots \quad (1)$$

and a similar expression for y . The (x/α_i) 's, $(x/\alpha_i \alpha_j)$'s and $(x/\alpha_i \alpha_j \alpha_k)$'s are first-, second- and third-order transfer coefficients and the α_i 's are the variables $x_1, \theta_1, y_1, \phi_1, \delta_v = \Delta v/v_0$ and $\delta_m = \Delta(m/q)/(m/q)_0$. A reference ray is assumed with all these variables equal to zero. The first order coefficients (x/α_i) 's are manipulated by varying the strengths of first-order focusing elements such as angles of electric or magnetic deflectors or quadrupole strengths. In a conventional double-focusing mass spectrograph or isotope separator of the simplest kind only two first-order terms are made equal to zero, namely x/θ and x/δ_v . In more sophisticated instruments, also at least the second order term x/θ^2 is made to vanish. The second-order terms can be manipulated by

varying the curvatures of deflecting magnet boundaries or by sextupole components, either separate or built into quadrupole lenses. With the much larger acceptance solid angle and velocity range of a recoil mass spectrograph the second- and higher-order aberration coefficients are much more important. In the simplest possible case, we can ignore the higher order effects of the source size (x_1 and y_1 in the power series) and assume symmetry about the $y=0$ plane, implying electric and magnetic deflection in the same plane. We can then limit the list of second-order aberrations to those shown in Table 1.

In point-to-point imaging systems $y/\theta\phi$ is coupled to x/ϕ^2 in such a way that if x/ϕ^2 is zero, $y/\theta\phi$ can be neglected. The term x/δ_m^2 only expresses a non-linearity in mass dispersion and can be neglected. We are still left with eight second-order aberration terms that need to be dealt with. An additional complication is that the velocity-chromatic terms must be corrected by introducing sextupole terms at positions where the velocity dispersion x/δ_v is large. For the high energy nuclei we are considering, a large velocity dispersion requires very strong electric fields - which are difficult to obtain in vacuum. The conclusion, then, is that a large solid-angle, large velocity-range instrument with high resolution is maybe too tall an order. However, some valiant attempts have been made at making such corrections - and with considerable success. One such instrument, in the design state, is being discussed by L. H. Harwood in one of the following papers.²

We will now discuss some instruments in use or in the design state. We will classify them according to their applications as fusion, spallation, or fission spectrographs. This may seem arbitrary, but one reason for treating the fusion instruments as one group is that the beam separator is such an important part of the apparatus. Indeed, some of the instruments discussed are simply beam separators with none or very little mass dispersion. Time-of-flight measurements are then being used to determine the mass number, but no separation of products, for further study, is attempted.

3. Fusion Spectrographs

a) The SHIP

The SHIP (Selector for Heavy-Ion reaction Products) has been in operation at Gesellschaft für Schwerionenforschung in Darmstadt, West Germany, since 1976.^{3,4,5} As it will be discussed in the following paper by G. Münzenberg⁶, I include it here only to indicate where it belongs in the family of recoil instruments. Figure 3 shows an optical diagram of SHIP. It consists basically of two quadrupole triplets and two separate-function velocity selectors. It can operate in more than one optical mode by varying the relative fields in the magnets. Figure 3 shows the preferred mode which produces a velocity dispersion in the middle, where the reaction products are separated from the main beam, and also a velocity dispersion at the exit for further background reduction.

The SHIP is used strictly as a beam separator, and the mass number A and Z are determined by time-of flight in conjunction with a ΔE -E telescope.

b) The MIT-BNL Energy-Mass Spectrograph (EMS)

Figure 4 shows a schematic diagram of the EMS^{7,8,9} as originally built by the MIT heavy-ion group at Brookhaven National Laboratory and completed in 1975. A velocity selector (Wien filter) deflects the particles vertically according to their velocity, and a modified Split-Pole spectrograph deflects them horizontally according to momentum. The result is as illustrated in the figure, that particles with identical mass-to-charge ratio m/q fall on the slanted lines on the detector. Because of the large momentum range of the Split-Pole, virtually the complete charge state spectrum is accepted in one exposure (See Fig. 1). The velocity range is about ± 4 percent which is sufficient to take in most of the spectrum of recoils from HI,xn reactions on heavy nuclei... The solid angle is only about 0.6 msr but there is no principal reason why a similar instrument could not be made with a larger solid angle.

