Selective Excitation of One-, Two-, and Three-Nucleon Configurations in Transfer Reactions Induced by Heavy Ions

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A study is reported of one-, two-, and three-nucleon transfer reactions induced by 114-MeV ^{12}C ions on targets of ^{12}C, ^{16}O, and ^{40}Ca. A prominent feature is the extreme selectivity of the reaction mechanism in exciting simple one-, two-, and three-particle stretched configurations in the residual nuclei.

At the present time there is a growing emphasis on the study of new types of correlation in nuclear motion through multinucleon transfer reactions induced by heavy ions.[1] In this Letter, we show that when transfer reactions are initiated by heavy ions at beam energies of 10 MeV/nucleon on light- and medium-mass nuclei, they show a remarkable selectivity in exciting simple one-, two-, and three-nucleon configurations, a feature which can be of great value in developing and checking theoretical models.

A $^{12}C^{4+}$ beam of intensity 50 nA and energy 114 MeV from the variable energy cyclotron of the Harwell Atomic Energy Research Establishment was used to bombard 150-μg/cm^2 targets of calcium oxide on 30-μg/cm^2 backings of ^{12}C. The reaction products were identified in a telescope of solid-state detectors, using power-law identifiers[2] and a modification[3] of the technique[4] of double identification. As Fig. 1 shows, the technique permits excellent separation of heavy ions from ^6Li to ^{13}C, although each ion covered an energy range of 40 MeV approximately. Energy spectra were accumulated for the reactions (^{12}C, ^{12}C), (^{12}C, ^{11}C), (^{12}C, ^{11}B), (^{12}C, ^{10}C), (^{12}C, ^{10}B), (^{12}C, ^{10}Be), and (^{12}C, ^9Be) on targets containing ^{12}C, ^{16}O, and ^{40}Ca at several angles between 7° and 35°. These reactions produced thirty clearly identifiable particle groups, permitting an energy calibration accurate to 100 keV. The differential cross sections for reactions on ^{12}C at forward angles are of the order 1 mb/sr for single-nucle-

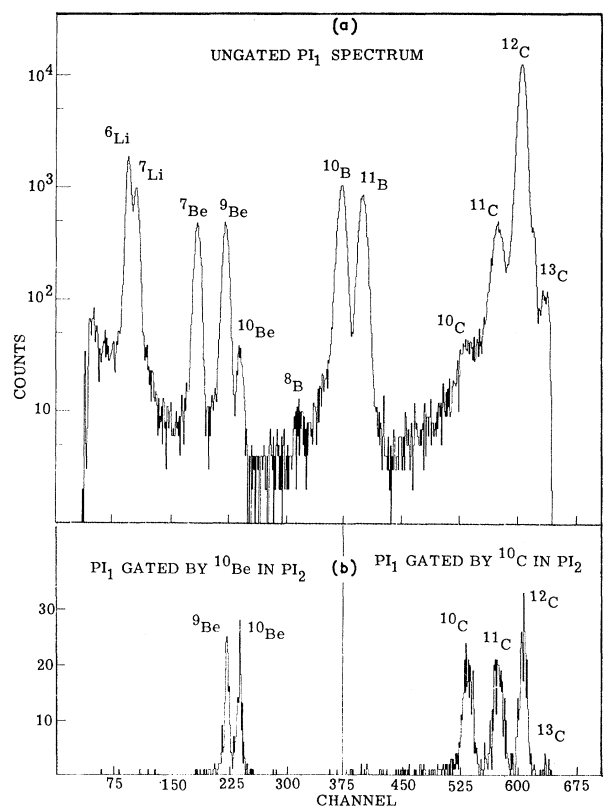

FIG. 1. Particle identification spectra from reactions taken with a telescope of semiconductor detectors, comprising ΔE_1 and ΔE_2 of thickness 75 and 50 μm, a 2-mm E detector, and a rejection detector for long-range products. Two identifications of each particle were made in power-law identifiers. PI_1 was based on ΔE_1 and ΔE_2+E, and PI_2 on ΔE_2 and E. (a) Example of PI_1 showing that low-yield products are superimposed on the tails of adjacent high-yield groups, due to anomalous energy losses in the ΔE counter. The probability of a repeated anomalous loss in a second ΔE counter is small, and this is illustrated in (b) which shows the effect of gating PI_1 with single-channel analyzer windows set on ^{10}Be and ^{10}C in PI_2. Complete separation was achieved by rejecting only 5% of the data.

