Possible L-Dependent Angular Distributions in the Reaction ^{48}Ca(^{14}N, ^{13}C)^{49}Sc †

M. J. Schneider, C. Chasman, E. H. Auerbach, A. J. Baltz, and S. Kahana
Brookhaven National Laboratory, Upton, New York 11973
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The reaction ^{48}Ca(^{14}N, ^{13}C)^{49}Sc has been investigated at 50 MeV using a magnetic spectrometer. Angular distributions were extracted for 16 levels below 5.8 MeV excitation. The relative yields of levels were found to be similar to (^{3}He,d). The ground-state angular distribution (transferred $L=4$) peaked at the most forward angle observed (9° c.m.), but the yields of other strong levels ($L \leq 2$) did not. This apparent L-dependence was reproduced by no-recoil distorted-wave Born-approximation calculations using weakly absorbing potentials.

The angular distributions obtained in transfer reactions induced by heavy ions not far above the Coulomb barrier have been characterized as arising from simple semiclassical considerations. The common assertions are that the trajectories are governed by Coulomb forces and that the nuclear potential is very absorptive for close encounters of the projectile and target nucleus. In this picture large-angle scattering and reactions are sharply reduced because of the absorptive interaction at short distances. Likewise, forward-angle reactions are unlikely because the nuclear potential is small on the distant Coulomb trajectory. The resultant angular distribution is independent of transferred L and is more or less bell shaped, peaking at an angle corresponding to a grazing collision and falling rapidly at larger and smaller angles. A recent study of the (^{18}O, ^{16}O) two-neutron transfer reaction on the even Ni isotopes[1] has given evidence that these simple arguments are not always applicable: The measured angular distributions continue to rise at small angles for some isotopes. A simple interpretation of these results is that the absorptive potential may not be so strong as hypothesized, and hence the attractive real potential can deflect the projectiles from Coulomb trajectories to a more forward direction. In this paper we report on the single-particle transfer reaction ^{48}Ca(^{14}N, ^{13}C)^{49}Sc, in which are seen deviations at forward angles from the normal bell-shaped angular distributions. Distorted-wave Born-approximation (DWBA) calculations using weakly absorbing potentials exhibit an L (form factor) dependence for the detailed forward cross sections and reproduce the experimental observations.

The (^{14}N, ^{13}C) experiment was performed using a 50-MeV ^{14}N beam from the Brookhaven National Laboratory tandem Van de Graaff to bombard a 13-μg/cm^2 target enriched to >97% purity in ^{48}Ca. Reaction products were detected by three 50-mm × 10-mm silicon position-sensitive detectors in consecutive focal planes of the Massachusetts Institute of Technology multigap spectrograph, now at Brookhaven National Laboratory. Detector positions on the focal planes were staggered so that at any magnetic-field setting, each counter viewed the same excitation region (of width ≈ 1.2 MeV). The relative solid angles of all magnet gaps were carefully measured with Rutherford scattering of 50-MeV ^{14}N from thin tantalum and gold targets. Angular distributions for ^{13}C in the 6$^+$ charge state were taken for the low angles available in the multigap: $7\frac{1}{2}° \leq \theta_{lab} \leq 37\frac{1}{2}°$ in $7\frac{1}{2}°$ steps. Amplified signals for position times energy (XE) and energy (E) were digitally divided and stored in $64(X)\times 256(E)$ channel arrays in the Σ-7 computer.

The magnetic spectrometer was used because one of the purposes of the experiment was to search for forward peaking. The advantages of a spectrometer, crucial to the experiment's success, are as follows: ^{48}Ca(^{14}N, ^{13}C) has a positive ground-state Q value, and separation of particles by mass-energy product (mE/q^2) in the spectrometer eliminated interference of the elastic peak with the $Q \approx 0$ region, as occurs in a counter telescope. The fine resolution of the spectrometer (typically ~75 keV in this experiment) allowed extraction of angular distributions for all levels below 5.8 MeV, albeit with some ambiguity for the closest of them, ~80 keV apart.

