Population of high-spin states in ^{234}U by heavy-ion-induced transfer reactions

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(Received 24 June 1991)

The one-neutron pickup reaction ^{235}U(^{206}Pb,^{207}Pb)^{234}U at a laboratory energy of 1394 MeV was used to investigate the influence of collective motion at high spin on the single-particle nature of transfer reactions in the actinide region. Deexcitation γ rays were measured using a particle-particle-γ triple-coincidence method. The decay scheme of the reaction products was identified using p-γ-γ coincidences. Rotational states up to $28^+(30^+)$ were seen in ^{234}U. A comparison of rotational state population in both the p–γ-ray singles and the p-γ-γ coincidences is also made between data from the above reaction and from the reaction ^{235}U(^{58}Ni,^{59}Ni)^{234}U ($E_{\rm lab}=325$ MeV). For each system, angular distributions for both inelastic excitation and transfer are presented and one-neutron transfer reaction cross sections as well as grazing angles have been extracted. The reaction cross sections are compared to a recent semiclassical calculation based on Q_{gg} systematics. The present study demonstrates the feasibility of using heavy-ion-induced transfer reactions for spectroscopic studies.

I. INTRODUCTION

The influence of rotational motion at high spin on transfer reactions in various actinide and rare-earth nuclei has been investigated recently using heavy-ion-induced one- and two-neutron transfer reactions near the Coulomb barrier [1–7]. It was found that these reactions selectively populate high-spin states near the yrast line, apparently reducing the importance of the fission decay channel which can be dominant in (HI, xn) reactions on actinide nuclei. The unique feature of heavy-ion-induced transfer reactions is that the deformed nuclei in these regions will be inelastically excited to high-spin rotational states before transfer occurs around the distance of closest approach. This allows study of the influence of the collective rotation on the transfer population patterns.

To investigate this phenomenon we have performed the one-neutron pickup transfer experiments ^{235}U(^{58}Ni,^{59}Ni) ^{234}U and ^{235}U(^{206}Pb, ^{207}Pb) ^{234}U at bombarding energies near the Coulomb barrier. The goal of this work was to compare the high-spin one-neutron transfer populations in order to note any effects of the rotational excitation on the final spin population in ^{234}U. The grazing angle for each reaction as well as the total transfer cross section have been extracted. The cross section for the ^{206}Pb+^{235}U reaction is compared to a prediction of a semiclassical model for transfer reactions involving ^{208}Pb and is found to fit the systematics nicely.

Calculations of the inelastic excitation were also performed using the Rochester semiclassical Coulomb-excitation code GOSIA [8] and compared with the measured angular distributions.

II. EXPERIMENTAL METHODS

The initial experiment was performed at the Holifield Heavy Ion Research Facility using a 325 MeV beam of ^{58}Ni ions impinging on a 300-μg/cm^2 ^{235}U target with a 110-μg/cm^2 Ni backing. The scattered ions were observed in a parallel-plate avalanche counter (PPAC) in coincidence with γ-rays detected using the Spin Spectrometer [9] plus 14 Ge detectors (12 Compton suppressed). Further experimental details can be found in Ref. [3].

The second experiment was done using a 1394 MeV beam of ^{206}Pb ions, from the SuperHILAC at Lawrence Berkeley Laboratory, to bombard a 280-μg/cm^2 ^{235}U target on a 110-μg/cm^2 Ni backing. The target material, obtained from the Isotope Division of Oak Ridge National Laboratory, was enriched to 99.89% ^{235}U with a ^{234}U contamination of 0.034%. The target backing was faced upstream so as to reduce the energy loss and straggling effects of the scattered particles.

Both the recoiling U and the scattered Pb ions were detected by the Rochester six-sided position-sensitive parallel-plate avalanche counter in coincidence with the detection of deexcitation γ-rays by 14 Compton-suppressed Ge detectors. The PPAC's covered an angular range of 300°–360° in ϕ and 15°–111° in θ relative to the beam direction. The beamlike and targetlike fragments were partially resolved by their time-of-flight difference and the measured scattering angles. The γ rays were corrected for Doppler shift on an event-by-event basis using the measured kinematics. No attempt was made to exclude the neutron evaporation events; however, it has been found [3] using the Spin Spectrometer with the ^{58}Ni beam that these events represent only about 20% of the total.

