(^{6}Li, ^{6}He) Reaction as a Probe of Spin-Transfer Strength

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The (^{6}Li,^{6}He) reaction was studied on targets of ^{7}Li, ^{12}C, ^{14}C, ^{26}Mg, and ^{90}Zr at $E_{\rm Li}=210$ MeV. A striking proportionality between cross sections for Gamow-Teller transitions and the corresponding β-decay strengths is observed. This should serve as a calibration of the reaction for use in studies of spin-transfer strength in nuclei. A variety of tests suggests that the reaction proceeds predominantly by a one-step mechanism.

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Spin-dependent phenomena in nuclei, such as the quenching of Gamow-Teller (GT) strength[1] and pion precursor effects,[2] are of great interest and promise to shed light on nonnucleonic components of the nuclear wave function. While most studies of spin phenomena have employed the (p,n) reaction[1,2] or the (^{3}He,t) reaction,[3,4] the (^{6}Li,^{6}He) charge-exchange reaction has long been proposed as an improved spin probe.[5,6] Provided that the reaction mechanism is one step, the quantum numbers (J^π,T) of ^{6}Li and ^{6}He $(1^+,0)$ and $(0^+,1)$, impose the selection rules $\Delta S=1$ and $\Delta T=1$, i.e., the reaction transfers one unit of spin and isospin to the target nucleus. This makes the reaction more selective of spin transfer than (p,n) or (^{3}He,t), which results in a reduced $\Delta S=0$ background. There is also the prospect of higher resolution than (p,n) and, perhaps, of greater sensitivity to higher-spin states. But there has been much debate, for the low bombarding energies (32–62 MeV) at which the reaction has been widely studied,[7-12] about the importance of the one-step process relative to competing sequential nucleon-transfer processes involving, e.g., $^6\mathrm{Li}\rightarrow{}^7\mathrm{Li}\rightarrow{}^6\mathrm{He}$.[13,14] These second-order processes are expected to become less important as the bombarding energy is increased.[15] Indeed, a recent analysis[16] of the reaction on ^{14}C at 93 MeV concluded that it is predominantly one-step in character.

To put this conclusion on a firm basis requires a systematic survey over a range of nuclei. A previous survey[8] at 34 MeV indicated sizable contributions from multistep processes. This Letter reports the first survey at an energy (210 MeV) where one might expect the one-step process to dominate. Most importantly, we find a close proportionality between measured (^{6}Li,^{6}He) cross sections at forward angles, where $\Delta L=0$ transfers are strong, and known GT strengths. This *calibration* allows the use of the reaction to determine GT strengths [B(GT)] for unknown transitions, independent of detailed knowledge of the relevant reaction mechanism. A variety of tests of the nature of the reaction mechanism is also described.

Measurements were carried out on targets of ^{7}Li, ^{12}C, ^{14}C, ^{26}Mg, and ^{90}Zr with the S-320 spectrograph and focal-plane detector of the National Superconducting Cyclotron Laboratory. The most complete set of data, including a measurement at 0°, was taken for the case of ^{14}C. Spectra measured at 3.5° are shown in Fig. 1. The resolution of about 450 keV was adequate to resolve most of the low-lying 1^+ levels of interest: the ground states of ^{12}N and ^{14}N, the strongly excited 3.95-MeV level of ^{14}N, and the 1.06-MeV level of ^{26}Al. The ground state $[(\frac{3}{2})^-]$ and the 0.43-MeV $[(\frac{1}{2})^-]$ state of ^{7}Be, both of which are populated purely by GT transitions in our reaction, were not completely resolved but were decomposed with good accuracy by means of a peak-fitting program. In ^{26}Al, two 1^+ levels at 1.85 and 2.07 MeV were unresolved and were treated as a doublet in the analysis. The peak at 2.3 MeV in ^{90}Nb was taken to correspond to the peak at the same excitation energy seen in the (p,n) reaction at 120 MeV,[17] where it was identified as an aggregate of 1^+ levels.

In the (p,n) reaction at 120 MeV,[17] the giant GT resonance appears at forward angles as a dominant broad peak centered at 8.7-MeV excitation in ^{90}Nb. The structure is less pronounced in the present measurement (see the inset in the lowest panel of Fig. 1), because the linear momentum transfer q at small angles is such that $\Delta L=0$, 1, and 2 amplitudes are large. Thus the GT resonance rides on the tail of the higher-lying higher-multipole excitations. Two-step processes may also contribute, al-

