In-beam spectroscopy of neutron-rich nuclei: New application of massive-transfer reactions

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In-beam γ-ray spectroscopic studies have been performed using massive-transfer reactions induced by ^{7}Li ions on ^{100}Mo and ^{154}Sm targets to assess the characteristics of the technique and to obtain new spectroscopic information for ^{104}Ru and ^{156}Gd. This method opens new regions of neutron-rich nuclei for spectroscopic studies and provides a favorable population of high-spin states. Massive-transfer reactions are found also to provide an excellent filter for isolating events leading to specific reaction products.

[NUCLEAR REACTIONS ^{100}Mo, ^{154}Sm (^{7}Li, $Xxn\gamma$), $X=p,d,t,\alpha$, $E=48$ MeV. Measured $\gamma(E_X)$, $\gamma\gamma(E_X)$. ^{104}Ru, ^{156}Gd deduced levels.]

Recent studies of heavy-ion reactions using particle-γ coincidence methods show that a nonequilibrium process variously called massive transfer,[1–3] breakup fusion,[4] or incomplete fusion[5] occurs with substantial cross section. In this process, most of the incident heavy ion is captured by and fuses with the target while the remainder is observed as an energetic, usually charged, forward-peaked fragment (FPF). As discussed elsewhere,[3] massive-transfer (MT) reactions are potentially valuable for in-beam spectroscopic studies. In this paper we report on MT reactions of ^{7}Li with targets of ^{100}Mo and ^{154}Sm. The motivation was to assess the experimental advantages attributed to MT such as exit-channel selectivity, the population of high-spin states, and the availability of so-called equivalent beams of exotic neutron-rich projectiles. For example, FPF's of p and α from massive transfer with ^{7}Li are equivalent to ^{6}He and t beams, respectively.

Experiments were carried out using a 48-MeV ^{7}Li beam from the Texas A&M University cyclotron. Two Ge(Li) detectors were placed at $\pm 90°$ relative to the beam. The FPF was observed at 20° with a three-element telescope (detector thicknesses of 300, 1000, and 5000 μm; $\Omega = 40$ msr) which was covered with a 72-mg/cm^2 Al absorber to stop scattered beam. Self-supporting metal targets enriched in ^{100}Mo and ^{154}Sm had thicknesses in the range of 2–5 mg/cm^2. Events consisting of a particle in the counter telescope and a γ ray in one or both of the Ge(Li) detectors were recorded for subsequent off-line analysis.

The excitation energy of the system formed by transfer of a massive fragment to the target is related to the energy of the FPF. Thus it is possible to select an exit channel by setting an energy window on the FPF spectrum. The energy ranges of particle spectra in coincidence with γ rays from the ^{100}Mo target were 10–34, 12–45, and 13–48 MeV for p, d, and t, respectively. The upper limit for protons was determined by detector thickness. The γ-ray spectra coincident with successive $\approx$2-MeV-wide bins across these particle spectra have been analyzed for the relative yields of ^{102,103,104}Ru. All strong lines could be assigned to a Ru isotope. The yields normalized to 100% for each bin are plotted as a function of the energy available for neutron and γ-ray emission (E^*) in Fig. 1. The data in Fig. 1, which are analogous to relative excitation functions for in-beam spectroscopy, show that the yield of a particular product can easily be maximized and isolated from other reaction

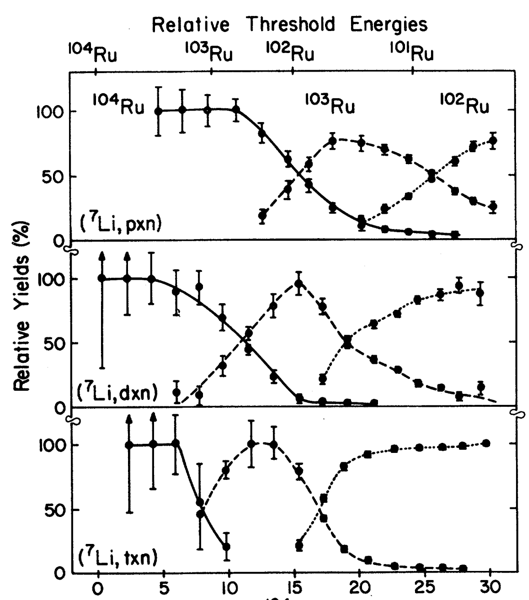

FIG. 1. Relative excitation functions for ^{102,103,104}Ru from ^{100}Mo[^{7}Li, $(p,d,t)xn\gamma$]. Curves are drawn to guide the eye.

products by selecting an appropriate FPF energy window.