The spectrum in Figure 1 is a horizontal cut across the mass lines of Figure 4. The detector was a set of nuclear track plates and the reaction angle was 5 degrees. The instrument was used down to 2 degrees in this form, but at zero degree the background of scattered beam particles was too high for nuclear track plates. The main beam was actually collected on one of the plates of the electrostatic

deflector. This had some thin baffles attached to it⁹, but enough low-energy scattered particles made it through the selector to be bothersome. As discussed below, the velocity selector has since been divided up in such a way that the beam can be captured in a Faraday cup.

c) The MIT-BNL Recoil-Mass Selector (RMS)

In order to improve the beam-tail rejection at zero degree, the velocity selector for the EMS was divided up as shown in Figure 5. This figure also illustrates the use of the velocity selector alone, without the Split-Pole.¹⁰ Instead, two quadrupole pairs are used to focus the evaporation residues on a solid-state detector preceded by a gas ΔE detector. The quadrupole pair Q1, Q2 focuses the evaporation products to a waist approximately in the middle of the Wien filter. Since the main beam, in a typical fusion reaction has approximately the same magnetic rigidity $B\rho$ as the reaction products, the beam with its halo of elastically scattered particles is approximately focused in the Faraday cup. This helps in cutting down one source of background of low-energy scattered beam particles. Another source of beam background is the tail of low-energy particles present in the main beam or otherwise emerging directly from the target area. A certain fraction of the beam tail consists of particles with velocities comparable to the velocities of the evaporation residues.

It is not unusual for a charged-particle beam of 10^{11} particles per second to have a low-energy tail with a total of 10^7 particles per second of which perhaps 10 percent would have velocities in the band passed by a velocity selector such as the one used in the EMS. These particles, however, differ significantly from the evaporation residues in their E_k/q and p/q values. They are therefore separable by an electrostatic or magnetic deflector. Both the SHIP and the RMS make use of this fact, in that the first deflecting element is an electrostatic deflector although overall the instruments are velocity selectors.

The RMS is being used to measure total fusion cross sections down to the microbarn level. Also, it is being used to produce and identify new alpha-radioactive nuclides far from the line of stability. The recoils are imbedded into the E-detector and subsequently decay, producing an alpha-particle spectrum in the detector. In recent runs the beam particles with the correct velocity to pass through the velocity selector have produced counting rates of the order of 200 per second. A gas ΔE counter in front of the E-counter, operating in anti-coincidence effectively removes these events from the alpha spectrum.

d) The MIT-ORNL Recoil-Mass Selector

A very simple and inexpensive beam separator is being designed by the MIT group to be installed at the Holifield Heavy-Ion Research Facility at Oak Ridge (Fig. 6).

The instrument has a separate-function velocity selector built as one integrated mechanical unit. The electrostatic deflectors have effective lengths of 40 cm and plate separations of 6 cm. The power supplies can deliver ± 200 kV. If the deflectors can hold this voltage, particles with an E_k/q ratio of up to 7.6 MeV can be deflected by 10 degrees in each electrostatic deflector and ~ 20 degrees in the magnetic field. The instrument can be used for particles with higher E_k/q ratio, but the deflection angles will be smaller, so that the apertures may have to be narrowed to obtain adequate separation.

This velocity selector will be set up initially, at least, with only a quadrupole pair to refocus the evaporation residues onto the detector. A single magnet or Split-Pole may be added at a later date to produce a complete mass spectrgraph.

e) The Michigan State RPMS

A recoil product mass separator is being built for the heavy ion research facility at Michigan State University. The original layout of the instrument is shown in Figure 7. The latest plans call for a simplified instrument but it is of interest to discuss the original layout because it contains a rather elaborate system of sextupole correctors for second order aberrations. As shown in Figure 7, the velocity selector (ExB) produces a velocity dispersion through a part of the system. This dispersion is effectively cancelled by

the dipole D. From the dipole to the end of the system there is a mass dispersion (not shown).

The quadrupole triplet M4-6 contains sextupole distortions which correct for the velocity dispersive terms $x/\delta v$ and $y/\delta v$ without introducing aberration terms x/δ^2 and x/ϕ^2 , both of which are small to start with.

The quadrupole triplet M10-12 has sextupole distortions to correct for the mass dispersive aberrations. It was found by RAYTRACE calculations that these sextupoles introduce fairly strong higher order aberrations and also, because of the complexity of the system, a simpler design is now being contemplated. This will be discussed in the paper by Harwood and Nolen².

f) The Daresbury Recoil Separator

Figure 8 shows the optical layout of a separator being constructed at Daresbury Laboratory in England.¹¹ The first-order layout is quite similar to the original Michigan State design. The last quadrupole singlet shown in Figure 8 has now been replaced by a triplet and two sextupole lenses have been included for second order correction. As shown in the figure, the velocity selector is separated into two sections such that the primary beam can be extracted without striking the electrostatic deflector. The mass dispersion at the detector is about 5 mm/percent in this optical mode.

