phonon response but do not discuss the expected form of $S(\omega)$ quantitatively. A more careful characterization of the temperature and wave-vector dependence of $S(\omega)$ for both Nb_3Sn and $SrTiO_3$ is planned for the near future, in order that various possible theoretical alternatives can be assessed.

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Li-Induced Nucleon-Transfer Reactions between 1*p*-Shell Nuclei: Isospin and Fractional-Parentage Studies*

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Angular distributions for the one-nucleon transfer reactions $^{14}N(^6Li, ^7Li)^{13}N$ and $^{14}N(^6Li, ^7Be)^{13}C$ were investigated at $E(^6Li) = 32$ MeV and were compared with finite-range distorted wave calculations and theoretical spectroscopic factors. These one-nucleon transfer reactions induced by complex nuclei are described by the calculations just as well as those induced by light projectiles. A detailed study of the relative cross sections of the isobaric-spin analog transitions shows deviations from isospin symmetry that are due to Coulomb effects.

Among the interactions between complex ions, one of the most fundamental is single-nucleon transfer which, when studied with light projectiles, has yielded much of the nuclear-structure information currently available. Beams of heavy ions ($A \geq 10$) have also been used in a few detailed studies of single-nucleon transfer—both at relatively low energies[1] at which descriptions in terms of specialized models are applicable[2] and at higher energies to which those theoretical models have been extended.[3] The relative spectroscopic factors deduced in the reported studies are in fair agreement with results from light-ion-induced transfers. No corresponding studies with

Li ion beams have been reported[4] so far, probably because these transfers cannot be correctly described in terms of either the zero-range distorted-wave (DW) theory or the Buttle-Goldfarb approximation.[2] Significant improvements may be expected from newer codes[5,6] based on finite-range DW formalisms.

We have performed experiments on ^{6}Li-induced neutron and proton pickup from the $1p$-shell nuclei ^{10}B, ^{11}B, ^{12}C, and ^{14}N. However, this Letter reports only certain aspects of the reactions ^{14}N(^{6}Li, ^{7}Li$_{g.s.}$)^{13}N$_{g.s.}$, ^{14}N(^{6}Li, ^{7}Li$_{1st}$)^{13}N$_{g.s.}$, ^{14}N(^{6}Li, ^{7}Be$_{g.s.}$)^{13}C$_{g.s.}$, and ^{14}N(^{6}Li, ^{7}Be$_{1st}$)^{13}C$_{g.s.}$, which are particularly interesting because their reaction products form the ^{7}Li-^{7}Be and ^{13}C-^{13}N isobaric-analog-state doublets. Therefore, the spectroscopic factors for neutron and proton transfer should be equal if the mass-7 and mass-13 nuclei involved are true isobaric doublets, and if the reaction mechanism at an energy far above the Coulomb barrier conserves isospin. We investigated the effects of isospin impurity by comparing the relative cross sections for reactions to analog final states, and, in addition, we demonstrated the ability of DW calculations to predict the magnitude of absolute cross sections for the neutron and proton transfer. The importance of such isospin and fractional-parentage studies in heavy-ion surface interactions has already been discussed in the early work of Poth, Birnbaum, and Bromley[7]; but poor resolution and, at that time, the theoretical difficulties in treating the transfer of p-shell nucleons restricted them to only semi-quantitative conclusions.

Our experiment was performed in an 18-in. scattering chamber where a melamine $(CH_2N_2)_n$ target was bonbarded with 32-MeV ^{6}Li ions from the Argonne FN tandem Van de Graaff. Spectra of ^{6}Li, ^{7}Li, and ^{7}Be emerging from the target were recorded simultaneously in separate quadrants of a 4096-channel analyzer; typical mass-7 spectra are displayed in Fig. 1. The outgoing particles were detected and identified electronically by use of a counter telescope consisting of three silicon detectors: a ΔE detector 20 μm thick, an E detector 170 μm thick, and an anticoincidence detector $\bar{A}$ 500 μm thick. The resolution achieved in the spectra was of the order of 100 keV (full width at half-maximum).

The counts due to elastic ^{6}Li ions were rejected at far forward angles where the counting rates were very high and the kinematic shifts were small; elastic scattering at these far forward angles was measured in separate runs. At larger angles, the elastically scattered ^{6}Li ions were recorded together with the other particles. The data were normalized both by current integration and by a monitor counter which also measured the deterioration of the target during the course of the bombardment.