At each magnetic-field setting, mE/q^2 is given by position on the focal plane, and varies slowly across the length of one detector. Therefore, after a detector is calibrated in energy, m/q^2 (and hence the identity) of any particle hitting the detector is well determined. The precision with which m/q^2 is determined depends on the energy resolution of the detector. This totally eliminates

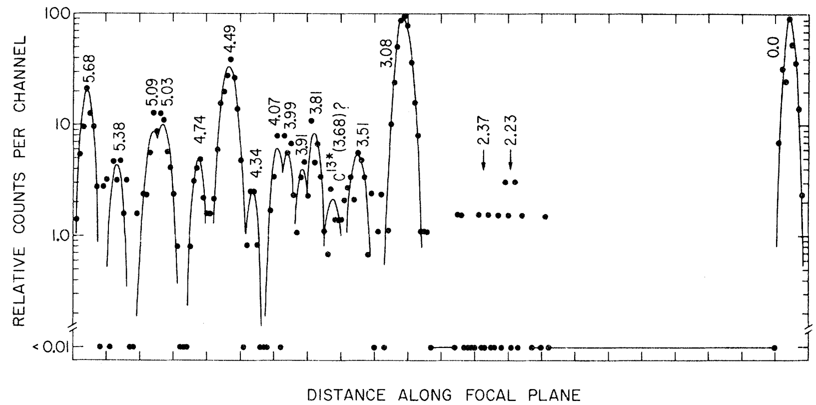

FIG. 1. Spectrum of $^{48}Ca(^{14}N, ^{13}C)^{49}Sc$ at $\theta_{lab}=22\frac{1}{2}°$, $E_{lab}=50$ MeV. This spectrum comprises six individual overlapping position-sensitive detector spectra, each taken at a slightly different spectrometer field setting. These have been normalized to each other, leaving the vertical scale arbitrary.

ambiguity between, e.g., ^{12}C and ^{13}C, whose m/q^2 differ by 8% (for $q=6$), while the energy resolution of the detectors is better than 1% at these energies. 99% of the elastically scattered ^{14}N's were emitted in the two highest charge states in the angular range observed. Calculations[2] indicating similar behavior for nearby masses, along with the highly negative Q values for competing reactions, eliminated any possible confusion between ^{13}C and other ions of the same mass and charge. ~79% of the ^{14}N's were emitted in the highest charge state, in agreement with these calculations,[2] independent of angle. These calculations also predict that 90% of the reaction ^{13}C's are emitted in the 6^+ charge state; hence the observed 6^+ yield multiplied by 1.11 gives the yield to all charge states.

Figure 1 shows a composite ^{13}C spectrum at $\theta_{lab}=22\frac{1}{2}°$, comprising six overlapping individual counter spectra. Immediately striking is the range of excitation energy over which strong states are seen. The classical distance of closest approach is matched for the incoming and outgoing channels (an approximate condition for maximum cross section[3]) at $Q\approx-4$ MeV, corresponding to $E_x\approx 6$ MeV. Hence below this energy one expects the level-strength envelope to decrease with E_x. In the analogous reaction ($^{16}O, ^{15}N$), done at 48 MeV,[4] matching takes place at $Q\approx-3$ MeV, just below the ground state, and there level strengths decrease sharply as E_x increases, as is expected. In ($^{14}N, ^{13}C$), curiously, there is little evidence of such a decrease as E_x departs from the optimum value. For this reaction the "Q window" is broad enough to permit observation of at least 6 MeV of excitation. Although surprising at first glance, this broadness is in fact predicted by no-recoil DWBA calculations.

The strongest states in the spectrum are those known to be largely single particle in nature. [The ground state is $\pi f_{7/2}$ with a ($^3He,d$) spectroscopic factor $S=1.0$, and the 3.08-MeV level is $\pi p_{3/2}$ with $S=0.68$.[5]] Particle-hole states (of both parities) are seen weakly. These results strongly reinforce the assumption implicit in use of DWBA that ($^{14}N, ^{13}C$) is mainly a direct one-step process. It is notable that relative yields of levels in ($^3He,d$) and ($^{14}N, ^{13}C$) match very closely (Fig. 2), despite strength variations over 2 orders of magnitude within each reaction. ($^{14}N, ^{13}C$)

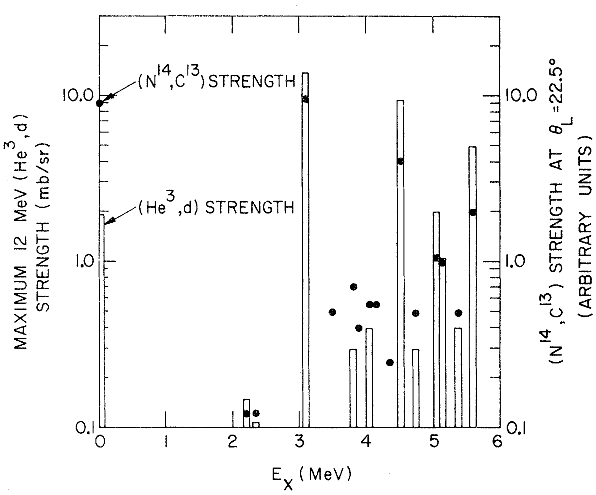

FIG. 2. Comparison of relative yields of levels in ($^{14}N, ^{13}C$) and ($^3He,d$) (see Ref. 5). For those levels seen in both reactions, relative strengths generally match within a factor of 2, except for the ground state, ~4.5 times stronger in ($^{14}N, ^{13}C$) on this scale.

