

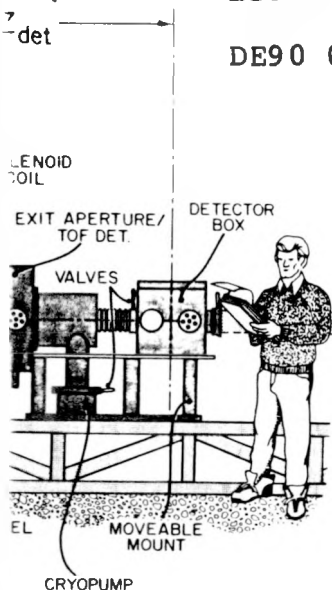
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A RECOIL MASS SPECTROMETER FOR THE HHIRF FACILITY



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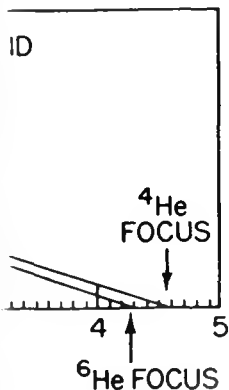
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ABSTRACT

A Recoil Mass Spectrometer (RMS) is to be built that will carry out a broad research program in heavy-ion physics. The RMS will make possible the study of otherwise inaccessible exotic nuclei. Careful attention has been given to match the RMS to all the beams available from the HHIRF accelerators, including those beams with the highest energy as well as massive particles for use in inverse reactions. With the use of inverse reactions, the production of secondary radioactive beams is possible. This is due to the design of the spectrometer. The RMS is to be a momentum achromat followed by a split electric dipole mass spectrometer of the type operating at NSRL at the University of Rochester. The RMS is essential for many of the proposed experiments on short lived and/or low cross section products. This work was supported in part by the U. S. Department of Energy by contracts DE-AC07-76ID01570, DE-FG05-86ER40256, and DE-FG05-88ER40407.

INTRODUCTION

For many years scientists have studied nuclei far off stability, both via their radioactive decays and in-beam gamma-ray spectroscopy. (Several reviews^{1,2,3}) have examples of work relevant to this discussion.) As the regions of known nuclei are pushed out to more neutron deficient nuclei, the cross sections for their production in heavy-ion reactions are so small (\leq a few mb) that they are difficult or impossible to study by traditional in-beam gamma-ray techniques. However, there are important physics questions to be answered by studies of these lighter nuclei. New ways have been sought to identify these nuclei.



ergy-loss absorber to filter RNBs.

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Several groups have responded by recognizing the power of a Recoil Mass Spectrometer (RMS). The Daresbury RMS⁴⁾ is operational (yielding exciting results), the RMS at Legnaro⁵⁾ (LNL), Italy, and the RPMS⁷⁾ at MSU are becoming operational, and Argonne National Laboratory's Fragment Mass Analyzer⁶⁾ (FMA) is being built. These will be discussed briefly. Several spectrometers will not be discussed, but are important to the current work in nuclear physics. MARS⁸⁾ is being built at Texas A&M, and LARA¹⁶⁾ is being built at Munich. The LISE¹⁷⁾ and SPEG¹⁸⁾ spectrometers are in use at GANIL.

The importance of these spectrometers is clear. At the University of Rochester, where the first successful RMS of the current design was developed¹⁵⁾, studies of nuclei far from stability that have production cross sections ≤ 1 mb have been underway for several years. This spectrometer was combined with a segmented neutron detector⁹⁾ and germanium detectors to produce a powerful tool for in-beam spectroscopy. These in-beam gamma-ray-recoil-mass-neutron coincidence studies were the first ones done. As noted by the Daresbury group when these results were first reported¹⁰⁾, the results clearly justified their large effort. Included in the initial studies were the identification, for the first time, of levels¹¹⁾ in ⁷³Br and the extension to higher spins of the known bands in a number of nuclei^{10,11)} in this region. The success of these studies strongly encouraged the expansion of the research with the Rochester RMS.

The rigidity and primary beam rejection abilities of these spectrometers were not designed to cover inverse reactions where one uses a heavy projectile on a light target. The inverse reactions are important when very low cross-section products are to be studied. Kinematic focusing can increase the intensity through the RMS by large factors and the high velocity recoils allow Z identification in a ΔE detector. These factors can be the difference in success and failure in an experiment. Thus, a RMS, which would be connected to the higher energy accelerators at the Holifield Heavy Ion Research Facility and which would be capable of separating products in inverse reactions, has been proposed and funded.