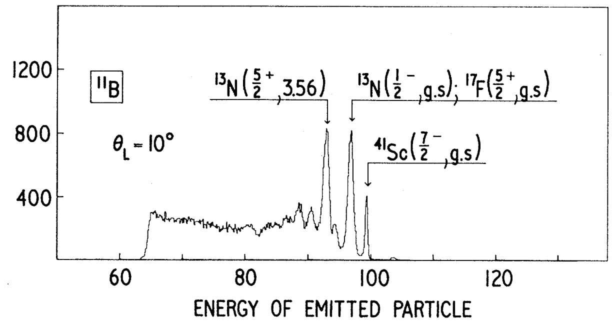

FIG. 2. Single-proton transfer reaction induced by 114-MeV ^{12}C ions on ^{12}C, ^{16}O, and ^{40}Ca.

on, two-nucleon (np), and three-nucleon transfers, compared to 50 μb/sr for the transfer of two protons or two neutrons.

Energy spectra for one-, two-, and three-nucleon transfer reactions are shown in Figs. 2, 3, and 4. A prominent feature is the selectivity in exciting only a few levels. A similar effect has been noted by Lu, Zisman, and Harvey[5] in (α, d) reactions, and by Poth, Overley, and Bromley[6] in their pioneering studies of single-nucleon transfer induced by heavy ions. The mechanism of the reactions appears to be dominated by a surface interaction. Each nucleon transfers angular momentum mvR when it is captured near the surface of the target, where m is the nucleon mass, v is the relative velocity of the ions, and R is the radius of the target nucleus. An incident ^{12}C beam of 114 MeV corresponds to an angular momentum per nucleon of approximately $2\hbar$ for ^{12}C and ^{16}O, and $3\hbar$ for ^{40}Ca targets, assuming a radius parameter of 1.4 fm. The validity of this semiclassical model is illustrated in Fig. 2 for single-proton transfer. For ^{12}C and ^{16}O the strongest excitations correspond to the addition of a $d_{5/2}$ nucleon to produce the single-particle state of spin and parity $\frac{5}{2}^+$ at 3.56 MeV in ^{13}N, and the ground state ($\frac{5}{2}^+$) of ^{17}F. Similarly the ground state ($\frac{7}{2}^-$) of ^{41}Sc is strongly excited by adding an $f_{7/2}$ nucleon to ^{40}Ca. Corresponding results were observed for single-neutron transfer. The ground state ($\frac{1}{2}^-$) of ^{13}C and ^{13}N were also appreciably populated showing the presence of a significant p-wave contribution in this case.

A spectrum for (^{12}C, ^{10}B) is shown in Fig. 3(a). Each level appears as a doublet due to the formation of ^{10}B in its ground and first excited state at 0.717 MeV. There was no evidence for strong excitation of ^{10}B to higher states. Only one strong excitation appears for each target. The levels at 8.96 MeV in ^{14}N and 1.127 MeV in ^{18}F are known[7,8]