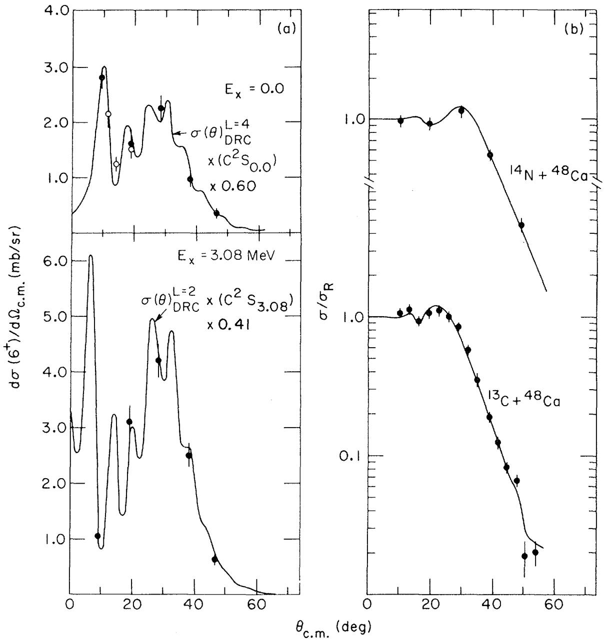

FIG. 3. (a) Angular distributions of $^{48}Ca(^{14}N, ^{13}C)$ to the ground state ($L=4$) and 3.08-MeV state ($L=2$) of ^{49}Sc. Multigap data, filled circles; scattering-chamber data (see added note), open circles. Reproduction of the 3.08-MeV state is representative of other strong $L \leq 2$ states. The factors by which the DWBA calculations are multiplied to match the data are given in the figure. (b) Elastic scattering of ^{14}N and ^{13}C from ^{48}Ca at 50 MeV. The former data were taken in the multigap and the latter in a scattering chamber. Solid lines, fits to elastic data with Woods-Saxon parameters given in the text.

also weakly excites two known ^{49}Sc levels ($E_x = 3.91$ and 3.99 MeV) not seen in (^{3}He, d) at 30 MeV bombarding energy.[6] Their appearance in this experiment may give an indication of the strength of multistep processes.

DWBA calculations for $^{48}Ca(^{14}N, ^{13}C)$ were carried out using the heavy-ion finite-range code DRC,[7] which makes no recoil correction. Optical parameters were obtained from fits to measured elastic scattering of 50-MeV ^{14}N and ^{13}C from ^{48}Ca (Fig. 3). There was considerable degeneracy in parameters which fitted the elastic data. In particular very little sensitivity to the imaginary well depth was found. (Optimum χ^2 was obtained by varying cross-section normalizations within ± 5%, well within the target-thickness uncertainty.) A set of parameters for a Woods-Saxon well which gave good χ^2 was the following: real well depth $V = 70$ MeV; imaginary well depth $W = 10$ MeV; diffusivity $a = 0.5$ fm, all in both channels; and radii $R = 7.470$ and 7.326 fm in the incoming and outgoing channels, respectively, for both real and imaginary wells. These absorptive wells are considerably shallower than those used in most other heavy-ion work, but weak absorption has been instrumental in reproducing the general features of the isotope-dependent variations in Ni(^{18}O, ^{16}O) angular distributions at this laboratory.[1] In the DWBA calculation the transferred proton was taken to be bound in ^{14}N and ^{49}Sc with the appropriate separation energies in wells of $r_0 = 1.25$ fm and $a = 0.65$ fm.

Spectroscopic factors for ^{49}Sc were extracted using the expression $\sigma_{expt} = (C^2S_1)(C^2S_2)\sigma_{DRC}$, where σ_{DRC} is the prediction of the distorted-wave calculation, and C^2S_1 and C^2S_2 are the spectroscopic factors for the proton in ^{14}N and ^{49}Sc, respectively. C^2S_1 for the $p_{1/2}$ proton in ^{14}N was taken equal to 0.688.[8] Spectroscopic factors for all but one very weak state agreed with those extracted from (^{3}He, d)[6] within $^{+250}_{-65}\%$, showing that an arbitrary overall normalization is unnecessary with the level of absorption used here.