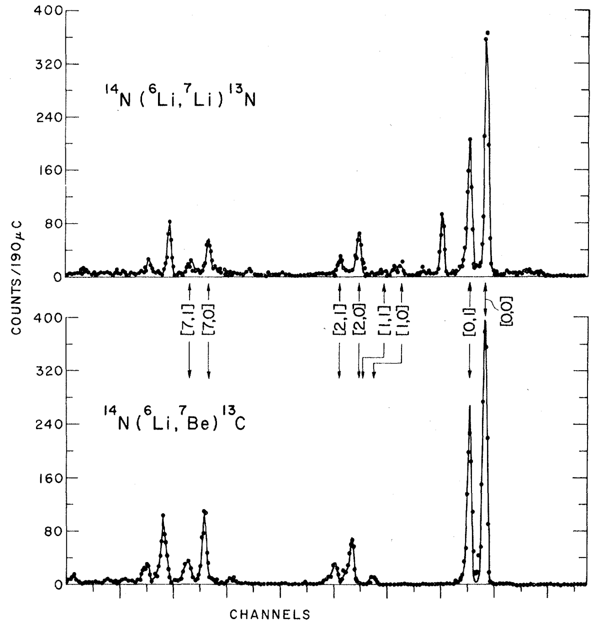

FIG. 1. Spectra from reactions induced by 32-MeV ^{6}Li ions incident on ^{14}N. The ^{7}Li and ^{7}Be spectra were obtained simultaneously with a counter telescope at $\theta_{lab} = 14°$. The notation $[i,j]$ indicates the ith and jth excited states of C and D, respectively, in the reaction ^{14}N(^{6}Li, C)D.

The angular distributions over the range $\theta_{lab} = 7-44°$ ($\theta_{c.m.} = 10-65°$) are shown in Fig. 2 for the reactions ^{14}N(^{6}Li, ^{6}Li$_{g.s.}$)^{14}N$_{g.s.}$, ^{14}N(^{6}Li, ^{7}Li$_{g.s.}$ and ^{7}Li$_{1st}$)^{13}N$_{g.s.}$, and ^{14}N(^{6}Li, ^{7}Be$_{g.s.}$ and ^{7}Be$_{1st}$)^{13}C$_{g.s.}$. The errors in the relative cross sections for ^{6}Li scattering and the production of ^{7}Li and ^{7}Be are determined from statistical errors only, since these data were obtained simultaneously with the same geometric arrangement, target, and beam. Absolute cross sections were estimated on the basis of a technique which appears to be reasonably reliable in studies of light-ion reactions. There it is seen that any choice of optical-model parameters that provides a reasonable fit to the elastic-scattering data yields the same forward-angle cross section as any other choice meeting the same criterion. With any such choice of parameters, we find that a good fit to the elastic ^{6}Li data is possible only for absolute cross sections in a narrow range (± 15% variation). This absolute cross section is in accord with the value estimated on the basis of target thickness, integrated beam current, and solid angle subtended by the detectors.

As is seen in Fig. 2, the angular distributions for all four transfer reactions are similar in shape —most especially the distributions for analogous transitions—but the experimental cross sections differ in magnitude, the ratios being

$$R_1 = \frac{d\sigma}{d\omega}[{}^7\mathrm{Be}_{\mathrm{g.s.}}]\Big/\frac{d\sigma}{d\omega}[{}^7\mathrm{Li}_{\mathrm{g.s.}}] = \frac{d\sigma}{d\omega}[{}^7\mathrm{Be}_{1\mathrm{st}}]\Big/\frac{d\sigma}{d\omega}[{}^7\mathrm{Li}_{1\mathrm{st}}] = 1.20 \pm 0.05,$$

$$R_2 = \frac{d\sigma}{d\omega}[{}^7\mathrm{Li}_{\mathrm{g.s.}}]\Big/\frac{d\sigma}{d\omega}[{}^7\mathrm{Li}_{1\mathrm{st}}] \approx \frac{d\sigma}{d\omega}[{}^7\mathrm{Be}_{\mathrm{g.s.}}]\Big/\frac{d\sigma}{d\omega}[{}^7\mathrm{Be}_{1\mathrm{st}}] = 1.6 \pm 0.1,$$

where the nuclide indicated in a square bracket is the particle detected. The cross-section ratios R_2 would be expected to differ from 1 because the ground state and excited state of a mass-7 nucleus have different structures, i.e., the parentage is ^{6}Li plus a nucleon.

The reason for the difference between the proton and neutron transfer cross sections related by the ratios R_1 is not immediately clear. The reactions ^{14}N(d, ^{3}He)^{13}C$_{\mathrm{g.s.}}$ and ^{14}N(d, t)^{13}N$_{\mathrm{g.s.}}$ at $E_d = 28$[8] and 52 MeV[9] showed identical angular distributions, and a Barshay-Temmer test[3] via the reaction ^{12}C(^{14}N, ^{13}N$_{\mathrm{g.s.}}$)^{13}C$_{\mathrm{g.s.}}$ showed the cross sections for the production of ^{13}N and ^{13}C to be equal except at angles greater than 30°. Even after removing a purely kinematical factor by multiplying the ratio R_1 by the ratio of the relative wave numbers of the mass-7 nuclei in the exit channels, about a 15% difference between the corresponding Be and Li cross sections remains. If there were pure isospin symmetry, this ratio should be unity. Neither Coulomb nor nuclear distortion of scattered waves would be expected to produce this large difference between the cross sections, since the ^{7}Be and ^{7}Li angular distributions show no major differences in shape though each varies by nearly 3 orders of magnitude within the angular range studied. Furthermore, the deviation from $R_1 = 1$ cannot be entirely attributed to isospin impurities in the mass-7 system since both the ground states and the first excited states were shown[10] to constitute isobaric-spin doublets to a very good approximation.