SPECTROMETER DEVELOPMENT

The recoil mass spectrometer described here is designed to analyze heavy nuclear products from a heavy-ion-induced reaction. Several papers^{12,13,14)} give reviews of spectrometers used in nuclear physics, including recoil mass spectrometers. The intent here is not to reproduce those discussions but point to the important factors that make a RMS, and in particular the RMS being constructed for HHIRF, unique in its abilities.

The development of spectrometers has been influenced by several problems that limit identification of the nuclear products. The direct identification of the heavy-ion reaction products by detectors has been

limited by two problems. First, the reaction products and the elastically scattered beam particles usually both lie in the forward direction. For a simple particle detector this gives a high gross count rate that masks the low count rate of the reaction products. The second problem for detectors alone is that for the more massive recoils ($A \geq 100$), the energy resolution of the detectors is insufficient to determine mass using time-of-flight and direct-energy measurements. Highly developed magnetic spectrometers, such as those discussed in the review¹²⁾ by Enge, allow analysis of the heavier fragments by dispersing across the focal plane depending on various properties, but they have inadequate beam rejection at 0° . Devices such as beam filters or velocity selectors have been developed to separate the products of interest from the beam, but they leave the balance of the analysis to downstream detectors which still lack energy resolution for heavy fragments. Only in recent years has there been an effort to combine the beam rejection function and the analysis function into one "recoil spectrometer."

DESIGNS WITH VELOCITY FILTERS

The RPMS at MSU⁷⁾ uses a Wein filter as its first separation element for beam rejection. Following the Wein filter are nine quadrupoles and a dipole (QQQWQQQQQDQQQ). The chromatic aberration in this system is large, and, if completely cancelled, the higher-order terms become a problem. This spreads the line widths to the point that the mass resolution is 100 for 8% and 200 for $\pm 4\%$ in ΔE . This is for a recoil energy of a maximum of 30 MeV/nucleon. The solid-angle acceptance is 1 msr. Although a good system for fragmentation or reaction studies, it is limited for other studies.

The RMS at Daresbury⁴⁾ (QQQWQQQSSDQQQ) is very similar to the MSU design. The velocity selector is separated into two parts allowing the primary beam to be dumped without striking the electric plates. The solid-angle acceptance is about 1 msr, and sextupoles have been added to correct some of the aberrations. The velocity acceptance is $\pm 2\%$ with a mass dispersion of 10 mm/%. The use of an elegant and complex detector at the focal plane enhances the recoil identification, so the low mass resolution is somewhat misleading. For spectroscopy work the target is surrounded by an array of Compton-suppressed germanium detectors. Future plans call for the use of a germanium ball arrangement of twenty detectors called Poly-Tessa. However, the 35 cm distance from the target to the first element may present problems.

ZERO ENERGY DISPERSION DESIGNS

The design of the RMS at Rochester¹⁵⁾, the RMS at Legnaro⁵⁾, and the FMA⁶⁾ at ANL are based upon the same premise: by having a system with no spatial (x/δ_E) or angular (θ/δ_E) energy dispersion, the energy aberrations will not be present or very large for the system. By

having an energy focus, both (x/δ_E) and (θ/δ_E) vanish (δ_E is the fractional energy dispersion $\Delta E/E$). The selection of an electric dipole before and after a magnetic dipole (EDE) is the configuration used to produce an energy focus. The differences between these spectrometers involve how the higher-order corrections are applied and how the intermediate optic constraints result in different focusing and beam rejection.

The Legnaro design (QQESDSE) uses only the two quadrupoles to focus through the entire spectrometer. No intermediate focus is formed. There is an energy focus, but this does not occur with any spatial focus. In the dispersive plane, the focus is quite good, but in the vertical plane the beam size is approximately 6 cm. The second-order corrections that are made are used in part to make the mass-focal plane tilt go to zero. The FMA at Argonne is virtually identical to the Legnaro in that it is a QQEDEQQ configuration. The sextupoles present in the Legnaro design are replaced by a curved poleface boundary on the central dipole. The final quadrupole doublet is used to reduce the vertical beam size to a approximately 1.5 cm.

