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A REACTION PRODUCT MASS SEPARATOR FOR ENERGETIC PARTICLES AT MSU

L.H. HARWOOD and J.A. NOLEN, Jr.
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

A reaction product mass separator which has been designed and is under construction at the National Superconducting Cyclotron Laboratory (Michigan State University) is described Unslowed reaction products emerging from the target are dispersed according to their mass-to-charge ratio (m/q) and focused to points on a focal plane The prototype system will transmit particles in the 1–30 MeV/u range The design of a system for up to 200 MeV/u is also discussed The types of experiments to be done are given as well

1. Introduction

A major area of nuclear physics is the study of exotic nuclei, i.e. nuclei far from the valley of β-stability. Production of exotic nuclei and their subsequent study has often been hampered by limitations in beam energy or intensity. Studies of exotic nuclei have also suffered from high background radiation levels, low detection efficiencies, etc. To overcome these last problems and take advantage of the beams at the new Michigan State University heavy-ion cyclotron facility a Reaction Product Mass Separator (RPMS) [1, 2] has been designed and is being constructed. This device is described below as are current plans for a second RPMS capable of accepting higher energy particles, up to 200 MeV/u.

2. Basic concept

In order to study the decay of exotic nuclei it is desirable to have them separated from the beam and other sources of radiation so that the detection system can operate in a friendly environment. Also, having the exotic nuclei concentrated spatially is advantageous to minimize the size of the detectors needed and to enhance the signal-to-noise ratio. Finally, the more exotic the nucleus is, the shorter (on the average) is its lifetime. Hence, fast transit times are desirable so that the nuclei do not decay before they can be studied. One often-used device in such studies is the conventional on-line mass separator [3]. Such separators have certain limitations, however. Because the reaction products must be stopped, thermalized, reionized, and accelerated, the study of nuclear levels is limited to those with lifetimes of at least 10–100 ms, thereby precluding those with lifetimes in the millisecond range and isomers in the microsecond range. The other major problem with ion sources is their sensitivity to the chemical nature of the ions. The chemistry of the nuclei can change a system's sensitivity greatly. For example, the alkali metals are easily ionized and thus produce good ion beams; refractory elements, on the other hand, are hard to ionize and are harder to make into ion beams. Great progress has been made in the production of "difficult" ion beams, but the chemical sensitivity problem still remains.

The ion source can be eliminated from the system by focusing the products directly as they leave the target. One such device, called the EMS (energy-mass spectrometer) [4], has been built by the MIT group at Brookhaven National Laboratory This device disperses vertically in velocity and horizontally in momentum thereby creating slanted lines of constant mass-to-charge ratio. This device retains excellent momentum resolution, but does not cencentrate the yield of a given m/q species into a small detection volume. Hence, this system is more suited for reaction mechanism studies than for decay studies of low yield reaction products. The Lohengrin fission-product separator at Grenoble is somewhat similar in concept to the EMS, however, and it has been used for decay studies [5, 6].

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At MSU, we have chosen to construct a device which focuses the reaction products directly from the target onto a focal plane with m/q dispersion. The device is triple focusing, i.e. in the vertical and horizontal opening angles as well as momentum. A similar separator is currently under construction at Daresbury [7]. The SHIP [8] system at GSI is also similar in some aspects, but it is primarily used as a broad range recoil collector at 0° with a very small dispersion at the focal plane; i.e. it is primarily a beam eliminator as opposed to a mass separator. The MSU separator is also designed for higher energy reaction products, up to 30 MeV/u in the prototype and 200 MeV/u in the final version. The various heavy ion reaction production mechanisms, described next, indicate the need for a device capable of operation over a very large range of ion rigidities. Following the discussion of production mechanisms, the details of the present designs are presented.

3. Production of exotic nuclei via heavy ion reactions

Near the Coulomb barrier ($\approx$3–4 MeV/u) fusion is the dominant reaction mechanism for heavy ion reactions. Fusion-evaporation studies have been used extensively to produce nuclei far from β-stability and in extreme conditions, e.g. in very high spin states, and those studies can be found throughout the literature.

Direct transfer of a few nucleons becomes important just above the Coulomb barrier and has also been used for the study of exotic nuclei. Usually, direct reaction studies concentrate on performing direct mass measurements and as such look only at the low-lying, discrete levels. There is also a continuum of higher-lying states which represent much larger cross-sections. We could use this continuum for the study of the decays of the nuclei and thereby overcome the usual problem of small cross-sections for a given discrete state.

As the energy increases to 10 MeV/u, deeply inelastic reactions dominate. Gurreau *et al.*[9] have recently used deeply inelastic reactions to prove the particle-decay stability of several nuclei.