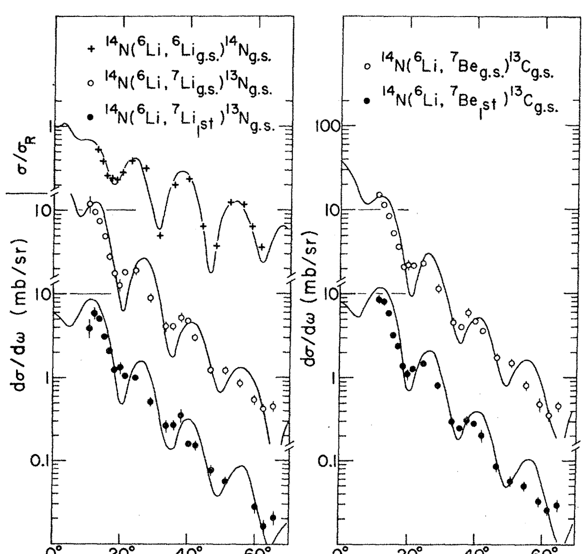

FIG. 2. Angular distributions for ^{14}N(^{6}Li, ^{6}Li)^{14}N, ^{14}N(^{6}Li, ^{7}Li)^{13}N, and ^{14}N(^{6}Li, ^{7}Be)^{13}C. The curve through the elastic-scattering data points represents an optical-model fit. The curves through the reaction data are DW results as discussed in the main text.

In order to understand both our angular distributions and our results for R_1 and R_2, we have used the finite-range DW program RDRC of Schmittroth, Tobocman, and Golestaneh.[6] The optical-model parameters employed (Table I) were obtained from fitting the ^{6}Li elastic-scattering data obtained in the present work. For the outgoing channel, the only change in parameters was to make the appropriate change in charges and masses. The values of the orbital angular-momentum transfer L are severely restricted by triangle selection rules and by parity.[2,6] In the case of p-shell nuclei, only $L = 0$ and $L = 2$ are treated by the program, although $L = 1$ is also

TABLE I. Optical-model parameters used in a potential of the form $V(r) = -V_0(1+e^x)^{-1} + 4iW_D(d/dx')(1+e^{x'})^{-1} + V_c$, where $x = (r-R)/a$, $x' = (r-R')/a'$, and V_c is the Coulomb potential.

V_0	114.2 MeV
R	3.37 F
a	0.79 F
W_D	20.3 MeV
R'	4.46 F
a'	0.57 F
R_c	3.37 F

possible. The neglect of the $L=1$ contribution is not significant since it is weaker than the dominant $L=2$ contribution[11]; and, being out of phase with the $L=2$ and $L=0$ contributions, it merely fills in the minima of the angular distribution. As a result, the spectroscopic factors are the only arbitrary free parameters available to normalize the calculated results (Fig. 2). This success in fitting the data justifies the use of the program to explore the reasons for the differences between the cross sections for neutron and proton transfer.

Assuming the same spectroscopic factor for neutron and proton transfer, we find that at the energy $E(^6\mathrm{Li})=32$ MeV distortion effects are minor and hence not the reason for $R_1 \neq 1$. That is, using incorrect charges to enhance Coulomb distortions or consistently employing different optical-model parameters leads to only small differences between the cross sections for neutron and proton transfer. Furthermore, if the calculation is carried through with identical form factors for the bound-state wave functions, distortions have no sizable effect on the cross section. The calculations reproduce the experimental ratio $R_1=1.20$ only if the proper neutron and proton form factors are used. Thus, the difference between the cross sections must originate in the difference between the bound-state wave functions appearing in the form factor of the calculation. In addition to their influence on the binding energy, Coulomb effects cause the shape of the proton wave function to deviate from that of the neutron wave function. These bound-state wave functions were computed in appropriate Woods-Saxon wells for which the Schrödinger equation was solved to reproduce the observed value of the neutron and proton separation energies in both the mass-14 and mass-7 systems. The calculations show that in both the initial and final states the proton wave function is slightly larger than the neutron wave function in the exterior region where the transfer reaction occurs. The reason for the large difference between the cross sections is that the proton wave function is larger in *both* the initial and the final nuclei, and the resultant amplification of small differences finally leads to the experimentally observed ratio R_1.[12] In the equivalent nucleon pickup reactions, $(d, {}^3\mathrm{He})$ and (d, t), the measured equality of cross sections[8,9] may arise from either or both of two factors. (1) The reaction may not be restricted to regions of the surface of the target where there is a proton excess. (2) The mass-3 wave function is of the 1s character peaked at the origin.

