Neutron-Rich Rare Isotope Production Around the Fermi Energy

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Peripheral reactions between massive nuclei at the Fermi energy domain involve considerable exchange of nucleons. As a result, rare isotopes (either proton-rich or neutron-rich) can be produced with large cross sections. This possibility, in regards to the production of neutron rich nuclides was recently explored in the reaction of neutron-rich ^{86}Kr-beam with a neutron-rich ^{64}Ni-target.

In a recent experiment, a 25 A MeV $^{86}Kr^{22+}$ beam from the K500 superconducting cyclotron, with a typical current of' ~1 pnA, interacted with a ^{64}Ni target of thickness 4 mg/cm^2. The reaction products were analyzed with the MARS spectrometer [1]. The primary beam struck the target at 0^0 relative to the optical axis of the spectrometer. The direct beam was collected in a small square Faraday cup (blocking the angular range 0-1°), while the fragments were accepted in the angular range 1.0-2.7°. 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 (5x5 cm) three-element ($\Delta E_1, \Delta E_2, E$) Si detector telescope. The ΔE_1 detector was a position-sensitive Si strip detector of 63 μm thickness whereas the ΔE_2 and the E detector were single-element Si detectors of 150 and 950 μm, respectively. Time of flight was measured between two PPACs (parallel plate avalanche counters) positioned at the dispersive image and at the focal plane, respectively, and separated by a distance of 13.2 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 of the MARS first dipole, was used to determine the magnetic rigidity $B\rho$ 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 beams of ^{40}Ar and ^{86}Kr at 25 MeV/nucleon.

The determination of the atomic number Z was based on the energy loss of the particles in the first ΔE detector and their velocity. The Z resolution was 0.5 units (FWHM) for near-projectile fragments. The ionic charge q of the particles entering MARS was obtained from the total energy $E_{tot} = \Delta E_1 + \Delta E_2 + E$, 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, $B\rho$ in Tm, $\beta = v/c$ and $\gamma = 1/(1-\beta^2)^{\frac{1}{2}}$. The measurement of the ionic charge q had a resolution of 0.4 units (FWHM). Since the ionic charge must be an integer, we assigned integer values of q for each event by putting windows $(\Delta 1 = 0.4)$ 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:

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

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

$$A/q = \frac{\mathrm{B}\rho}{3.107\beta\gamma} \qquad (3)$$

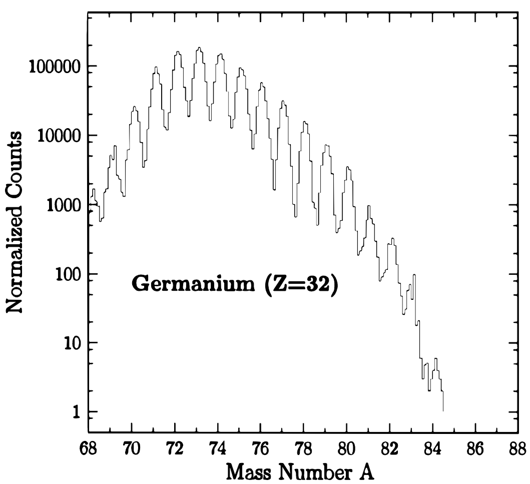

Figure 1: Mass histogram of Germanium (Z=32) isotopes.

(q is the integer ionic charge determined as above) with an overall resolution (FWHM) of about 0.6 A unit (See Fig. 1).

Combination and normalization of the data at the various magnetic rigidity settings of the spectrometer, and summation over all ionic charge states (with corrections applied for missing charge states), provided fragment distributions with respect to Z, A, and velocity. Fig. 1 shows the mass spectrum of Z=32 isotopes in full resolution. Results on the mass distributions (cross sections) of several elements are shown in Fig. 2 (solid points) and are compared to reaction simulations appropriate for this energy regime.