At high energies ($\approx$100 MeV/u), fragmentation of the projectile by the target nucleus is a large part of the cross section. The fragments can have any combination of neutron and proton numbers available in the projectile. Westfall et al. [10] have reported the first observation of 14 nuclei. This experiment was hampered by the low beam intensities at the Bevalac. The MSU Coupled Superconducting Cyclotrons [11] will provide beams of up to 200 MeV/u with intensities several orders of magnitude higher than the Bevalac. This added intensity will mean that the Berkeley work can be extended to more exotic nuclei and that the decay modes of the previously observed nuclei can be studied.

Hence, it is desirable to build a separator capable of being used from the low rigidies of fusion recoils ($\sim$1 MeV/u) to the very high rigidities of beam fragments of up to 200 MeV/u.

4. System specifications

As part of the MSU Phase II facility, funding was granted to build an RPMS. As part of this project a prototype system was designed and is being constructed. Its description and the current plans for the final system follow.

4.1. Prototype RPMS

There are three types of dispersive elements: (1) magnetic dipoles which disperse in momentum, (2) electric spectrums which disperse in energy, and (3) Wien filters (crossed electric and magnetic fields; also called velocity filters) which disperse in velocity. To achieve a device with mass dispersion, two or more of these devices must be combined. We have chosen to use a Wien filter and magnetic dipole because of design and construction considerations. An electric septum which would fit our needs would have to be about 5 m long and have plates with a curvature determined by the highest rigidities to be transmitted. Such a device could not be used in an optimum way at lower particle rigidities because of the larger deflection angles. A Wien filter, on the other hand, can be turned to pass high rigidity ions (with low dispersion) or alternatively, low rigidity ions (with high dispersion), because the central ray always passes undeflected.

We have obtained a 5 m long Wien filter on

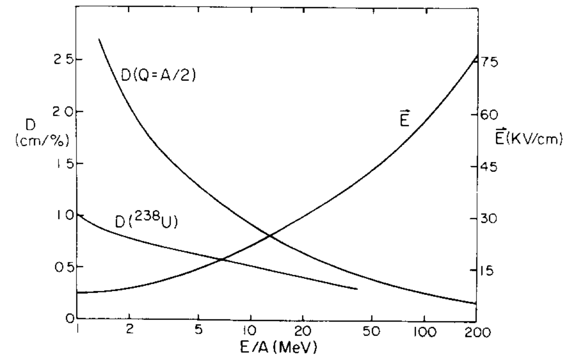

Fig 1 Dispersion of the Mark VI particle separator A magnetic field of 470 G (580 G can be attained) is assumed The optics are such that a range of 20 mr filled the 10 cm gap between the plates.

loan from Lawrence Berkeley Laboratory to use as the main component of an RPMS. This is a Mark VI particle separator previously used at the Bevatron. Fig. 1 shows the first order resolving power attainable with this device at about 1 msr solid angle in a preliminary RPMS design.

The other pieces of equipment to be used in the prototype system are four 8 inch aperture magnetic quadrupole singlets and a dipole from the MSU 50 MeV cyclotron's beam transport system. The length of the system had to be less than 15 m from target to focal plane in order to fit into the available space.

The optics calculations were done with the computer code TRANSPORT [12] by including the Wien filter matrix elements of Ianiouviciu [13]. Requiring a double focus at the focal plane and tapering the transverse envelope to fit through the 6.5 cm gap of the dipole yielded the system shown in fig. 2. The deflection angle in the magnetic dipole varies with the particle rigidity for which the system is tuned. Hence, the beam line to the right of the dipole in fig. 2 is mechanically movable.

The first order m/q resolving power of this system is 1000 for ions with $q = A/2$ at 20 MeV/u, e.g. 800 MeV Ca^{20+} ions. However, there are large second order aberrations, primarily the chromatic aberrations of the quadrupoles, which dominate the calculated line widths. Problems with the correction of the second order aberrations in various types of recoil separators are discussed by H. Enge in these proceedings. In the prototype RPMS being described here no second order correction elements are used. Some reduction of the effect of the chromatic aberration is achieved in this design, however, by offsetting the object position and axis of the first quadrupole doublet from the axis of the remainder of the system. This arrangement then passes those rays for which the chromatic aberration tends to enhance the first order dispersion and effectively eliminates those rays for which they tend to cancel No solid angle is lost by using only one half of the quadrupole apertures in the dispersion direction because the 20 cm quadrupole aperture is twice as large as the 10 cm electrostatic plate gap in the Wien filter. The full 20 cm aperture is still useable in the nondispersive direction because the related aberrations are less significant and the Wien filter acceptance is also larger in this direction.