TABLE II. Single-nucleon configurations and spectroscopic factors used in the DW calculations.

Nucleus	$S_{p1/2}$	$S_{p3/2}$
$^{14}\mathrm{N}_{\mathrm{g.s.}}$	1.38	0.008
$^7\mathrm{Li}_{\mathrm{g.s.}}$ and $^7\mathrm{Be}_{\mathrm{g.s.}}$	0.29	0.43
$^7\mathrm{Li}_{1\mathrm{st}}$ and $^7\mathrm{Be}_{1\mathrm{st}}$	0.04	0.85

The explanation of the difference in the cross sections for neutron and proton transfer reactions involving mirror nuclei allows use of the program for spectroscopic studies such as calculation of the ratio R_2. If the mechanism involved in the $(^6\mathrm{Li}, {}^7\mathrm{Li})$ and $(^6\mathrm{Li}, {}^7\mathrm{Be})$ reactions is simply the pickup of a nucleon, then the cross section is proportional[6] to $\sum_L S_1 S_2 \sigma_L{}^{\mathrm{DW}}(\theta)$, where $\sigma_L{}^{\mathrm{DW}}(\theta)$ is the finite-range DW cross section for the nucleon transfer. The spectroscopic factors S_1 and S_2 (Table II), which measure the fractional parentage of the $^{13}\mathrm{C}+p$ (or $^{13}\mathrm{N}+n$) and $^6\mathrm{Li}+p$ (or $^6\mathrm{Li}+n$) systems, are taken from the calculation of Cohen and Kurath.[13] No arbitrary free parameters are available to normalize the results (Fig. 2) of the finite-range calculations, and no cutoff was used. All curves fit both the shapes and absolute magnitudes of all four angular distributions reasonably well, and consequently the ratio R_2 is reproduced within its experimental uncertainty.

In summary, the single-nucleon transfer reactions $(^6\mathrm{Li}, {}^7\mathrm{Li})$ and $(^6\mathrm{Li}, {}^7\mathrm{Be})$ on $^{14}\mathrm{N}$ have been measured with good resolution at an energy well above the Coulomb barrier. With the use of finite-range DW calculations, the differences between the cross sections for these mirror reactions are understood in terms of the differences between the neutron and proton form factors at large distances. Thus, no sizable isospin impurities have been detected in the mechanism of the transfer reactions investigated here. The success in predicting absolute cross sections provides additional impetus for using heavy-ion reactions as spectroscopic tools and indicates that these reactions may be more sensitive to certain features of nuclear wave functions than are light-ion reactions.

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Search for 0^+ Antianalog Strength with Even-Target (^{3}He, p) Reactions

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Results from even-target (^{3}He,p) reactions in the Ca–Fe region have been surveyed. It is found that the 0^+ T_{lower} antianalog states are excited with much less strength than expected from isobaric-spin coupling rules.

It has been observed that (^{3}He,p) reactions on even targets proceed strongly to the isobaric analog states (IAS) of these 0^+ states that are excited strongly in the (t,p) reaction on the same target (see, e.g., Nolen *et al.*[1] and Caldwell, Pullen, and Hansen[2]). This feature is a consequence of isobaric-spin invariance which, apart from reaction dynamics, relates the direct (h,p) (we let h denote the projectile ^{3}He) and (t,p) cross sections by

$$d\sigma^{h,p}((Z,N)\to(Z+1,N+1);\; T_A, T_A\to T_A+1, T_A) = \tfrac{1}{2}(T_A+1)^{-1}d\sigma^{t,p}((Z,N)\to(Z,N+2); T_A, T_A\to T_A+1, T_A+1), \quad (1)$$

where the target A has Z protons, N neutrons, isospin T_A, and isospin projection T_A.

Let us now consider a situation where protons and neutrons in the target nucleus (Z,N) are filling the same shell and where the two nucleons transferred in the (t,p) or (h,p) reactions are deposited in the next higher shell. The lowest 0^+ state of the nucleus $(Z,N+2)$ excited by this category of (t,p) transitions may be the ground state or an excited state, depending on the position of nucleus (Z,N) with respect to a closed neutron shell. In the following, we denote this 0^+ state of nucleus $(Z,N+2)$ the 0^+ parent state. In the $(Z+1,N+1)$ nucleus there may exist a 0^+ state, the so-called antianalog state (AAS), with the same