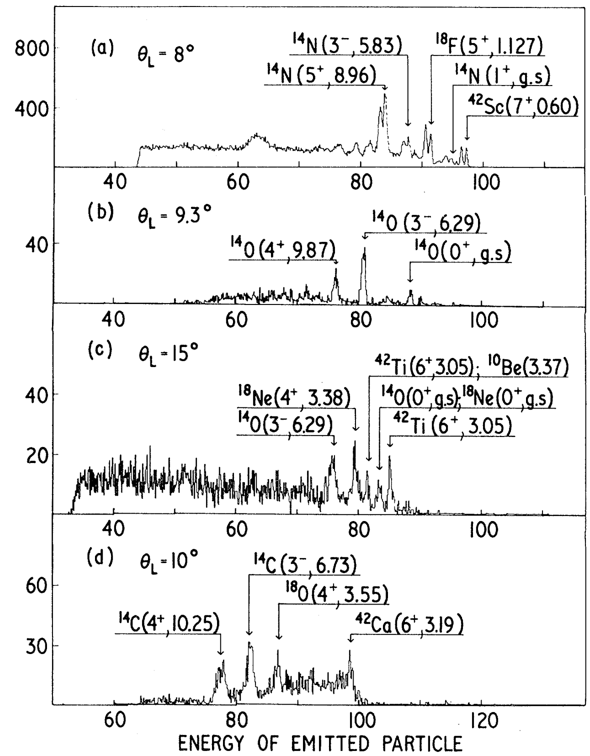

FIG. 3. Two-nucleon transfer reactions induced by 114-MeV ^{12}C ions on ^{12}C, ^{16}O, and ^{40}Ca. (a) (^{12}C, ^{10}B) reaction on a composite target. (b) $2p$ transfer (^{12}C, ^{10}Be) on a pure ^{12}C target. (c) (^{12}C, ^{10}Be) reaction on a composite target. (d) $2n$ transfer (^{12}C, ^{10}C) on a composite target.

to be almost pure $(d_{5/2})^2{}_{5^+,0}$ configurations, while in ^{42}Sc the 0.6-MeV level has the configuration $(f_{7/2})^2{}_{7^+,0}$. These selective excitations support

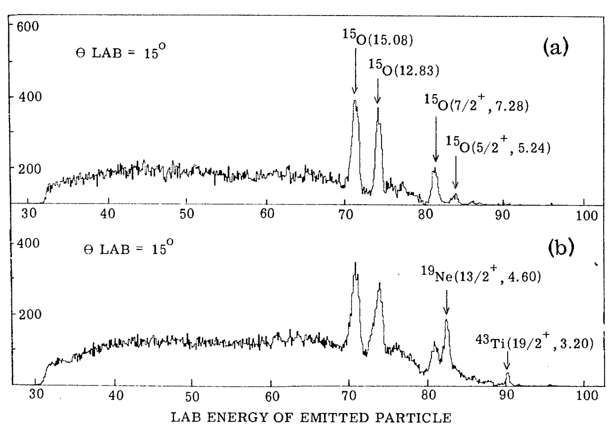

FIG. 4. Three-nucleon transfer reaction (^{12}C, ^{9}Be) induced by 114-MeV ^{12}C ions (a) on a pure ^{12}C target and (b) on a composite target of ^{12}C, ^{16}O, and ^{40}Ca. Unlabelled groups correspond to states in ^{15}O as shown in (a).

the model. The appearance of the 5.83-MeV level in ^{14}N of configuration $(d_{5/2}p_{1/2})_{3^-,0}$ and the ground state $(p_{1/2})^2{}_{1^+,0}$ again indicates an appreciable contribution from a p wave in reactions on ^{12}C. The preferential excitation of the stretched-particle configurations appears to be a feature of transfer reactions initiated by heavy ions with incident energies in the region of 10 MeV/nucleon. In the case of two-proton or two-neutron transfers, the exclusion principle allows only states of even spin with $T=1$; and, as Fig. 3(d) shows, the only observed state from the reaction $^{40}Ca(^{12}C, {}^{10}C)^{42}Ca$ is the 6^+ state at 3.19 MeV with the configuration $(f_{7/2})^2{}_{6^+,1}$. The analog state in ^{42}Ti has not been previously observed, but from the systematics we can identify this configuration with the state excited at 3.05 MeV in the reaction $^{40}Ca(^{12}C, {}^{10}Be)^{42}Ti$ [Fig. 3(c)]. This excitation is in excellent agreement with the predictions of Coulomb displacements in mass 42 by Bertsch[9] and Jänecke.[10] In the $2p$ transfer a second group is produced by simltaeous excitation of the 6^+ state and ^{10}Be in its first excited state.