Furthermore, if two or more different types of FPF are detected which are isotopic (e.g., *p*, *d*, and *t*), one effectively obtains cross-bombardment information which can be useful in assigning γ rays to particular reaction products. With FPF energy gates selected from Fig. 1, the γ-ray spectra which maximize the yield of ^{104}Ru have been generated (see Fig. 2). Essentially no interfering transitions from neighboring nuclei are observed. Note that the spectra associated with different FPF are not expected to be identical since they result from reactions which probably have different entry-state populations.

The strong transitions in ^{104}Ru at 358.0 and 530.5 keV are known from previous work.[6] Three new strong transitions are indicated in Fig. 2. Also a partial level scheme derived from γ-γ coincidence, relative excitation, and cross-bombardment data along with results of previous studies[6] are shown. Results of a microscopic boson expansion calculation[7] are given for comparison. Additional details and a more complete level scheme will be presented elsewhere.[8]

The bottom spectrum in Fig. 2 shows γ rays resulting from the capture of an α particle by the target. In the α-gated spectra, transitions[6] in ^{103}Tc and ^{157}Eu were found which represent capture of a *t* by ^{100}Mo and ^{154}Sm, respectively. Particle capture to bound states may be a characteristic feature of MT.

With respect to angular-momentum transfer a comparison between MT induced by ^{7}Li and conventional fusion reactions is best assessed for deformed nuclei where high-spin states are better known. For this purpose data were taken with a ^{154}Sm target. We concentrate on levels in ^{156}Gd rather than ^{158}Gd since there is a recent in-beam study[9] of this nucleus using the $(\alpha,2n)$ reaction for comparison. The ground-state rotational band (GSB) in ^{156}Gd was observed to the 16^+ level by MT while states up to 14^+ were reported in Ref. 9. The sum of five γ-γ coincidence spectra gated by member of the GSB in ^{156}Gd is shown in Fig. 3. This spectrum provides evidence that the transition at 583.4 ± 1.0 keV is the $16^+ \rightarrow 14^+$ member of the GSB.

The effect of increasing the mass of the transferred projectile fragment on the intensities of the ^{156}Gd GSB members is shown in Fig. 4. The energies of the FPF gates were chosen to maximize the yield of ^{156}Gd in a manner similar to that discussed above for ^{104}Ru. As one would expect, the intensities of high-spin states in the GSB increases with mass of the transferred fragment from ^{4}He to ^{5}He to ^{6}He transfer [(^{7}Li,$t2n$), (^{7}Li,$d3n$), (^{7}Li,$p4n$) reactions, respectively]. The yields for the $(\alpha,2n)$ reaction[9] which are also shown in Fig. 4 are lower than those for the (^{7}Li,$t2n$) reaction which is the MT equivalent of $(\alpha,2n)$. This enhanced feeding of high-spin states when compared to fusion reactions was one of the early recognized[10] features of MT.

We have demonstrated that in-beam spectroscopy with MT is under some circumstances superior to conventional fusion reactions. With ^{7}Li-induced reactions it is possible to reach nuclei such as ^{104}Ru which were previously less accessible for study. In