III. RESULTS

The γ-ray spectra coincident with the detection of scattered ions for the ^{206}Pb and ^{58}Ni projectiles are shown in Fig. 1 (upper and lower, respectively) gated on the center-of-mass scattering angles around the grazing regions; i.e., $83° < \theta_{c.m.} < 133°$ for $^{206}\text{Pb}+^{235}\text{U}$ and $128° < \theta_{c.m.} < 153°$ for $^{58}\text{Ni}+^{235}\text{U}$. The spectra are corrected for Doppler shift and are summed over all Ge detectors. As can be seen, the discrete lines in this spectrum are mainly due to the inelastic and one-neutron pickup reaction channels. The half-integral spin values label the transitions within the two signature bands of ^{235}U and the integral spins denote the rotational band transitions in ^{234}U. The signature of the band is labeled by α. All transitions labeled connect states with spin I to states with spin $I-2$. These lines were identified using known transition energies [10,11], their Doppler shifts, γ-γ coincidence spectra, and their angular distributions. The "cleanliness" of the spectrum in part results from the insensitivity of the experimental setup to fission fragments.

Inelastic transitions were seen up to $\frac{53}{2}^- \rightarrow \frac{49}{2}^-$ ($\frac{51}{2}^- \rightarrow \frac{47}{2}^-$) for the $\alpha = +\frac{1}{2}(-\frac{1}{2})$ signature bands. Even though the statistics with the Pb beam are limited, six more units of angular momentum in each band are observed than when using a Ni projectile. The one-neutron transfer lines in ^{234}U are indicated here only for reference. It should be noted that the ^{234}U lines are unresolved from the inelastic lines with increasing spin. This highlights the importance of using the p-γ-γ coincidence technique to resolve doublets.

Shown in Fig. 2 are the p-γ-γ-ray spectra for Pb (upper) and Ni (lower) projectiles, again gated on scattering angles around the grazing region as well as on the $8^+ \rightarrow 6^+, 10^+ \rightarrow 8^+$, and $12^+ \rightarrow 10^+$ γ-ray transitions of ^{234}U. The poorer quality spectrum in the case of the Pb projectile is due to Doppler broadening as well as incomplete mass separation of the beam-like and target-like fragments. Even with poor statistics the $28^+ \rightarrow 26^+$ transition of ^{234}U is seen clearly in the upper part of Fig. 2 and there is a candidate for the $30^+ \rightarrow 28^+$ transition at 510 keV. This is six units of angular momentum higher than that seen in the p-γ-γ plot for the case where the projectile was ^{58}Ni and, to our knowledge, is the highest spin state populated by heavy-ion-induced single-nucleon transfer.

The angular distribution for the $^{58}\text{Ni}+^{235}\text{U}$ one-neutron transfer reaction is shown in Fig. 3. Here the inelastic data ($\frac{21}{2}^- \rightarrow \frac{17}{2}^-$ transition in ^{235}U) are displaced above the transfer data by a factor of four for clarity. The solid line represents a semiclassical Coulomb excitation calculation made with the Rochester code GOSIA. The calculation is arbitrarily normalized to the data (open squares) at $\theta_{c.m.} = 128°$. At larger angles the GOSIA calculation no longer reproduces the data points signaling the opening of channels more complicated than Coulomb excitation. The transfer data (the $8^+ \rightarrow 6^+$ transition in ^{234}U) are denoted by the open diamonds. The angular distribution of the transfer data was fit using a prescription given by Bass [12] which assumes a Gaussian distribution of angular momenta, centered around the grazing value, that contribute to the transfer process. This assumption for the shape of the angular momentum distribution determines the shape of the angular distribu-

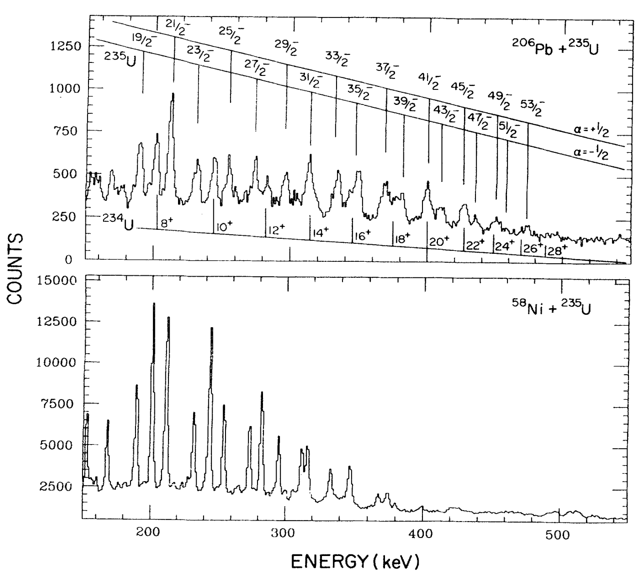

FIG. 1. Particle-gamma spectra for the Pb (upper) and Ni (lower) projectiles. The half-integer spin transitions belong to the two signature bands of ^{235}U. Even integer spins belong to the ground state band of ^{234}U. The latter are shown only for reference. Angle gates have been placed around the respective grazing regions as noted in the text.