The simulations of the present reaction involve the deep inelastic transfer code of Tassan-Got [2] for the primary interaction stage. Following the creation of the primary fragments, the statistical de-excitation of the excited primary fragments was simulated using the code GEMINI [3]. Each partial wave distribution was appropriately weighted and combined to give the overall fragment Z, A (and velocity) distributions. In Fig. 2, the mass distributions for elements Z=30-35, calculated by this model

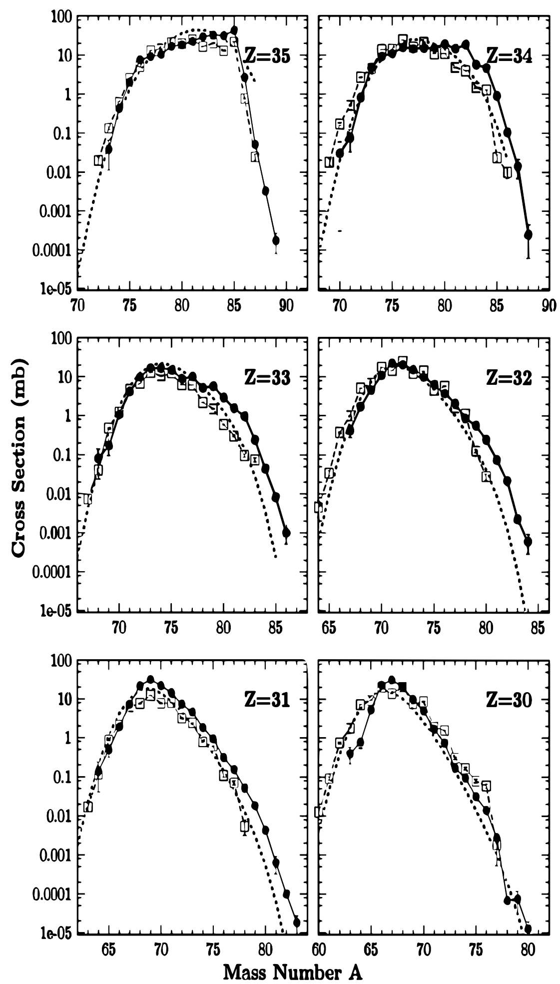

Figure 2: Mass distributions of several elements from the reaction of 25 MeV/nucleon ^{86}Kr with ^{64}Ni. The present data are shown by full circles. Open squares are simulations according to DIT/GEMINI and the dotted line is from the high-energy parametrization EPAX (see text).

are shown as open squares. The heavy dashed lines are predictions of the EPAX parametrization [4] 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. 2, neutron-rich nuclides are produced in substantial yields. For near projectile elements, an enhancement in the production is observed that cannot be described by the simulations. This enhancement takes place at masses close to the beam and, thus, in the very peripheral reactions where the nucleon exchange can be restricted to the neutron-rich surface region of the target nucleus. Further investigation of this finding is currently underway.

In Fig. 3, the gross features of the distributions are described. In Fig. 3a, the mass yield curve is presented. The measured data are given as open symbols. The result of the DIT/GEMINI calculation, filtered by the spectrometer angular and momentum acceptance, is given by the dashed line, whereas the full line gives the total (unfiltered) yield. Using the ratio of filtered to unfiltered calculated yield, correction factors for the acceptance of the spectrometer were obtained as a function of mass and were applied to the measured yield data to obtain the total yield, given by the full symbols in the figure. These correction factors were also employed to obtain total isotope production cross sections (as e.g., given in Fig. 2) from the measured yields. In Fig. 3b, the measured yield distributions as a function of Z (relative to the line of β stability, $Z\beta$) and A are presented as contour lines. The calculated values from DIT/GEMINI are shown as a thick full line (without acceptance cut) and as a thick dashed line (with acceptance cut). The thin dashed line is from the EPAX parametrization [4]. Finally, in Fig. 3c, the velocity vs. mass distributions are given. The present data are shown as contours as in Fig. 3b. The thick full line is from the DIT/GEMINI calculation without acceptance cut and the dashed line is with acceptance cut. In general, we see that the DIT/GEMINI calculations are able to provide a satisfactory quantitative description of the observed gross distributions. Also, it does a fair job in predicting the absolute values of the production cross sections (except for the very n-rich isotopes, as already pointed out).

