Rare Beam Production around the Fermi Energy

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The possibilities of rare isotope production around or below the Fermi energy regime are explored in this work. At present, the reaction of a 25 MeV/nucleon ^{86}Kr beam with a ^{64}Ni target has been investigated for the production of neutron-rich nuclides in the region Z=28-36.

In a recent measurement, a 25 MeV/nucleon ^{86}Kr^{22+} beam from the K500 superconducting cyclotron, with a typical current of ~1 pnA, interacted with a ^{64}Ni target of thickness 1.1 mg/cm^2. The reaction products were analyzed with the MARS spectrometer [1] with the Wien filter and the last dipole turned off. The primary beam struck the target at 0^o relative to the optical axis of the spectrometer. The full angular acceptance of 9 msr was employed whereas the momentum acceptance was restricted to 2% to limit the background of primary beam. MARS optics [1] provides one intermediate dispersive image and a final achromatic image (focal plane). At the focal plane, the fragments were collected in a large area (5×5 cm) two-element ()E, E) Si detector telescope. The)E detector was a position-sensitive Si strip detector of 147 :m thickness whereas the E detector was a single-element 950 :m Si detector.

Time of flight was measured between a parallel plate avalanche counter (PPAC) at the dispersive image and a thin plastic scintillator ~1 m before the focal plane. These were separated by a distance of 12.5 m. The PPAC at the dispersive image was also X-Y position sensitive and used to record the position of the reaction products. The horizontal position, along with NMR measurements of the field in the first dipole, was used to determine the magnetic rigidity *∃Δ* of the particles. Thus the reaction products were characterized by an event-by-event measurement of dE/dx, E, time of flight, and magnetic rigidity.

The response of the spectrometer/detector system to ions of known atomic number Z, mass number A, ionic charge q and velocity was calibrated using low intensity primary beam at its nominal energy (25 MeV/nucleon) and also at two lower energies (22 and 24 MeV/nucleon) obtained using Al degraders of known thickness. Also trace amounts of an analog beam of 25 MeV/nucleon ^{129}Xe^{33+}, present in some runs, were used in the calibration procedure.

The relation between magnetic rigidity and horizontal position at the dispersive image was calibrated by observing the position of the primary beam in various charge states as a function of the magnetic rigidity settings of the spectrometer. The magnetic rigidity resolution (FWHM) was about 0.3%. The time-of-flight measurement provided a resolution of about 2 ns (mainly restricted by the scintillator) and resulted in a velocity resolution of about 1%.

The determination of the atomic number Z was based on the measurement of the energy loss of the particles in the)E detector. In a simple)E - E spectrum, the Z lines of the various elements were clearly separated (see also Fig. 1). The ionic charge *q* of the particles entering MARS was obtained from the total energy E_{tot}=)E+E, the velocity and the magnetic rigidity according to the expression:

$$q = \frac{3.107}{931.5}\frac{E_{tot}}{B\rho(\gamma-1)}\beta\gamma \qquad (1)$$

where E_{tot} is in MeV, B*Δ* in Tm, *∃* = *v/c* and *(* = $1/(1 - ∃^{2})^{1/2}$. The measurement of the ionic charge q had a resolution of 0.6 q units for near-projectile fragments (Fig. 1).

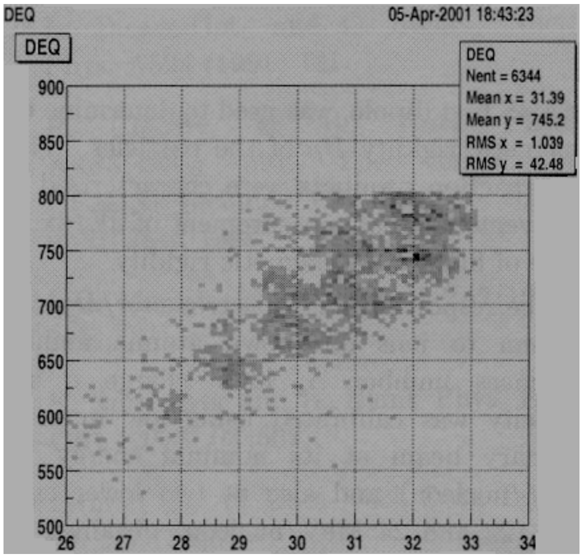

Figure 1: Two-dimensional)E versus q histogram showing separation of Z lines (top is Z=35) and for each Z-line the q's present.

