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(^{16}O, ^{15}N) Reactions on *fp*-Shell Target Nuclei*

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A systematic investigation of the one-proton transfer reaction (^{16}O, ^{15}N) on *fp*-shell target nuclei has been performed at bombarding energies near and above the Coulomb barrier. Angular distributions are qualitatively explained in terms of semiclassical theories. Peak cross sections show a marked Q dependence due to the importance of angular-momentum matching. The main features of the studied reactions are well reproduced both qualitatively and quantitatively by finite-range distorted-wave Born-approximation calculations.

Heavy-ion–induced reactions on medium-weight nuclei involving the transfer of one or more nucleons have been of much interest recently.[1-6] These investigations promise new insight into few-nucleon correlations and perhaps information on core-excited states. In order to employ these reactions with confidence as a spectroscopic tool, a quantitative understanding of the reaction mechanism is imperative. To this end we have performed a systematic study of ^{16}O-induced transfer reactions on *fp*-shell nuclei at energies near and above the Coulomb barrier. In this Letter we present only the data and analysis for the (^{16}O, ^{15}N) one-proton transfer reaction, which is the least complicated of the reactions studied and is directly comparable with the analog (^{3}He, d) reaction. Semiclassical theories have been used to understand the qualitative features of the reaction mechanism; and finite-range distorted-wave Born-approximation (DWBA) calculations provide a good quantitative description of the data, thus demonstrating the applicability of DWBA theory to these reactions.

The experiments were performed with the Argonne National Laboratory tandem Van de Graaff accelerator. Enriched targets, typically 100 μg/cm^2 thick, were bombarded with 42.0-, 48.0-, and 56.0-MeV ^{16}O ions. The emerging particles were detected and identified by four ΔE-E counter telescopes, each consisting of a ~15-μm and a ~200-μm silicon detector, mounted at 10° intervals in the 70-in. scattering chamber. The resultant mass and energy signals were directly stored in the external memory of an ASI-210 online computer. The overall energy resolution, typically ~250 keV, was due in part to target thickness and kinematic broadening.

In the following we present a selection of the data, mainly on even-A calcium isotopes. Figure 1 shows angular distributions obtained at $E(^{16}\mathrm{O}) = 42$, 48, and 56 MeV for the ^{48}Ca(^{16}O, ^{15}N) reaction to the $\frac{7}{2}^-$ ground state and to the most prominent $\frac{3}{2}^-$ excited state of ^{49}Sc. Angular distributions at $E(^{16}\mathrm{O}) = 48$ MeV for the corresponding states for each of the final Sc nuclei are shown in Fig. 2.

The simple shapes of the observed angular distributions are in qualitative agreement with well-known[7] semiclassical concepts based on localized Coulomb trajectories for the colliding ions. In this picture the cross section increases with angle because of the increasing overlap between

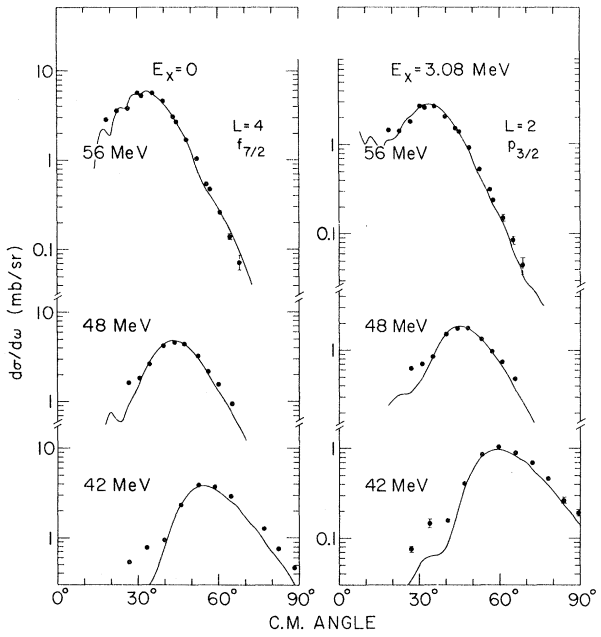

FIG. 1. ^{48}Ca(^{16}O,^{15}N)^{49}Sc angular distributions at E_{lab}=42, 48, and 56 MeV for transitions to the $\frac{7}{2}^-$ ground state and the lowest $\frac{3}{2}^-$ excited state. The L values denote the total angular momentum transfer. The solid curves have been calculated with the finite-range DWBA. The same overall normalization was used at all three energies, though a different normalization was applied for each transition.