The Rochester design uses a quadrupole triplet for both entrance and exit to the spectrometer (QQQEDEQQQ). The final triplet both magnifies the mass focus and the dispersion that occurs preceding it and brings about a spatial focus at the focal plane position as well.

The high separation of the reaction products and the elastically scattered beam particles is achieved because of the EDE configuration. The momenta (or p/q) of the beam particles and the fusion reaction products are very close, while their E/q are quite different. The electric deflector disperses based upon energy (E/q), thus allowing beam and reaction product separation to be a maximum.

The high-beam rejection is based on multiple scattering within the spectrometer if the beam strikes the first positive plate of the split electric dipole. For so-called normal reactions (projectile particle lighter than target nuclei), this will always work. If the beam does not strike the first electric dipole plates, this rejection is lost. If the energy of the beam particles (E_b) and the energy of the reaction recoils (E_r) both lie within the energy acceptance of the spectrometer, both types of particles will be focused on the focal plane if the rigidity of the spectrometer is sufficiently high to handle the recoils. Between the two extremes of the E_b much greater than E_r and $E_b \approx E_r$, a very large variety of reactions, focusing conditions, and beam rejection levels can be devised. The net result is that not all or necessarily a large number of reactions, particularly inverse reactions, can be used in a spectrometer of this type.

The rigidity of these spectrometers is relatively low at 6 MeV/q for the Rochester RMS and 9 MeV/q for Legnaro and Argonne machines. Any reaction producing a recoil of -5 MeV/nucleon cannot be studied in these systems (even assuming $Z=N$ and complete stripping).

RMS DESIGN

Careful attention was given to match the RMS to all the beams available from HHIRF accelerators, including those with the highest energy and massive particles for use in inverse reactions. For the tandem, the highest energy for fully stripped nuclei would be about 25 MeV/q for $N=Z$. This shows the need for the high rigidity. For the electrostatic deflectors used in this design, the maximum energy is about 15 MeV/q or 7.5 MeV/nucleon for the $N=Z$ and fully stripped recoils.

"All" inverse reactions must be handled by the RMS and the case of the primary beam reaching the focal plane is not acceptable. This is to say that the high beam rejection must work equally well for the inverse reactions. The kinematic advantage in using the inverse reactions is simply too large to lose for any reaction.

A completely new consideration for the spectrometer was the GAMMASPHERE project. At the time that the idea for GAMMASPHERE was formulated, none of the recoil spectrometers were considered to be important to its mission. After some consideration and the appearance of the early results from experiments at Rochester and Daresbury, the importance of the RMS to GAMMASPHERE was seen. The problem was that none of the existing or proposed spectrometers could operate at the large image or object distances required by GAMMASPHERE without significant loss of performance.

The target distance chosen in the present case is 75 cm. This gives good space for both gamma-ray and neutron detectors. Moreover, this distance with quadrupoles that have an aperture with a diameter of 20 cm still gives a large solid angle of 15 msr. The angular acceptance is not symmetrical, as the dispersive plane has an angular acceptance that is one-third that of the vertical plane. Any slits used to define the solid angle of the spectrometer will be positioned at the entrance to the first quadrupole. The first lens is diverging in the dispersive plane, and the second lens is converging.

A modification to the original RMS design was sought that would allow use of all inverse reactions, have large image and object distances, and meet the the high rigidity needs of HHIRF. The result that is presented here is the spectrometer that is currently being built for use at HHIRF. In developing such a spectrometer, what has also been developed is a very sensitive detector of radioactive beams.

The Momentum Achromat

The general description of the modification is that a momentum achromat has been added to the front of the original RMS design (see figure 1). The optics of the achromat are parallel-to-parallel in the dispersive plane. At the focal plane of the achromat, the center of Q3 (see figure 1), the dispersion is ~ 10 mm/% and the resolving power is

-350 at the full solid angle $\Omega = 25$ msr. The achromat is composed of five quadrupoles and two dipoles. The dipoles are 50° in bend angle with both dispersive in the same direction. The quadrupoles have 20 cm apertures. This achromat precedes a Rochester style RMS (i.e., a split electric dipole) that is basically the original design.