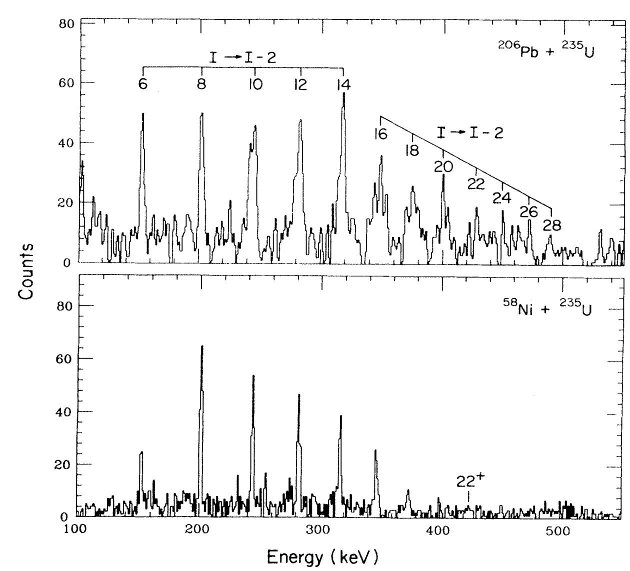

FIG. 2. Particle-gamma-gamma coincidence spectra for the Pb (upper) and Ni (lower) projectiles. The spectra have the same angular gate as in Fig. 1, as well as summed gates on the $8^+ \rightarrow 6^+$, $10^+ \rightarrow 8^+$ and $12^+ \rightarrow 10^+$ transitions of ^{234}U. Note the effect of the incomplete mass separation in the upper panel.

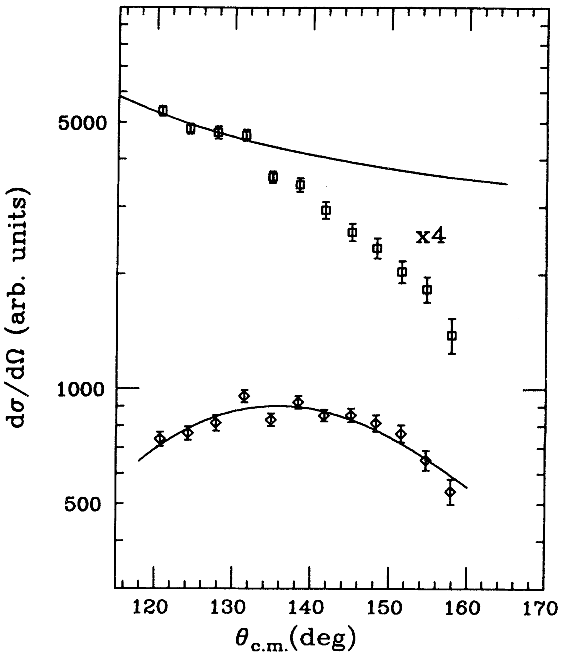

FIG. 3. Angular distributions with a Ni projectile for one-neutron transfer (squares, $8^+ \rightarrow 6^+$ transition in ^{234}U) and inelastic transitions (diamonds, $\frac{21}{2}^- \rightarrow \frac{17}{2}^-$ transition in ^{235}U). The upper solid line is a semiclassical calculation using the code GOSIA which is normalized to the inelastic data at 128°. The lower solid line shows the fit to the transfer data as described in the text.

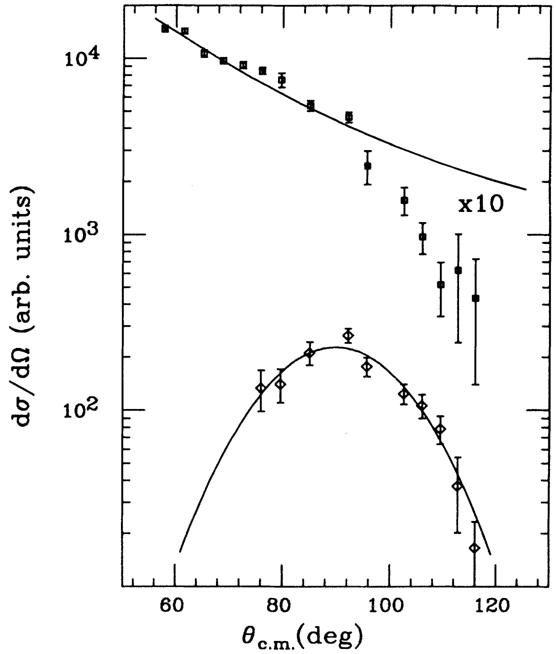

FIG. 4. Angular distributions with a Pb projectile. The symbols are as in Fig. 3. The GOSIA calculation is normalized to the inelastic data at 69°.

tion as well. In Fig. 3 the extracted center-of-mass grazing angle for the ^{58}Ni-induced transfer reaction to ^{234}U is $\theta_{\rm c.m.} \sim 136°$ and the angle-integrated cross section is 194±25 mb. The latter value includes correction for internal conversion.