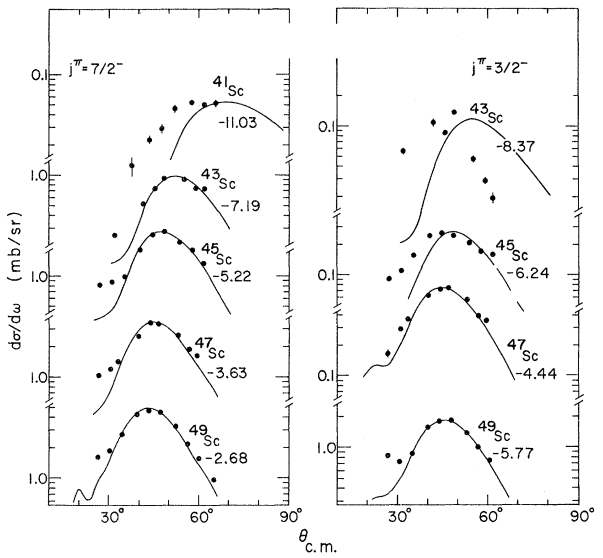

FIG. 2. Ca(^{16}O,^{15}N)Sc angular distributions at E_{lab} =48 MeV for transitions to the $\frac{7}{2}^-$ ground state and to the most prominent $\frac{3}{2}^-$ state. The numbers indicate Q values of the individual transitions. The DWBA calculations (solid curves) are individually normalized to the data.

the two nuclei, reaches a maximum which defines an "interaction radius" for the contact collision, then falls at backward angles because of increasing absorption. Transfer reactions should thus peak at more backward angles when they involve lower incident energy, more negative Q values, and a target nucleus of larger Z—as is indeed observed. The analysis of our data gives a consistent interaction radius $R = r_0(A_1^{1/3} + A_2^{1/3})$, where $r_0 = 1.75$ fm, in good agreement with previous investigations.[7]

The peak cross section for a fixed Q is not observed to change much with incident energy, as is illustrated (Fig. 1) for the transitions leading to ^{49}Sc, which implies that the semiclassically defined interaction radius is a useful concept even at energies above the Coulomb barrier. However, as can be seen from the transitions leading to the other Sc isotopes, the peak cross section does depend strongly on the Q value of the reaction: The more negative the Q value, the smaller the cross section. This reduction seems to result mainly from the momentum mismatch in the entrance and exit channels at very negative Q values, and this mismatch can be very severe for heavy ions because of the high angular momentum involved and the sharp surface localization of the reaction. Optical-model calculations indicate that although the ground-state transition in ^{49}Sc is nearly perfectly matched ($Q = -2.51$ MeV), the mismatch can be as much as 15 units of angular momentum in ^{41}Sc ($Q = -11.1$ MeV). Of course a mismatch is also expected for very positive Q values.