The semiclassical strong-absorption model predicts a single peak in all angular distributions at an angle corresponding to grazing collisions. The five strongest ^{49}Sc levels had such angular distributions, with one notable exception: The ground state showed a higher peak at the most forward angle observed, 9° (c.m.). If we assume that the transferred proton is in the $p_{1/2}$ orbit in ^{14}N, and ignore spin-flip and recoil effects, selection rules for (^{14}N, ^{13}C) dictate that only the $\pi f_{7/2}$ ground state is populated by $L = 4$. If tentative spin assignments[6] are correct, the other four strongest levels would be populated by $L \leq 2$, offering the possibility that angular distributions are influenced by L value as with light ions. Angular-distribution shapes calculated by the DWBA did indeed depend on *L for angles forward of ~ 15° (c.m.).* Above this angle, $L = 0$, 2, and 4 were quite similar in general shape, but the most forward peak appeared at 10° for $L = 4$ and 6° for $L = 2$. This result was insensitive to changes in E_x between 0 and 5 MeV. This 4° difference was crucial in reproducing the experimentally seen increase in the ground-state yield and decrease in the 3.08-MeV $p_{3/2}$ (and other $L \leq 2$) yield at the most forward datum point (9°). Correct prediction of observed forward peaking (or lack thereof) arose naturally in this case from the weak-absorption assumption: The prediction was insensitive to changes in W between 6 and 14 MeV, but the forward peak shrank drastically for $W = 25$ MeV. Figure 3 shows how the calculations reproduced the experimental angular distributions. The pattern of small oscillations superimposed on large oscillations suggests passage of the projectile through the nuclear surface region without strong absorption. The fine oscillations are produced by interference between surface-penetrating orbits and grazing orbits on the far side of the nucleus. There is no experimental evidence yet for the existence of the small oscillations, but the narrow forward peak appears to be authentic. Although inclusion of recoil could alter these fits, it would not be expected to change the prime conclusions to be drawn from the study on two-neutron transfer[1] and the present paper on single-proton transfer: Absorption of heavy ions in the nuclear interior appears to be weaker than has been previously recognized. In addition this work demonstrates that weak absorption leads to dependence of angular distributions on form factor shapes, i.e., on transferred L.

Added note.—Recent DWBA calculations which include recoil effects (A. J. Baltz and S. Kahana, to be published) yield angular distributions for the "normal" L transfers ($L = j + \frac{1}{2}$) largely unchanged in shape and slightly stronger than those shown above. Non-normal transfers possible for our cases possess $L = j - \frac{1}{2}$ and therefore contribute weakly (~few percent in magnitude) to the cross sections. Hence DWBA predictions for this reaction obtained in a no-recoil approximation are changed little when recoil effects are included.

In an ongoing experiment, additional data for the ^{49}Sc ground state were taken with a counter telescope in the conventional manner and have been added to Fig. 3. These data give additional evidence of the forward peak for $L = 4$.

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Short-Lived α Emitters of Thorium: New Isotopes $^{218-220}$Th

O. Häusser, W. Witthuhn,* T. K. Alexander, A. B. McDonald, J. C. D. Milton, and A. Olin†
Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada
(Received 5 June 1973)

The α-decay energies and half-lives of three new thorium isotopes, $^{218-220}$Th, have been measured by a simple recoil technique. The observed α-decay widths are in qualitative agreement with Mang's shell-model theory.

The sudden decrease of α-decay reduced widths in translead elements with neutron numbers $N < 128$ has been known for more than a decade.[1] Initially interpreted as an indication of a sudden change in the nuclear radii, the data have since found a more natural explanation by considering the shell structure of parent and daughter nuclei.[2] For daughter nuclei near the neutron shell closure at $N = 126$, the extra binding implies correspondingly short half-lives in the submillisecond region. The majority of nuclei near $N = 128$ have so far been studied by the helium-jet transport technique[3-6] which is useful for parent half-lives in excess of 1 msec. The short-lived nuclei of interest have been observed as members of a decay chain starting from sufficiently long-lived parent nuclei. More recently, a measurement has been reported[7] making use of the pulsed beam from a heavy-ion cyclotron. The present Letter presents measurements of α-decay energies and half-lives of $^{217-220}$Th, so far the most proton-rich nuclei near $N = 128$. The experiment was performed