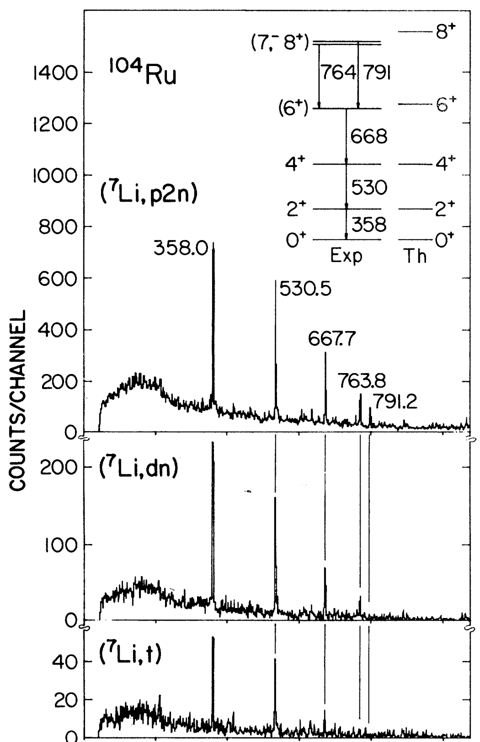

FIG. 2. In-beam γ-ray spectra for ^{104}Ru from ^{100}Mo + ^{7}Li. Partial level scheme shown at upper right. Calculated levels (Th) from Ref. 7.

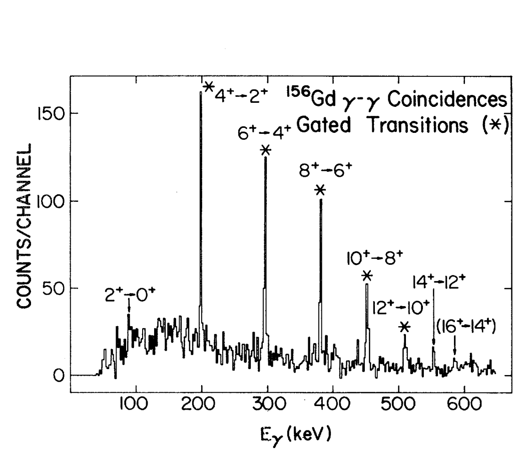

FIG. 3. Summed γ-γ coincidence spectra for ^{156}Gd.

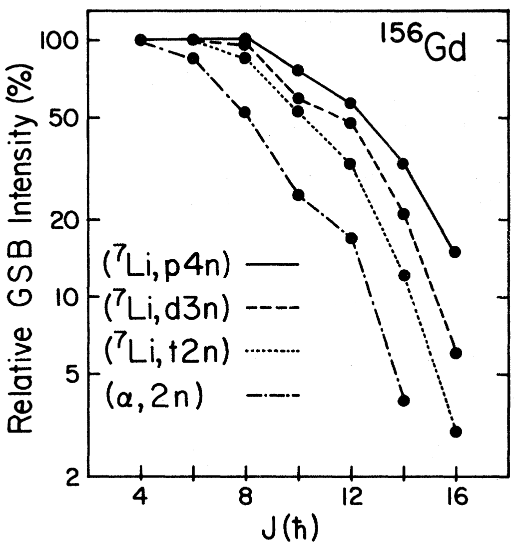

FIG. 4. Comparison of relative GSB intensities in ^{156}Gd from ^{154}Sm + ^{7}Li and from ^{154}Sm(α, 2n) (Ref. 9). Curves are drawn to guide the eye.

addition, one obtains more favorable feeding of high-spin states in ^{156}Gd than is possible with conventional (α, 2n) reactions. Potentially the use of equivalent capture reactions could open yet other areas of neutron-rich nuclei for study.

The use of MT for γ-ray spectroscopy requires particle-γ and particle—γ-γ coincidence measurements with relatively low data rates. Offsetting this is the fact that a single experiment provides a wealth of information. In the present case excitation functions, cross bombardments, and γ-γ coincidences were simultaneously measured for several final products. A different detector arrangement would add γ-ray angular distributions to the list. In addition the γ-ray spectra are extremely free of interference from room background, decay of activities in the target, and transitions from neighboring isotopes. The selectivity of MT is based on the observation of a single FPF for each event and thus does not require a high-geometry particle detector to be effective. Even a small counter telescope placed at a forward angle subtends a substantial fraction of the MT cross section because of the FPF angular distribution. Control of target thickness, beam energy spread, and detector resolution (only $\approx$1 MeV required) is much less demanding than in typical high-resolution particle spectroscopy. Extension of in-beam spectroscopy following MT to higher bombarding energies and to other heavy-ion projectiles appears promising.

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