DWBA calculations were performed with the program RDRC.[8] This program treats finite-range effects by expanding the form factors of projectile and target in a harmonic-oscillator basis, but recoil effects are neglected. However, this shortcoming is minimized in calculations of the one-proton transfer reaction. Strongly absorbing heavy-ion potentials (V =100 MeV, W =40 MeV, r_0 =1.22 fm, a =0.49 fm) were employed in the analysis since they obviate the need of a cutoff radius. These parameters, which are similar to those of Voos, von Oertzen, and Bock,[9] were obtained by fitting the ^{48}Ca+^{16}O elastic-scattering data of Strohbusch *et al.*[10] Since there are no available data on ^{15}N scattering from *fp*-shell nuclei, the same parameters were used for both the entrance and exit channels except that the diffuseness for the ^{15}N scattering was arbitrarily increased from 0.49 to 0.60 fm in order to yield a best fit to the angular distributions for

^{48}Ca(^{16}O, ^{15}N)^{49}Sc at 48 MeV. (The peak in the calculated angular distribution was found to shift to forward angles with increasing diffuseness.) The proton parameters ($r_0 = 1.2$ fm, $a = 0.65$ fm) for the calculation of the bound-state wave function are those used by Hiebert, Newman, and Bassel[11] for the (^{3}He, d) analysis.

The results from the DWBA calculation are included as solid curves in Figs. 1 and 2. In Fig. 1, different overall normalizations are used for the transitions to the $\frac{7}{2}^-$ and $\frac{3}{2}^-$ states, although the normalization employed for each state was the same at all three incident energies; in Fig. 2 the individual curves are normalized to the data. The DWBA calculations in Fig. 1 are seen to give an excellent fit to the data for ^{48}Ca(^{16}O, ^{15}N)^{49}Sc and to predict correctly the variation of the cross sections with incident energy. Good overall agreement is also obtained for the transitions to the other scandium isotopes (Fig. 2), although the calculations fail to reproduce the experimental peak positions for the most negative Q values. This might be expected since DWBA calculations with light projectiles often have difficulties in the case of a large momentum mismatch.

In Fig. 3 we show the Ca(^{16}O, ^{15}N) "reduced" peak cross sections—the experimental values divided by the proton spectroscopic strength $(2J+1)C^2S$ from (^{3}He, d) experiments[12]—plotted as a function of the Q value. The strong Q dependence displayed in this way is well reproduced by the DWBA calculations (solid curves). Both theoretically and experimentally, the optimum Q value determined for each of the two final states is close to that which matches the angular momentum in the ingoing and outgoing channels. The fact that the cross section for low L transfer is the one most rapidly affected as Q deviates from the optimum value also appears to be a consequence of angular-momentum–matching restrictions. Thus, Fig. 3 confirms that only at conditions of mismatch is high L transfer favored over low L transfer; and since sensitivity to angular momentum is an inherent feature of heavy-ion reactions, similar strong Q-dependent effects —although not as directly demonstrable as here —should exist for all such reactions.

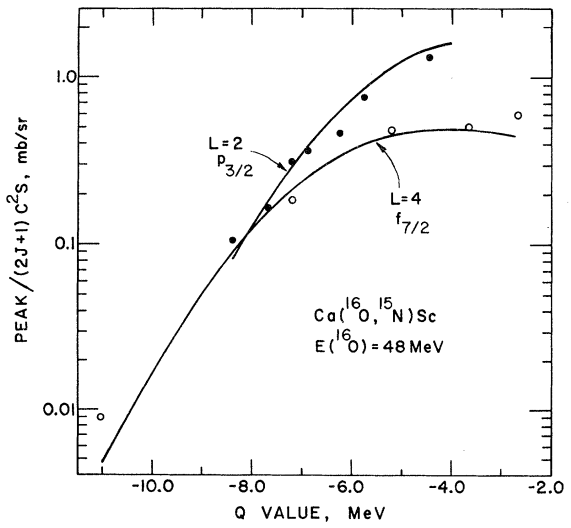

FIG. 3. Experimental peak cross sections divided by the corresponding (^{3}He, d) spectroscopic factors for the $f_{7/2}$ ground state and for prominent $p_{3/2}$ states. The solid curves are the DWBA peak cross sections multiplied by an overall normalization factor $N = 1.5$.