From a practical standpoint, using the present cross section results, we can make estimates of rare beam rates from intense beams at this energy regime. Assuming a beam of 100 pnA ^{86}Kr at 25 A MeV 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 6 mb) the rate is ~ 3.6 x 10^5 particles/s. Second, for the more exotic ^{87}Se (two-proton removal + three-neutron pickup product, cross section ~ $12\mu b$) the rate is about 800 particles/s. Such yields of rare isotopes may enable a variety of nuclear structure and nuclear reaction studies in the Fermi energy regime.

We have also investigated the production of n-rich isotopes in the reaction ^{124}Sn (21 MeV /nucleon) + ^{124}Sn, where we focused our attention to fragments with Z=20-30. The data analysis of these data is nearly approaching completion. Additionally, we recently completed a systematic set of measurements of the reactions: a) ^{86}Kr (25 MeV /nucleon) on ^{64}Ni and ^{58}Ni and b) ^{86}Kr (25 MeV /nucleon) on ^{124}Sn and ^{112}Sn. From these data we expect to investigate systematically the effect of the target isospin on the production of rare isotopes.

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. We plan to use these reactions to produce and separate rare isotope beams using the Superconducting Solenoid Line, which approaches completion. Apart from in-flight possibilities, a project of exploiting this type of reaction for rare isotope production in an IGISOL-type concept is currently under way at Texas A&M [5].

References

[1] R. E. Tribble, R. H. Burch, and C. A. Gagliardi, Nucl. Instrum. Meth. Phys. Res. A **285**, 441 (1989).

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

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

[4] K. Summerer and B. Blank, Phys. Rev. C **61**, 034607 (2000).

[5] *"A Proposed Facility Upgrade for the Texas A&M University Cycloton Institute,"* accessible at: http://cyclotron.tamu.edu.

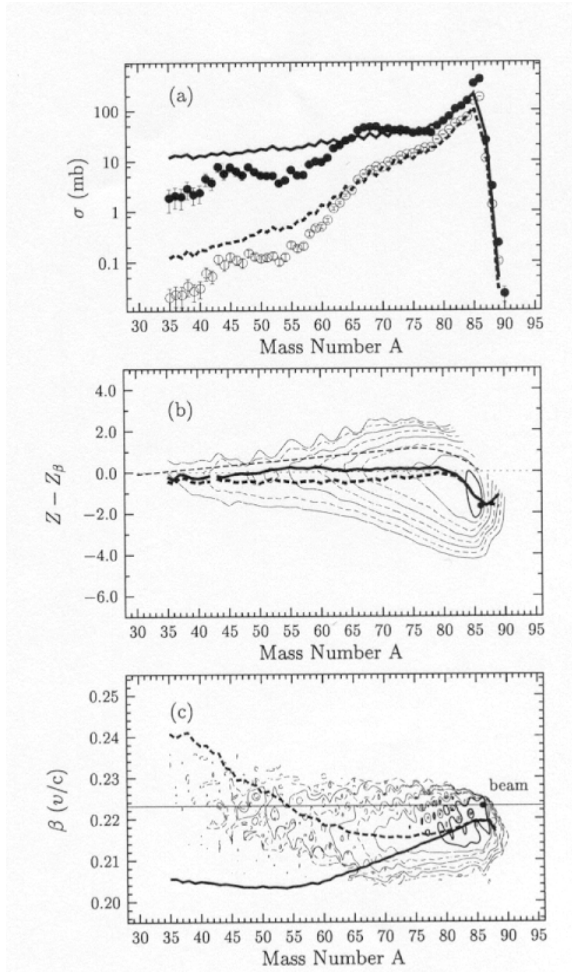

Figure 3: Fragment distributions for the reaction 25 MeV/nucleon ^{86}Kr + ^{64}Ni. (a)-isobaric yield distribution. Data are shown as solid circles (total cross sections) and open circles (with acceptance cut). The full line and the dashed line (with acceptance cut) are the results of DIT/GEMINI (see text). (b)-yield distributions as a function of Z (relative to the line of ∃ stability, $Z_∃$) and A. Successive contours correspond to a decrease of the yield by a factor of 2. The calculated values from DIT/GEMINI are shown as I) thick full line: without acceptance cut and ii) thick dashed line: with acceptance cut. Thin dashed line: EPAX parametrization. (c)-velocity vs. mass distributions. Data are shown as contours as in (b). The thick lines are as in (b). The horizontal full line represents the beam velocity.