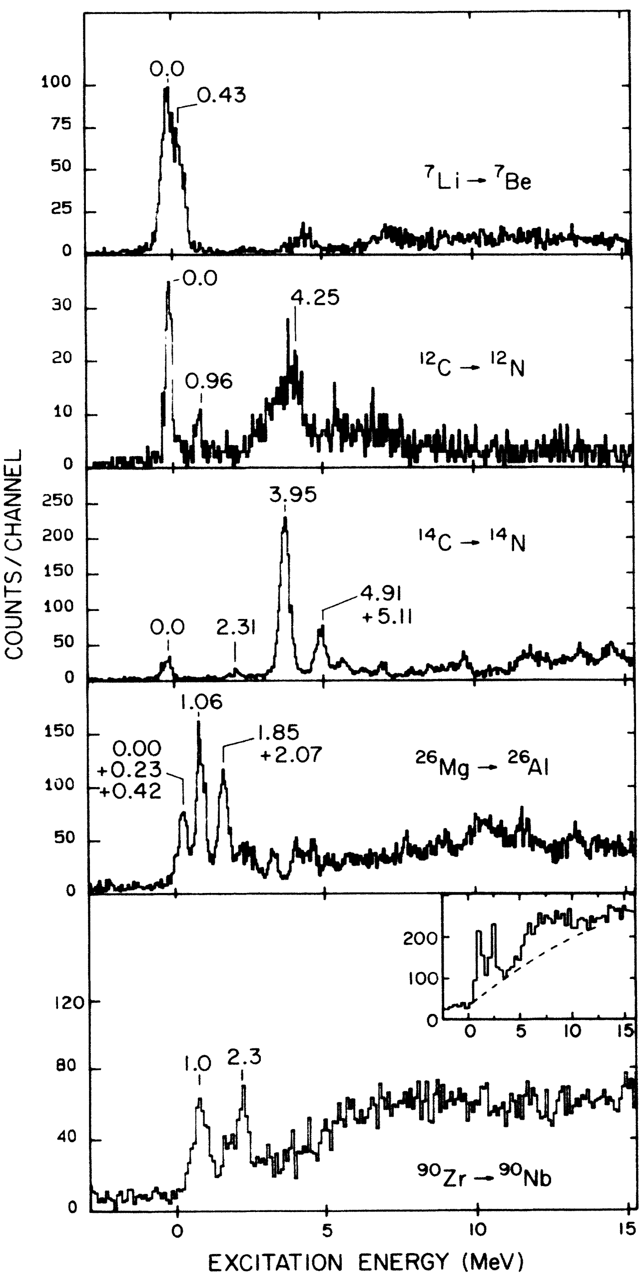

FIG. 1. Spectra measured at $\theta_{lab}=3.5°$ for the (^{6}Li,^{6}He) reaction at 210 MeV on targets of ^{7}Li, ^{12}C, ^{14}C, ^{26}Mg, and ^{90}Zr. The inset in the lowest panel is the ^{90}Nb spectrum plotted on a compressed scale to show the giant GT resonance centered at $E_x=8.7$ MeV more clearly.

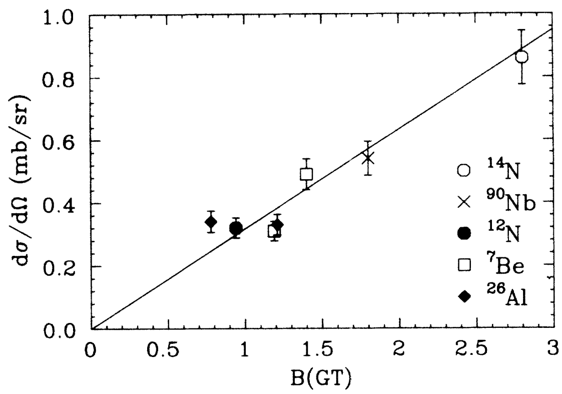

FIG. 2. Plot of (^{6}Li,^{6}He) cross sections at 210 MeV for a fixed qR, corresponding to $q=100$ MeV/c for the case of the ^{14}C target, vs B(GT) values. The final-state nuclei in the reactions of Fig. 1 are listed.

though, at least for low-lying excitations, the present results seem consistent with the one-step process.

The most important issue is the extent to which the forward-angle cross sections measure GT strength. The angular distributions for the various GT transitions, when converted to plots of cross sections against qR, had roughly the same shape and had magnitudes closely proportional to B(GT) values. R is the sum of the projectile and target radii, calculated as $1.2(A_p^{1/3}+A_t^{1/3})$ fm. The B(GT) values (see compilation by Goodman *et al.*[18]) are those determined from β-decay data for all cases except $A=90$, for which a (p,n) measurement[17] leading to ^{90}Nb provided the strength. As shown in Fig. 2, the correlation between measured cross sections at a fixed value of qR (corresponding to $q=100$ MeV/c for the $A=14$ case, which is close to the second maximum in the angular distribution) and known B(GT) values is striking. Because it is difficult to extract unambiguously, we have not included the GT resonance in ^{90}Nb in this figure. However, if we assume a background shown by the dashed line in the inset in Fig. 1, the resonance is 4.0 times as strong as the 2.3-MeV peak, in agreement with the ratio 4.6 of B(GT) values found in the (p,n) work.[17]