The absolute magnitudes of the DWBA cross sections (Fig. 3) have been obtained by assuming a spectroscopic factor of 2 for proton pickup from the ^{16}O projectile and an overall normalization factor of 1.5. The overall normalization required will of course depend on the parameters used in the calculation, particularly on those entering into the bound-state well. With the normalization $N = 1.5$, Fig. 3 shows that spectroscopic factors extracted from the (^{16}O, ^{15}N) data generally agree to within 30% with those from the analogous (^{3}He, d) reaction (for values of C^2S which range from 0.1 to 1.0).

We find also that the DWBA calculations with the same parameters as for the Ca isotopes give a good description for heavier targets. Figure 4 compares the DWBA angular distributions calculated with the same parameters as for the Ca iso-

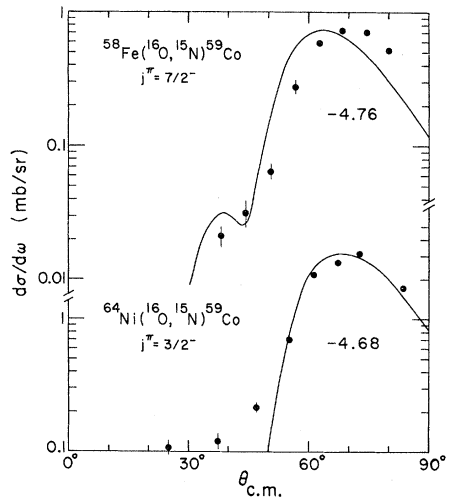

FIG. 4. DWBA fits to the experimental ^{58}Fe(^{16}O, ^{15}N)^{59}Co and ^{64}Ni(^{16}O, ^{15}N)^{65}Cu angular distributions.

topes with the experimental data from the (^{16}O, ^{15}N) reactions on ^{58}Fe and ^{64}Ni. The good agreement also includes the spectroscopic factors determined with the same normalization as before. For ^{58}Fe, a spectroscopic factor 0.28 from the (^{16}O, ^{15}N) reaction compares with 0.17 from the (^{3}He, d) reaction[13]; for ^{64}Ni the corresponding values[14] are 0.81 and 0.80, respectively.

In conclusion, the reaction mechanism appears to be well understood, both qualitatively in terms of a semiclassical picture and quantitatively with the finite-range DWBA theory. This should provide a useful starting point for the understanding of the more complex many-nucleon transfer reactions.

We are grateful to Professor W. R. Tobocman for making his DWBA program RDRC available to us. We also thank W. C. Wilkin and J. Kulaga for their assistance in the data analysis.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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Possible Variation of the Gravitational Constant over the Elements*

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We re-examine the theory and data of the Kreuzer experiment to measure the relative difference $\Delta\kappa/\kappa$ in the gravitational constant κ between two elements. Significant errors appear in the statistical analysis of Kreuzer which vitiate his conclusions. The upper bound for F and Br from his experimental data correctly becomes $(\Delta\kappa/\kappa)_{max} = 2\times10^{-2}$, about 10 times the limit already set on the general vairation of κ over the elements by direct use of a Cavendish balance.

Kreuzer[1,2] has conducted an experiment in which a plastic cylinder submersed in a mixture of organic liquids of nearly the same density was moved slowly past the arms of a Cavendish balance. This balance was used as a null detector to supply an equivalent imbalance signal proportional to a counterbalancing torque. By varying the temperature of the system, the differential density produced between the solid and the liquid was measured to determine the point of neutral buoyancy of the cylinder. At this temperature, the masses of the plastic cylinder and displaced fluid are equal, and any signal from the Cavendish balance as the cylinder is moved past its arms implies a difference $\Delta\kappa$ in the Newtonian gravitational constant κ for the chemical elements in the cylinder and the liquid.

The purpose of this work is to show that the very low value 5×10^{-5} as an observational upper bound on $\Delta\kappa/\kappa$ for fluorine and bromine, reported by Kreuzer, is invalid on the basis of his experimental data. This incorrect result has been widely used to infer conclusions in gravitational phenomenology, which are necessarily questionable,