Figure 4 shows the angular distribution for the ^{206}Pb $+^{235}$U one-neutron transfer reaction to ^{234}U. Here the inelastic data (open squares, again the $\frac{21}{2}^- \rightarrow \frac{17}{2}^-$ transition in ^{235}U) are multiplied by a factor of ten for clarity and the Coulomb excitation calculation is normalized to the data at $\theta_{\rm c.m.} = 69°$. Using the prescription given above, the grazing angle for one-neutron transfer was found to be at $\theta_{\rm c.m.} \sim 90°$. After correction for internal conversion, a value of 372±42 mb is found for the one-neutron transfer cross section. Comparable experimental conditions led to a value of 369±44 mb for the one-neutron cross section for the reaction ^{232}Th(^{206}Pb, ^{207}Pb)^{231}Th in Ref. [6].

In a recent paper, Rehm *et al.* [13] have summarized the available one- and two-nucleon heavy-ion transfer data on ^{208}Pb and have formulated a simple semiclassical model. The model is very successful in predicting few-nucleon transfer cross sections based only on Q_{gg} systematics, binding energies of the initial and final systems, and estimates of the level densities in each system. Nuclear structure considerations are ignored, but these only seem to contribute as fluctuations to the general systematics of the cross sections. The angle- and energy-integrated cross section for one-nucleon transfer is then

$$\sigma(Q_{gg}) = S_p(A) S_t(A) N \left[1 + \mathrm{erf} \left[\frac{Q_{gg} - Q_{\rm opt}}{W} \right] \right] , \quad (1)$$

where S_p and S_t are the single-particle spectroscopic factors in the projectile and target, respectively, Q_{gg} is the ground state to ground state Q value, and $Q_{\rm opt}$ is the optimum Q value (= 0 for neutron transfer). The width of the Q window is denoted by W and N is the normalization constant. With the above data set Rehm finds values for the parameters of $N = 1.73 \times 10^4$ and $W = 5.8$ MeV. The spectroscopic factors are values scaled relative to ^{58}Ni as the projectile and ^{208}Pb as the target and can be found from Fig. 10 of Ref. [13].

This quantity has been calculated for each of our cases [14] and the results are presented in Table I. The experimental data should be interpreted as lower limits since fission may be present after the transfer. The transfer datum for the ^{206}Pb $+^{235}$U reaction fits nicely into the systematics for Pb reactions while the datum for the ^{58}Ni $+^{235}$U reaction falls below by ~40%.

IV. SUMMARY

In conclusion, one-neutron transfer reactions with heavy ions in the presence of strong Coulomb excitation

TABLE I. Comparison between measured one-neutron transfer cross sections and those calculated using the method of Ref. [13].

		σ_{1n} (mb)	
Reaction	Q_{gg} (MeV)	Present work	Ref. [13]
^{235}U(^{58}Ni, ^{59}Ni)	3.7	194(25)	340
^{235}U(^{206}Pb, ^{207}Pb)	1.4	372(42)	383

have been investigated for two systems. In both systems inelastic excitation of ^{235}U and one-neutron transfer to ^{234}U comprised a large part of the reaction cross section. For the Ni + U system the angular distribution is broad and centered about a center-of-mass angle of 136° which corresponds to a distance of closest approach of ~ 15 fm. The angle-integrated cross section for the one-neutron pickup reaction is 194 ± 25 mb. The angular distribution for the ^{206}Pb + ^{235}U system is more sharply peaked with a center at $\theta_{c.m.} \sim 90°$ (a distance of closest approach of ~ 18 fm) and the angle-integrated cross section here is 372 ± 42 mb. The integrated cross section extracted for the ^{206}Pb + ^{235}U reaction compares very well with a recent semiclassical calculation based on Q_{gg} systematics, binding energies of the initial and final systems, and estimates of their level densities.

It was found that the rotational-band population in both Coulomb excitation of ^{235}U and one-neutron transfer to ^{234}U was increased by six units of angular momentum by using a Pb over a Ni projectile. Spin states up to $28^+(30^+)$ were seen in ^{234}U even with poor statistics which is, to our knowledge, the highest rotational state populated by this method. This points to the possibility of detecting even higher rotational states using this method if the γ-γ coincidence rate could be increased. The next generation of detector systems (e.g., Gammasphere [15]) should provide a factor of ~ 100 increase in the p-γ-γ coincidence rate and hence make these studies more attractive, especially in reaching the high-spin states of unstable nuclei in this region.

Support for research at the University of Rochester was given by the National Science Foundation. The U.S. Department of Energy supported the research at the University of Tennessee, while support of research at LBL was given by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

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