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^{48}Ti + ^{104}Ru single-nucleon transfer at the barrier

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Single-nucleon transfer cross sections have been measured for the ^{48}Ti + ^{104}Ru reaction over a large angular range at an energy near the Coulomb barrier. Evidence has been found previously in γ-ray studies for superdeformed shapes in the compound system (^{152}Dy) reached by this reaction. Reaction channels which couple to these shapes may experience interaction time delays, which would be revealed experimentally by broadened angular distributions. Although an enhancement is found in the forward angle ^{49}Ti yields, this enhancement is small and may reflect uncertainties in the analysis.

At energies near the Coulomb barrier, cross sections for one- and two-nucleon transfer reactions are sensitive to the asymptotic behavior of the wave function of the transferred particle(s) and to the structure of the target and projectile nuclei, in a manner which is relatively insensitive to distortion of the elastic Coulomb waves by the nuclear potential.[1] These simplifying features have been exploited extensively in spectroscopic studies with light ion and light heavy-ion reactions, and have recently been utilized in studies with very heavy ions.[2-5] Nucleon-transfer reactions near the barrier with very heavy ions have an additional feature that the interaction can be described in terms of semiclassical Coulomb trajectories. This allows a particularly simple parametrization of angular distributions and excitation functions in terms of the distance of closest approach of the two nuclei.[2,4-6] Deviations from the semiclassical description of two-nucleon transfer[7,8] have been taken as possible evidence for pairing enhanced penetration of the nucleus-nucleus barrier, analogous to the Josephson effect, although this interpretation requires a clear understanding of the role played by excited configurations in the interaction.[7-9]

It has recently been noted that single-nucleon transfer reactions in very heavy systems can also be sensitive to time delays in the interaction.[10] Such delays may result from the two nuclei being trapped in a pocket of their mutual interaction potential and this has been suggested[11] as a possibly contributing cause for the narrow widths of lines observed in the spectra of positrons emitted in collisions of some massive systems.[12] A measurement[13] of sub-Coulomb transfer in ^{238}U + ^{238}U collisions shows evidence which might support the idea of interaction times which are long compared to those of Coulomb trajectories, although the authors note that uncertainties remain concerning the possible role of deformation in this system.

In the present measurement we have looked for evidence of a time delay in the ^{48}Ti + ^{104}Ru reaction (reaching the compound system ^{152}Dy) by measuring an angular distribution for the single-nucleon transfer cross section near the Coulomb barrier. Recent γ-ray studies[14] have revealed a rotational band corresponding to a superdeformed shape in ^{152}Dy and it has been postulated that the relative stability of this shape arises from a shell-stabilized secondary minimum in the ^{152}Dy potential energy surface,[15,16] a situation analogous to that responsible for fission isomers in the actinides. If the ^{48}Ti + ^{104}Ru channel couples to the deformed ^{152}Dy configuration, the expected effect would be to prolong the interaction time and thus lead to an enhanced forward-angle transfer yield. The extreme case of a time delay comparable to the rotation period of the dinuclear complex would result in a $1/\sin\theta_{\mathrm{c.m.}}$ component to the cross section. This has been suggested[17] to occur in the much lighter ^{28}Si + ^{28}Si system where pronounced resonance structures are found in large-angle elastic and inelastic scattering yields[18] and related structures have also been found in ^{40}Ca(^{16}O,^{28}Si)^{28}Si transfer yields.[19]

The measurement consisted of bombarding a carbon-backed ^{104}Ru target (80 μg/cm^2) with a 161.8 MeV ^{48}Ti beam produced at the Argonne National Laboratory ATLAS facility. Taking $V_{\mathrm{Coulomb}} = e^2 Z_1 Z_2 / R_{\mathrm{int}}$ with $R_{\mathrm{int}} = 1.16(A_1^{1/3} + A_2^{1/3} + 2)$ fm, then $E_{\mathrm{c.m.}}/V_{\mathrm{Coulomb}} = 0.95$, where $E_{\mathrm{c.m.}}$ is the center of mass energy. Reaction products emerging at angles $35° \le \theta_{\mathrm{lab}} \le 115°$ were analyzed in an Enge split-pole spectrometer. Mass identification was achieved by measuring the time of flight of the reaction products between a channel-plate detector located in the scattering chamber (before the magnet) and a position-sensitive avalanche counter located at the focal plane of the magnet. A second time-of-flight measurement was achieved using the rf time structure of the ATLAS beam instead of the channel-plate detector signal, and a second focal-plane position measurement was obtained for $\theta_{\mathrm{lab}} \le 90°$ from a proportional counter with position wire readout located behind the avalanche counter. With the background suppression possible using the redundant position and timing information, clear separation of the single-nucleon transfer from the elastic scattering yield was achieved for $\sigma_{1n}/\sigma_{\mathrm{elas}} \ge 2 \times 10^{-5}$. For smaller transfer probabilities charge exchange processes in the residue gas of the spectrometer resulted in background counts which masked the transfer yields. Although the nuclear charge was not measured, the comparatively large negative Q values for proton transfer reactions should result in a suppression of these channels relative to neutron transfer. The two-nucleon transfer cross sections were found to be relatively weak and a reliable angular distribution could not be extracted.