The Daresbury instrument can also be operated in

another optical mode in which the quadrupoles are adjusted to give maximum transmission. In this mode the vacuum chamber of the dipole is gas filled so that all particles of the same energy will have the same effective charge. Hence, the charge dispersion is eliminated. The mass resolutions, however, is much poorer than in the mode shown in Figure 8.

g) The Rochester RMS

T. M. Cormier and P. M. Stwertha¹² are building a recoil mass spectrometer for fusion studies at the tandem facility of the University of Rochester. The instrument consists of a separate function mass selector bracketed by two quadrupole triplets (Figure 9). The electrostatic deflectors are 15 degrees and the magnet 36.2 degrees. The focusing is arranged such that the velocity dispersion is zero at the detector and therefore the mass dispersion is non-zero. In effect the instrument has most of the features of a conventional double-focusing mass spectrograph. The magnet has curved boundaries to minimize second order aberrations.

h) The Munich RF Separator

All instruments discussed above employ static electric fields as well as magnetic fields for separating the reaction products from the beam. S. J. Skorka et al,^{13,14,15} have built a separate-function Wien filter with a radiofrequency electric field for operation in conjunction

with the Munich Tandem Accelerator.

Figure 10 is a schematic diagram of the apparatus. The beam is pulsed and the phase of the RF is chosen such that the electric field is at a maximum when particles of the desired velocity pass the deflector. In the particular case illustrated in the figure the full energy beam has twice the velocity of the reaction products (e.g., the reaction $^{40}\text{Ca} + ^{40}\text{Ca}$). In this case the electric field is reversed when the beam particles pass, resulting in a considerably larger angular separation of the two beams than in the electrostatic case.

The instrument also includes a quadrupole pair for focusing of the reaction products and a start and stop detector for time-of-flight determination of mass.

Another type of RF recoil separator has been proposed by Kankleit, et al ¹⁶. It employs a pair of RF deflectors (left-right) and no magnetic deflectors. Because of the offset between the RF deflectors, the instrument has a capability of E_k/q selection in addition to velocity selection.

1) Particle Spectrometers and Isochronous Magnet Systems

In a conventional time-of-flight apparatus the mass of a recoiling nucleus is determined by measuring its velocity (time-of-flight) and kinetic energy. The latter is normally measured by a surface barrier detector, and the mass resolution is limited by the energy resolution of the

detector which for heavy ions is of the order of 1 percent. If a magnetic spectrograph is used simultaneously for determining p/q of the particle, a much better mass resolution can be obtained. Pühlhofer, et al, ¹⁷ have demonstrated this with the particle spectrometer at GSI. One difficulty is that a particle spectrometer inherently is not an isochronous transfer system, i.e., the flight path through the system depends upon the angle of emission from the target. It is therefore necessary to have a detector that determines angle as well as position.

Another approach is to build a double spectrometer with mirror symmetry. The momentum (p/q) is measured in the mirror plane and the second part of the system restores isochronism. This approach has been taken in two designs, one for a spectrometer proposed for the French GANIL project ¹⁸, the other is a much smaller system being built for the Tandem Facility at the University of Washington by D. Storm, et al ¹⁹. Neither of these systems address the problem of beam tail separation, and will without an additional electric field have a high background count at zero degrees for fusion reactions.

4. Spectrographs for Spallation Products

High energy proton beams interacting with a heavy target such as uranium will produce a shower of light nuclides, some far from the line of stability. In recent experiments at

the BEVALAC (Berkeley, CA) a simple deflecting magnet is used for separating the various species.

A much more sophisticated system is being proposed by Vieira, et al,^{20,21}. Figure 11 shows the floor plan of this instrument. Fundamentally the optics of the system is so arranged that particles with different p/q but with the same m/q arrive at the detector simultaneously. The flight time through the system is a direct measure of the mass to charge ratio.

5. Fission-Product Separators

a) Gas filled magnetic spectrometers

These work on the following principle. The effective (mean) charge of an ion moving through a low pressure gas (typically 1 Torr) is approximately

$$\bar{q} \approx vZ^\alpha \quad (2)$$

where α is a constant. The effective magnetic rigidity is

$$B\rho = \frac{kAv}{\bar{q}} \quad (3)$$

where k is a constant. Combining the two equations we get

$$B\rho = \frac{kA}{Z^\alpha} \quad (4)$$

Since both A and Z are integers a measurement of Bρ, with sufficient resolution, in principle can be used to determine both.