Since the ionic charge must be an integer, we assigned integer values of q for each event by putting windows ()q = 0.6) on each peak of the q spectrum. Using the magnetic rigidity and velocity measurement, the mass-to-charge A/q ratio of each ion was obtained from the expression:

$$A/q = \frac{B\rho}{3.107\beta\gamma} \qquad (2)$$

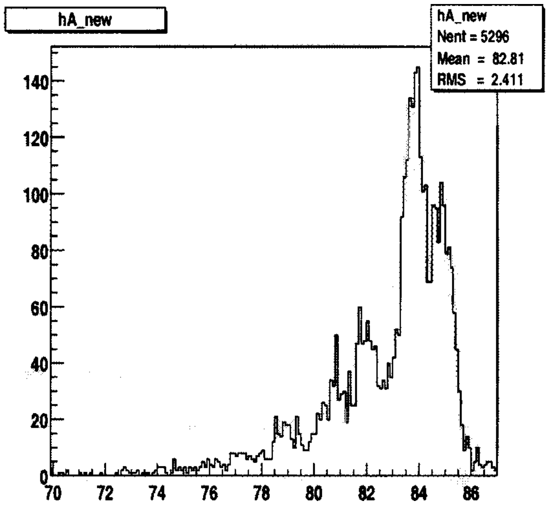

Figure 2: Mass Number A histogram. Mass A=84 is especially prominent at this spectrometer setting.

Now, combining the q determination with the A/q measurement, the mass A was obtained as:

$$A = q_{int} \times A/q \qquad (3)$$

(q_{int} is the integer ionic charge determined as above) with an overall resolution (FWHM) of about 1 A unit (Fig. 2).

The data of the present measurements were taken at B*Δ* settings well above that of the primary beam. This was appropriate for the production of very n-rich nuclides. However, the mass yield curves for each Z were not measured completely--only their n-rich side was covered. The present results are shown in Fig. 3 (solid points) and are compared to reaction simulations appropriate for this energy regime.

The calculations involve a deep inelastic transfer code for the primary interaction stage and a modern statistical evaporation code for the deexcitation stage. At the primary interaction stage, for a given impact parameter (partial wave), the interaction of the projectile and target nuclei are simulated using the Tassan-Got/Stephan model [2] for deep inelastic transfer assuming stochastic nucleon exchange. Following the creation of the primary fragments by this mechanism, the statistical de-excitation of the excited primary fragments was simulated usin GEMINI [3]. This code uses Monte Carlo techniques and the Hauser-Feshbach formalism to calculate the probabilities for fragment emission with $Z\leq 2$. Heavier fragment probabilities are calculated using the transition state formalism of Moretto [4]. Each partial wave distribution was approximately weighted and combined to give the overall fragment A, Z (and velocity) distributions. In Fig. 3, the mass distributions for elements Z=30-35, calculated by this model, are shown as open symbols. The open squares represent total production cross sections, whereas the open circles are obtained by filtering the simulated events by the MARS acceptance in angle and magnetic rigidity. The heavy dashed line is the prediction of the EPAX parametrization of relativistic fragmentation cross sections and is plotted here for comparison. (Note that, in high-energy fragmentation, nucleon-pickup products are not produced-or, at best, are highly suppressed compared to lower energy peripheral collisions).

As we see in Fig. 3, the present data are limited to only the highest masses for each element and are in reasonable agreement with the filtered simulations of the DIT/GEMINI calculation. It should be noted that the results of the filtered simulations are very sensitive to the parameters describing the equilibrium charge state distributions of the fragments. (For the present work, the parametrization of Leon et al. was used [6].)