In deriving cross sections, the transfer yields were normalized to the elastic yields with the same atomic charge states and obtained at the same time in the focal plane detector. Differences in the relative charge state population of the transfer channels and the elastic channel are expected to be negligibly small, with the charge-state distribution of the reaction products reset in the carbon foil at the entrance to the spectrometer (part of the channel-plate timing system). In general, the most probable charge state and two adjacent charge states were detected simultaneously at the focal plane. It was not possible to resolve the elastic and inelastic scattering yields, and the sum of these yields was used in the normalization procedure.

The absolute cross section normalization was obtained by calculating the cross sections for the elastic and inelastic channels using the coupled-channel code PTOLEMY[20] with a potential previously used in Ni + Ni studies.[21] (The deterioration during the course of the experiment of a monitor detector located in the scattering chamber prevented the measurement of an independent elastic scattering angular distribution.) The elastic and lowest lying 2^+ and 3^- states for both the target and projectile nuclei were included in the calculation. Uncertainties in this normalization procedure are believed to be small ($< 15\%$) because of the proximity to the Coulomb barrier.

The angular distribution obtained for the ^{104}Ru(^{48}Ti,^{49}Ti)^{103}Ru reaction is shown in Fig. 1. Since individual transitions could not be resolved, the inclusive cross section is shown. The average Q value for the reaction was found to be $\langle Q \rangle \simeq -2.5$ MeV, corresponding to a total excitation energy of 1.7 MeV in the final fragments. The most forward angle point (corresponding to $\theta_{\text{lab}} = 35°$) gives only an upper limit on the cross section which is set by background counts corresponding to charge exchange processes in the magnet as discussed above.

To test how well the measured angular distribution can be described by standard models (i.e., without additional interaction time delay), a distorted-wave Born approximation (DWBA) estimate was obtained using the code PTOLEMY,[20] again using the Ni + Ni potential of Ref. 21. Individual calculations were done for transitions to the ^{49}Ti ground state ($1f_{7/2}$) and first excited state (1.382 MeV, $2p_{3/2}$) coupled to the low-lying levels of ^{103}Ru ($E^* < 1$ MeV) using spectroscopic strengths from light-ion studies.[22,23] Angular distributions calculated for different transitions were summed. The resulting DWBA distribution is shown in Fig. 1, where the calculated distribution has been scaled up by a factor of 1.7 for comparison with experiment. Although the DWBA calculation underestimates the magnitude of the transfer process, this can reasonably be attributed to the restriction

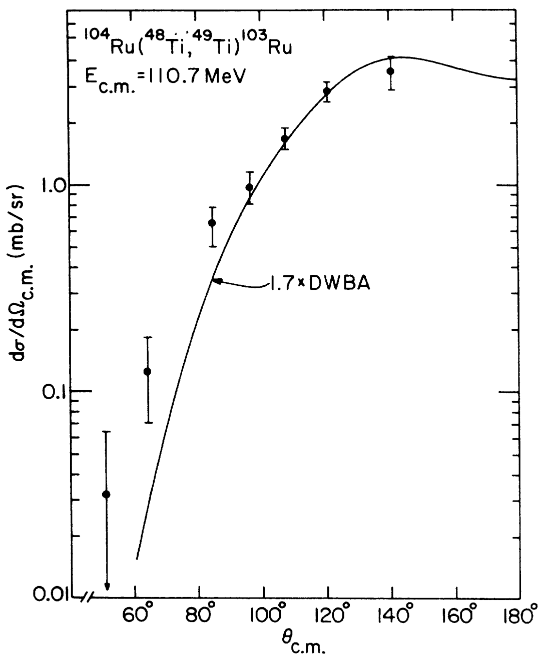

FIG. 1. Angular distribution for the ^{104}Ru(^{48}Ti,^{49}Ti)^{103}Ru reaction at $E_{\text{c.m.}} = 110.7$ MeV. The curve shows the results of the DWBA calculation discussed in the text.