The separator JOSEF at Jülich²² employs a 312-degree double-focusing magnet with a 1.25-meter radius. The mass resolution is $A/\Delta A \approx 110$ and the Z-resolution $Z/\Delta Z \approx 60$.

b) Parabolic Separators

The original parabolic mass separator used by Thomson to separate the isotopes of neon employed parallel electric and magnetic fields in the same region of space. The Lohengrin^{23,24} parabolic separator, operating at the high flux reactor in Grenoble has a magnet deflecting horizontally followed by an electrostatic field, deflecting vertically. The deflection angles are 45 degrees and 35.35 degrees respectively, chosen such as to produce stigmatic focusing. The curvatures of the entrance and exit boundaries of the deflectors are chosen such as to minimize second-order aberrations. The instrument is huge, the total distance from source to detector is 23 m. As in the classical Thomson instrument particles with the same mass-to-charge ratio m/q fall on parabolas, the position on the parabola being determined by the kinetic energy.

Lohengrin utilizes a 70-cm long detector slit which matches a section of a parabola. A mass spectrum is produced by varying the magnetic field. The source is a thin enriched ²³⁵U target subject to a high-intensity neutron flux.

The solid angle covered by the spectrograph is about 0.4 msr. A resolving power as high as $m/\Delta m=15000$ has been demonstrated. Figure 12 is an m/q spectrum of fission recoils shown with an identification scheme in A and q.

6. Conclusion

How do recoil mass selectors or spectrographs compare with conventional on-line isotope separators? First, the advantages: There is no ion source; hence, all elements are detectable and with the same basic efficiency which may be as high as 100 percent in some special cases. The time interval from creation to detection or collection is of the order of one microsecond as compared to about 10^{-2} sec for a separator with an ion source. A disadvantage is the multiplicity of charge states, which means reduced intensity if only one charge state is collected and produces overlapping mass spectra, which requires higher resolution. Another disadvantage is the larger solid angle normally required to collect a sufficient number of recoils. The result is poorer resolving power. Most of the instruments discussed above can not compete with the ISOL separators in this respect. Finally the target used in fusion reactions, for instance, is usually an order of magnitude thinner than used in ISOL instruments, representing another relative loss in intensity.

Clearly the recoil instruments can cover many areas that cannot, or cannot easily, be covered by ISOL instruments. The two techniques clearly overlap but also supplement each other.

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TABLE 1

Most Important Second-order Aberration Coefficients

x/θ^2	geometric
x/ϕ^2	"
$y/\theta\phi$	"
$x/\theta\delta_v$	velocity-chromatic
x/δ_v^2	" "
$y/\phi\delta_v$	" "
$x/\theta\delta_m$	mass-chromatic
x/δ_m^2	" "
$y/\phi\delta_m$	" "
$x/\delta_v\delta_m$	chromatic

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Figure Captions

1. Mass spectrum of evaporation-residue recoils from the reaction $^{32}\text{S}+^{58}\text{Ni}$ obtained with the apparatus shown in Figure 5. Also shown are elastically scattered ^{32}S ions from the low-energy beam tail.
2. Ion-optical transfer system.
3. Schematic diagram of the velocity filter SHIP.
4. (a) Schematic view of the MIT-BNL Energy-Mass-Spectrograph (EMS).
(b) Construction of mass lines on the detector.
5. Schematic view of the MIT-BNL Recoil Mass Selector (RMS).
6. A recoil mass selector planned for the Holifield Heavy Ion Research Facility at Oak Ridge.
7. A second-order corrected recoil mass spectrograph with sextupoles and quadrupoles combined.
8. The Daresbury recoil separator with a diagram showing the dispersion through the system.
9. The Rochester Recoil Mass Spectrometer.
10. The RF beam filter and time-of-flight spectrometer at the Munich Tandem.
11. A time-of-flight mass spectrometer which is both angle- and energy-isochronous, planned for detecting spallation

products at LAMPF.
 12. Fission product spectrum recorded with the parabolic spectro-
 graph Iohengrin.

Fig. 1

Fig 2

Fig. 4

Fig. 6

MSU-RPMS

Fig. 8

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ROCHESTER RECOIL MASS SPECTROMETER

Fig. 10

Fig. 1