In the near future, we plan to continue these measurements at an angle away from 0 degrees (to avoid the primary beam) and close to the classical grazing angle of 3.6° for this reaction. Also we plan to use a second PPAC instead of the scintillator to improve the timing and thus the mass resolution.

Using the present preliminary cross section results, and assuming a beam of 100 pnA ^{86}Kr at 25 MeV/nucleon striking a 10 mg/cm^2 ^{64}Ni target, we give two indicative rate estimates for rare beams: First, for ^{84}Se (two-proton removal product, cross section 0.2 mb) the rate is ~ 1.2 × 10^4 particles/see. Second, for the more exotic ^{87}Se (two-proton

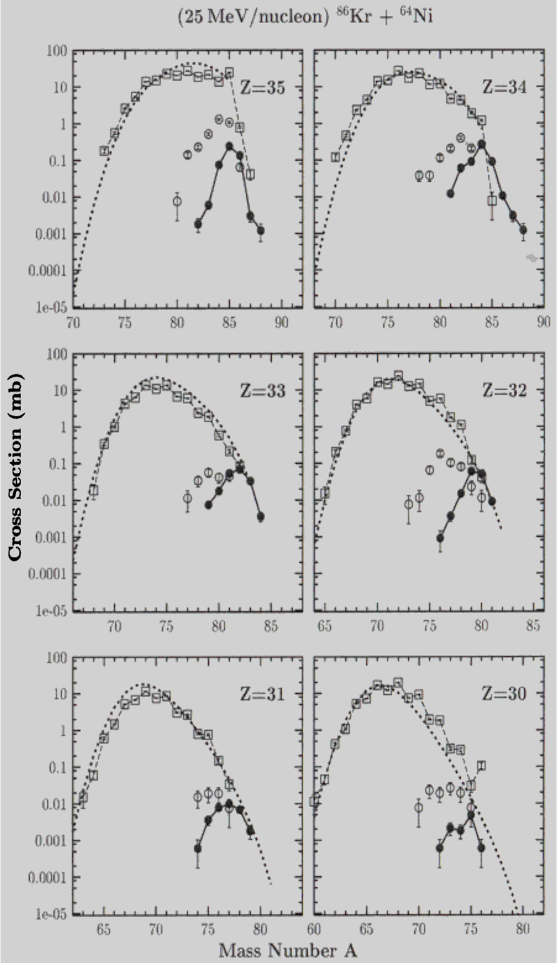

Figure 3: Mass distributions of several elements from the reaction of 25 MeV/nucleon ^{86}Kr with ^{64}Ni. The current preliminary data are shown by full symbols. Open symbols are simulations according to DIT/GEMINI and the dashed line is from the high-energy parametrization EPAX (see text).

removal+three-neutron pickup product, cross section ~ 3*:b*) the rate is about 200 particles/sec. Such yields of rare isotopes may enable a variety of nuclear structure and nuclear reaction studies in the Fermi energy regime.

In general, from the present experimental study and calculations, we see that such reactions, near the Fermi energy, involving nucleon exchange between the projectile and the target, can be utilized as an efficient way to produce very neutron-rich nuclei. Apart from in-flight possibilities, the option of exploiting this type of reaction (in normal or inverse kinematics) at these (or lower) energies for rare isotope production in an IGISOL-type concept is currently explored at Texas A&M.

References

[1] R. E. Tribble, R. H. Burch and C. A. Gagliardi, Nucl. Instr. and Meth. **A285** (1989) 441.

[2] L. Tassan-Got, and C. Stefan, Nucl. Phys. **A524** (1991) 121.

[3] R. Charity, *et al.*, Nucl. Phys. **A483** (1988) 391. The version of GEMINI included modifications made up to July, 1998.

[4] L. G. Moretto, Nucl. Phys. **A247** (1975) 211.

[5] K. Sümmerer and B. Blank Phys. Rev. C **61** (2000) 034607.

[6] Leon *et al.*, At. Data Nucl. Data Tables **69**, 217 (1998).