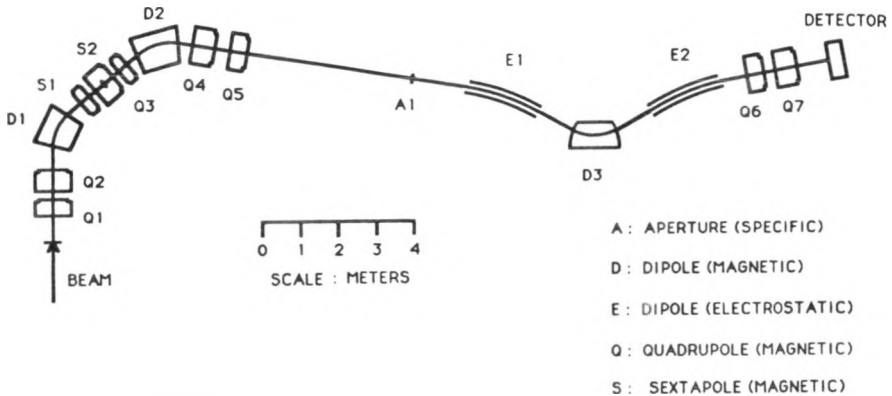


Figure 1. Schematic layout of the RMS. The flight path is to scale.

The achromat is designed such that there is a focus formed between the quadrupoles and the first electrostatic deflector. At this point the beam is completely removed, and an image of the target spot is reformed. Since the distance between the quadrupole and the electrostatic deflector is 6 meters, with this focus occurring 4.5 meters after the quadrupole, the achromat can be used independently of the rest of the RMS. This provides a momentum achromat of rigidity of 25 MeV/nucleon and a solid angle acceptance of 25 msr.

To understand the advantage and power of the addition of the achromat, consider the following example of inverse reactions at 5 MeV/nucleon: ^{156}Gd on ^{12}C . In this case ^{164}Yb is the reaction product of interest. For a RMS of the Rochester style, both the primary beam and the reaction products pass through the first electrostatic deflector unscattered. In the case of the ^{156}Gd on ^{12}C the most probable charge states (47 and 48) of the beam actually result in M/Q ratios that are focused at the focal plane.

Figure 2 shows the beam particles and the reaction products for the ^{156}Gd on ^{12}C case at the focal plane of the achromat. The most probable charge states are shown but without being weighted. That is to say that an equal number of rays are used in each charge state calculation and the figure does not represent the most probable population of each charge state. The reaction products clearly fill the space available at the focal plane while the beam particles are focused into lines.

The beam particles can easily be stopped while the reaction products are passed with only a small loss.

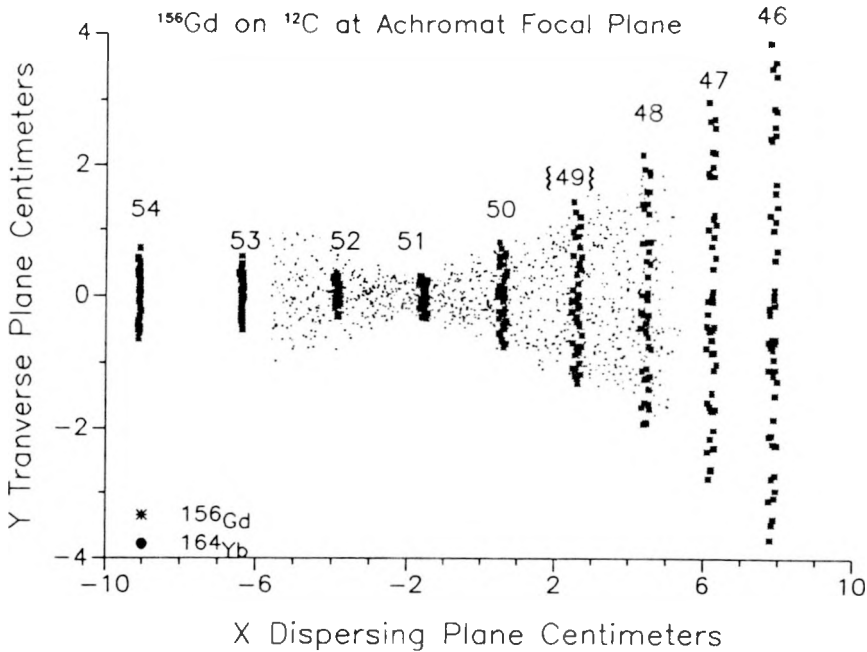


Figure 2. The reaction products and beam particles for the reaction $^{156}\text{Gd}(^{12}\text{C},4n)^{164}\text{Yb}$ at the focal plane the achromat. The most probable charge state for the beam is {49}. A few percent of the ^{164}Yb would be stopped with the beam, but this is a negligible amount.