The specifications for the prototype RPMS are given in table 1. A spectrum generated by pseudo-ray tracing with TURTLE [14] is shown in fig. 3. This spectrum illustrates both the mass resolution and the relative efficiencies for different masses since the same number of rays are input to the system for each mass.

To take advantage of the different heavy ion reaction mechanisms, the RPMS must be useable at different reaction scattering angles. Fusion and fragmentation products are concentrated near 0°, but deeply inelastic reactions are not. With a

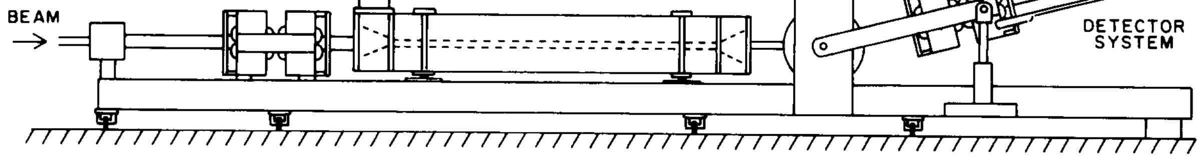

Fig 2. Schematic side view of the prototype RPMS.

Table 1

RPMS	Parameters	(Prototype)
Layout	QQWDQQ	(W ≡ Wien filter)
Length	14 3 m	
Max energy	30 MeV/u	
Angular Range	0°–30°	
Resolution	$\frac{M}{\Delta M}$ = 100 [a](base-to-base)	1 msr and 16% energy range
	= 200[b]	1 msr and 8% energy range

[a] Calculated for E/A = 20 MeV and M = 2Q with TURTLE
[b] Calculated for $^{40}Ca + ^{40}Ca$ fusion products at E_{Beam}/A = 5 MeV

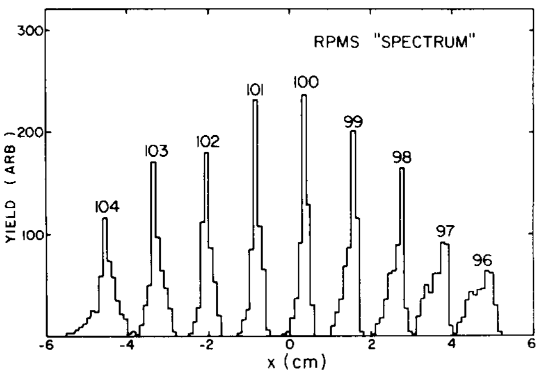

Fig. 3. A "spectrum" for the prototype RPMS for fusion-evaporation products The same number of rays were input to the system for each value of M/q; thus the peak areas show the relative efficiencies for each M/q The number over each peak corresponds to the mass number of the particles in that peak

14 m long device, rotation through 30° would require large amounts of floor space. We have chosen to let the beam do most of the moving, as illustrated in fig. 4. The RPMS carriage is pivoted at the detector box end. The centerline is positioned such that it is along a line at + 15° deflection of the beam by a dipole magnet. If the dipole is turned off the beam passes straight through it. If the RPMS is rotated slightly, the target again intersects the beam, but now the scattering angle is 15° rather than 0° as it was above. If the dipole deflects the beam by − 15°, it can be seen that the scattering angle becomes 30°. As fig. 4 shows, this system requires very little target motion (0.5 m) and thus very little floor space. This system will also work quite well for Phase II.

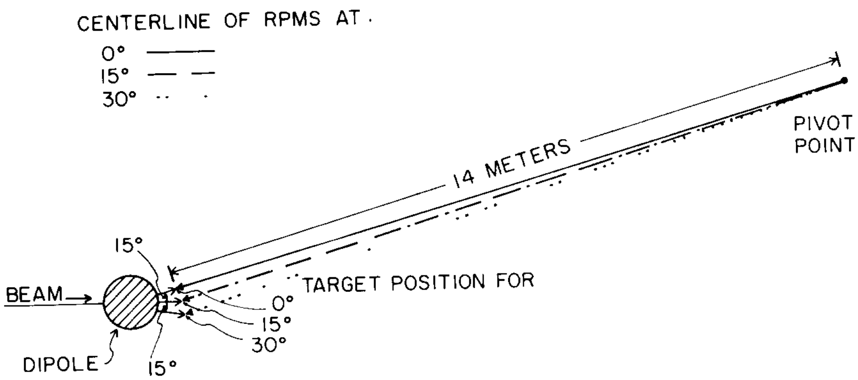

Fig. 4 Schematic illustration of the angle changing technique to be used for the RPMS The RPMS pivots near its focal plane position (upper right corner). The beam enters from the left. The dipole deflects the beam up by 15° for 0° incidence on the target. For 15° incidence the beam is undeflected and the RPMS target is moved the small distance necessary to intercept the beam 30° incidence is attained by a beam deflection of − 15° (15° down) and an additional small motion of the RPMS target