A spectrum for the reaction $^{12}C(^{12}C, {}^{10}Be)^{14}O$ on a pure ^{12}C target is shown in Fig. 3(b). The ground state and 6.29-MeV state have known[11] $(p_{1/2})^2{}_{0^+,1}$ and $(d_{5/2}p_{1/2})_{3^-,1}$ configurations, and our model strongly suggests the identification of the remaining excitation at 9.87 MeV with the $(d_{5/2})^2{}_{4^+,1}$ configuration. This state has not been previously observed, but it can be predicted by the model of Zuker, Buck, and McGrory[12] at approximately 12.56 MeV in ^{14}N. The systematics of Coulomb displacement energies of isospin multiplets[11] in mass-14 nuclei lead us to expect this configuration at approximately 9.8 MeV in ^{14}O. Part of the excitation at 9.87 MeV could be ascribed to the formation of the 6.29-MeV level together with ^{10}Be in its 3.37-MeV state since the equivalent excitation of 9.66 is encompassed by the observed width. The corresponding $2n$ transfer on ^{12}C to form ^{14}C is shown in Fig. 3(d). Since the spectrum was taken with a composite target, the ground state is obscured, but the 3^- level at 6.73 MeV is strongly excited, together with a state at 10.25 MeV, which we suggest is the 4^+, $T=1$ state. The validity of this identification is confirmed by the remaining strong excitations in Figs. 3(c) and 3(d) which are the known $(d_{5/2})^2{}_{4^+,1}$ configuration[11] states in ^{18}Ne and ^{18}O formed by the $2p$ and $2n$ transfers on ^{16}O.

The selective excitation is also a feature of the three-nucleon transfer reaction $(^{12}C, {}^{9}Be)$. As Fig. 4(b) shows, this reaction excites strongly only one state in ^{43}Ti at 3.2 MeV, and one state in ^{19}Ne at 4.60 MeV, which our model would identify as the stretched configurations $(f_{7/2})^3{}_{19/2^-}$ and $(d_{5/2})^2{}_{13/2^+}$. These identifications are substantiated by the recent observations of a $\frac{19}{2}^-$ isomeric state[13,14] in ^{43}Sc at 3.12 MeV, a $\frac{13}{2}^+$ state[15] at 4.61 MeV in ^{19}Ne, and at[16] 4.648 MeV in ^{19}F. The mirror reactions $(^6Li, t)$ and $(^6Li, {}^3He)$ on ^{16}O have also been shown[17] to populate analog $(\frac{13}{2}^+)$ states at 4.62 in ^{19}Ne and 4.65 MeV in ^{19}F. In ^{15}O we expect, in addition to the configuration $(d_{5/2})^3{}_{13/2^+}$, some contribution from $(d_{5/2})^2p_{1/2}$ and $d_{5/2}(p_{1/2})^2$. The spectrum is shown in Fig. 4(a) with excited states at 5.24, 7.28, 12.83, and 15.08 MeV. The first two states are known[18] to carry a large $[d_{5/2}(p_{1/2})^2]_{5/2^+,7/2^+}$ strength, and it is likely that the 12.83-MeV state is $\frac{11}{2}^-$ since the configuration $[(d_{5/2})^2p_{1/2}]_{11/2^-}$ has been tentatively assigned[5] to the 13.03-MeV level in the analog nucleus ^{15}N. The state at 15.08 MeV therefore remains as an obvious candidate for the $(d_{5/2})^3{}_{13/2^+}$ configuration in ^{15}O. This state has not previously been observed, but our excitation energy is in disagreement with theoretical predictions for this configuration at approximately 13 MeV using the model of Zuker, Buck, and McGrory.[12] A more detailed study of the states excited and of the reaction mechanism is in progress.

In this preliminary work the overall resolution was typically 300 keV in the laboratory. An extension of high-energy heavy-ion transfer reactions with good resolution could serve as a powerful probe for locating simple excitations in nuclei throughout the periodic table. The apparent simplicity of the reaction mechanism is also a challenge to the various theoretical approaches to heavy-ion interactions, such as the semiclassical model, the diffraction model, or the distorted-wave Born approximation.

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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