Electric-Magnetic-Electric Dipoles

The choice made for the present design is an electric-magnetic-electric dipole configuration following the achromat. The physical dimensions of these elements are 20° electrostatic deflectors with a radius of $\rho=600$ cm and a separation of 10 cm. The deflectors are separated by a magnetic dipole with a 50.0° bend angle and a radius of $\rho=140$ cm. The gap of the magnet is 10 cm with the pole faces having a no curvature. The magnet is weakly focusing with shim angles $\alpha=\beta=15^\circ$. The electric deflectors are planned to have a maximum field of 50 kV/cm. This would give $E\rho=30$ MV \approx 15 MeV/q.

Final Quadrupole Doublet

At the exit of the second electric deflector, a triple focus occurs in the dispersive plane. By adding the quadrupole doublet, a vertical

focus can be obtained, and the mass dispersion increased by changing the magnification. These improvements have their price in other aberrations becoming larger, but some of the worst of these can be corrected in the focal plane detector.

Design Summary

In summary, the RMS will have the following characteristics: a) a large acceptance solid angle of up to 15 msr; b) an energy range (ΔE) of 3.5%; c) a mass-to-charge ratio range (m/q) of $\pm 5\%$; d) a good mass resolution ($m/\Delta m \sim 770$ (FWHM) at 10.0 msr and ~ 540 (FWHM) at 15.0 msr; e) a mass dispersion (x/δ_m) of ≈ 43 mm/% ($\delta_m = \Delta m/m$ or the fractional mass deviation in percent); f) a magnification at the focal plane for the reaction products; g) an excellent primary beam rejection ($\geq 10^{13}$ in most cases) at 0° ; and h) a large target to first quadrupole distance of 75 cm. The spectrometer is to have the QQDSQSDQQEDEQQ configuration. The electrical rigidity ($E\rho$) has the design goal of 15 MeV/q. The magnetic rigidity ($B\rho$) for the dipoles is 14 kG-m (1.4 Tm) maximum with corresponding rigidity planned for the quadrupoles to match closely the spectrometer to the accelerators at ORNL.

The total transmission of the spectrometer is also very good with approximately 90% of the reaction products reaching the focal plane at the 10.0 msr solid angle. Continuing efforts to improve the spectrometer will occur during the engineering design phase, and with the establishment of the specifications. Final adjustments and refinements will occur to the spectrometer as fabrication, assembly, and testing occur.

PRODUCTION OF AND USE WITH RADIOACTIVE BEAMS

The RMS will be on a new beam-line at HHIRF. For several reasons that will not be covered here, it is advantageous that this beam-line be an achromat. A target location before this achromat will allow the production of light-mass ions ($A \leq 25$) and the removal of the primary beam. The design is for strongly forward focused reactions (e.g., $^{12}\text{C}+p$) so that 100% of the reaction products will enter the beam-line. These reaction products will also have almost the full beam energy.

Although the actual secondary beam production may be low ($\sim 10^7$ ions/s), so that production from this beam and a target at the primary target position of the RMS will be small, the RMS will allow selection of only the reaction products of interest. The RMS will be the gating condition to allow the study of these very weakly produced species with detectors like GAMMASPHERE at the primary target position. This is a very direct way to study the species of interest to the astrophysics cycles.

The same philosophy can be used for the production of radioactive beams at the primary target location of the RMS. In this case a

secondary beam is filtered by the achromat that comprises the first part of the RMS. The restriction in this case is that for the radioactive beam that is reformed at the focus of the achromat, only normal (non-inverse) reactions can be used, as the EDE part of the RMS will not reject the beam for inverse reactions.

CONCLUSION

The field of heavy-ion physics is developing its own instruments to address the problems and experiments unique to this area. The large solid angle, high beam rejection, large mass dispersion, large energy acceptance, and large mass resolution are combined into a device that has uses in nuclear structure studies, reaction studies, fusion studies, and radioactive beam production. The RMS described here is a new design that will have the capabilities to perform these functions. The rigidity chosen is within the limits of what can be produced today, but the capability of incorporating improvements is present in the design.

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