The beam will be stopped at different places in the RPMS according the angle and rigidities of the beam and reaction products. For fusion products (peaked near 0°), the Faraday cup will be placed at the entrance to the first quadrupole. For this prototype true 0° operation is not possible. The beam "halo" will be removed by the velocity dispersion of the Wien filter as well as by the m/q dispersion at the focal plane. The residual low energy tail of the beam which has the same m/q and velocity as the particle of interest cannot be eliminated by any electromagnetic system. Such background can often be separated at the focal plane by its range difference. For operation away from 0°, there will be a Faraday cup inside the target chamber.

4.2. Phase II

The prototype design is not satisfactory for the 200 MeV/u particles available from the Phase II cyclotron facility. These particles can have p/q (moment divided by charge) of 1.3 GeV/c whereas the 20 MeV/u particles have $p/q =$ 0.4 GeV/c; thus the quadrupoles must be much stronger for the high energies. The obvious solution to this problem is to lengthen the drift distance of the system. Also, we desire a focus after the Wien filter so that a velocity selection can be made on the particles by using an aperture at that position.

The current plans for Phase II RPMS are based on the "achromat" beam transport concept of Brown [15]. The basis of the system is a unit "cell" made up of a quadrupole triplet with equal drifts (each 3 m long) before and after it. The "cell" has simultaneous point-to-parallel and parallel-to-point focusing in both the dispersive and nondispersive planes. Two consecutive "cells" yield a negative unit transfer matrix; it follows that four "cells" yield the unit matrix. The Wien filter is situated such that its center lies on the boundary between first and second "cells", and the dipole is likewise placed on the boundary between the third and fourth "cells". Second order aberration correction in this system is then straightforward but is beyond the scope of this paper. This problem and the related problem of the induced higher order aberrations are discussed in ref. [16].

The present specifications for the Phase II RPMS are given in table 2. The design is not finalized at this time; calculations continue in order to further reduce the contributions of second and higher order aberrations to the line width.

The same technique will be used to change the angle for the phase II RPMS as will be used for the prototype. The magnetic multipoles will be superconducting for power savings. At present we are undecided whether to use Panofsky multipoles [17] or "cos($n\theta$)" multipoles as planned for ISABELLE [18]. The "cos($n\theta$)" design appears to have the simplest procedure for adding different multipole components but the Panofsky design is the simpler to build.

Table 2

RPMS	Parameters	(Phase II)
Layout	3MW6MD3M	(3M ≡ MMM; M[a] ≡ multipole)
Length	30 m	
Max energy	200 MeV/u	(p/q = 1 3 GeV/c)
Solidangle	$\Omega \leq 0$ 8 msr[b]	
Energy acceptance	8%	
Dispersion	8.5 mm/%[c]	
Resolution[c]	$\frac{M}{\Delta E}$ = 180 (base–base) 0.8 msr and ΔE = 8%)	
	= 320 (base–base) 0 8 msr and ΔE = 2%)	
	= 320 (base–base) 0 4 msr and ΔE = 4%)	

[a] Multipoles are superconducting. Quadrupole field gradient at 1 3 GeV/c is 3 kG/in

[b] 0.8 msr requires 4 in (radius) aperture multipoles.

[c] Calculated for E/A = 20 MeV/u and M = 2Q with TURTLE.

5. Summary

A prototype reaction product mass separator has been designed and is under construction for the MSU Superconducting $K = 500$ Cyclotron (Phase 1). This device will focus products from heavy ion reaction directly from the target onto a mass-dispersive focal plane. The products can then have their mass identified by measuring their position on the focal plane. Decay studies of the separated products can be done in a low-background region. The short flight time of the reaction products (1 μs for 1 MeV/u) allows studies of nuclei or nuclear levels with lifetimes as short as one microsecond Also, the device works equally well for all elements with no "easy or "hard" regions of the periodic table, but is limited to particles with $E/A \leqslant 20$ MeV. This device is expected to be on-line by mid-1981. Another RPMS is being designed to accept the 1–200 MeV/u products from reactions of the anticipated intense heavy ion beams of the Coupled Superconducting Cyclotron facility under construction at MSU (Phase II). We believe this device will enable us to investigate the limits of particle stability at the neutron-drip line below $Z = 20$. This device is expected to come on-line with the second cyclotron ($K = 800$) in 1985.

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