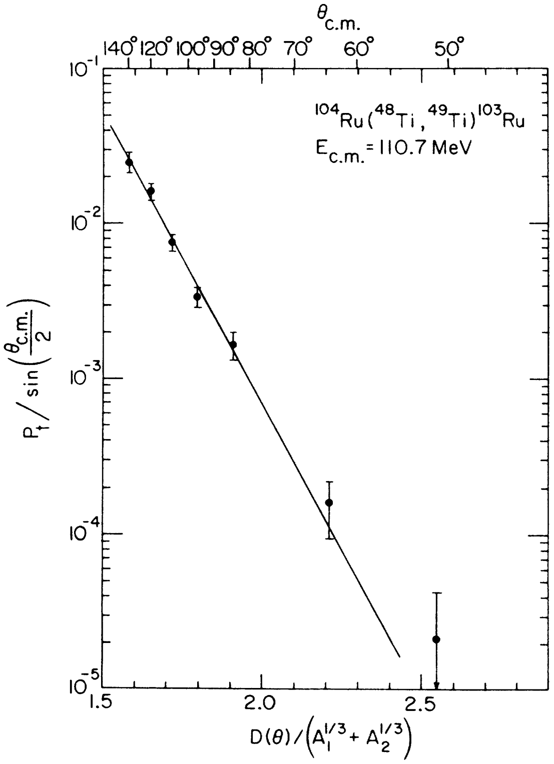

FIG. 2. Plot of the transfer probability as a function of the reduced distance of closest approach. The curve is the best fit to the data using the semiclassical expression described in the text.

of the calculation to low-lying states in ^{103}Ru. Including the full spectroscopic strength for the $^{103}\mathrm{Ru}(2d_{5/2})$ configuration, for example, results in a total cross section comparable to that observed experimentally. The DWBA calculation is found to reproduce the experimental behavior rather well with only a slight indication of an enhanced forward-angle yield. It also appears to be a common feature of DWBA calculations for heavier systems that narrower angular distributions are predicted than observed.[21,24,25]

An alternative way of characterizing these data is in terms of a semiclassical description[1] of the transfer process. For heavy systems with large values of the Sommerfeld parameter, the interaction of two nuclei can be described in a particularly simple form. The transfer probability P_t ($=\sigma_{1n}/\sigma_{\text{Ruth}}$) is related to the distance of closest approach between the two colliding nuclei by

$$P_t \propto \sin\left[\frac{\theta_{\text{c.m.}}}{2}\right]\exp[-2\alpha D(\theta)] ,$$

where $D(\theta)$ denotes the distance of closest approach between the nuclei

$$D(\theta_{\text{c.m.}}) = \frac{n}{k}\left[1+\csc\left[\frac{\theta_{\text{c.m.}}}{2}\right]\right] ,$$

n is the Sommerfeld parameter, and k is the entrance-channel wave number. The slope parameter α can be expressed in terms of the effective binding energy of the transferred nucleon B_{eff} by $\alpha=(2B_{\text{eff}}m\hbar^{-2})^{1/2}$. A plot of the angle scaled transfer probability $P_t/\sin(\theta_{\text{c.m.}}/2)$ as a function of the reduced distance of closest approach

$$[D(\theta_{\text{c.m.}})/(A_1^{1/3}+A_2^{1/3})]$$

is shown in Fig. 2. The best fit to these data using the above expression for the transfer probability gives $\alpha=0.52$ which corresponds to an effective binding energy of 5.6 MeV. This is somewhat weaker binding than estimated on the basis of the average of the ground state binding energies reduced by the average observed excitation energy ($B_{\text{eff}}^{\text{estimate}}=8.5-1.7$ MeV $=6.8$ MeV). Excluding the two smallest angle points [corresponding to the largest $D(\theta)$ values] in the fit for the slope parameter results in $\alpha=0.54$ and $B_{\text{eff}}=6.2$ MeV, again somewhat smaller than expected. Although a reduced value of B_{eff} is consistent with a longer interaction time, the present reduction is small and may rather indicate an inadequacy in the assumptions[1] of the semiclassical picture.

In summary, we have measured an angular distribution for the $^{104}\mathrm{Ru}(^{48}\mathrm{Ti},^{49}\mathrm{Ti})^{103}\mathrm{Ru}$ reaction at an energy close to the Coulomb barrier. This distribution has been discussed in terms of a DWBA calculation and a semiclassical description with both analyses indicating a small enhancement of the measured forward-angle yield. This enhancement is not dramatic and understanding its significance will require further, systematic measurements. No evidence was found to suggest a resonance scattering process through highly deformed ^{152}Dy shapes, where an interaction time delay comparable to the rotational period might be possible.

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