The good correlation that is found to exist for masses ranging from $A=7$ to 90 is a strong indication that the reaction at 210 MeV is predominantly one step in nature. It had been suggested previously[8] that even when multistep processes are important, as at lower energies, some proportionality between (^{6}Li,^{6}He) cross sections and B(GT) values may occur within a given nucleus, but not always for different nuclei. Regardless of the reaction mechanism, Fig. 2 provides an empirical calibration curve for the determination of B(GT) through measurement of (^{6}Li,^{6}He) cross sections.

A simple model-independent test of the nature of the reaction mechanism is to compare the ratio of one-step allowed and one-step suppressed transitions to states in a particular nucleus. Transitions to the 0.0-, 2.31-, and 3.95-MeV levels in ^{14}N were used for this purpose. The first two levels should be seen only very weakly in the one-step process. From β-decay studies the 1^+ ground state is known to have a B(GT) value only about 10^{-5} of that for the 3.95-MeV 1^+ level, whereas we find a ratio of 0.11. This is close to the ratio found[19] in the (p,n) reaction at the same energy per nucleon (35 MeV), where the difference from the β-decay ratio is attributed to the contribution of tensor and $\Delta L = 2$ central amplitudes.

A better indication of the reaction mechanism is the strength of the 0^+ isobaric analog state (IAS) at 2.31 MeV in ^{14}N. It is a good monitor for multistep processes in the (^6Li,^6He) reaction, since the only one-step contribution is through the nonlocal part of the exchange interaction. It is known[20] that this is a $\Delta = 1$ process, which is weak at 0°. The ratio of the cross section of the IAS to that of the 3.95-MeV level is about 0.05 at forward angles. Both the ground state and the IAS are suppressed by a factor of 2 at 210 MeV compared with the results[10] at 62 MeV, confirming the expectation[15] that multistep processes are less significant at the higher energy.

Another test of the reaction mechanism is whether one-step calculations can reproduce the data for a transition allowed in the one-step process. The angular distribution for the 3.95-MeV level in the ^{14}N is compared in Fig. 3 with one-step microscopic distorted-wave Born-approximation (DWBA) calculations. In this approximation, only the $V_{\sigma\tau}$ component of the central part of the effective interaction and the tensor component contribute significantly to the reaction. By a fit of the calculations to the data, the strengths of these components were determined. The DWBA code used was a modified version[12] of DWUCK which allowed for the finite size and cluster structure of the projectile and included the central direct (D), central exchange (E), and tensor direct (T) terms in the interaction, but not the tensor exchange term. Definitions of interaction strengths and other details are given in Ref. 12. A ^6Li optical-model potential obtained[21] from 156-MeV elastic scattering on ^{12}C was used for both ^6Li and ^6He. Shell-model wave functions obtained with an interaction due to Millener[22] were used for the target and final nuclear states. Calculations corresponding to D, $D+E$, and $D+E+T$ were performed with a Yukawa interaction of 1-fm range for $V_{\sigma\tau}$ and with various ratios of the tensor to the $V_{\sigma\tau}$ strength. The best fit was obtained with the ratio 0.135.

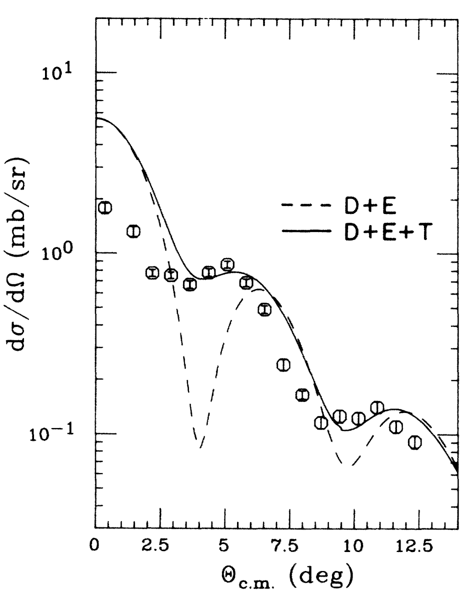

FIG. 3. Angular distribution for the reaction $^{14}C(^6Li,^6He)^{14}N$ at 210 MeV to the 3.95-MeV 1^+ level of ^{14}N. The curves are DWBA calculations described in the text.

The result of this $D+E+T$ calculation and of the $D+E$ calculation, each separately normalized to the data, are shown by the solid and dashed lines, respectively, in Fig. 3. The calculated D and $D+E$ angular distributions were nearly identical in shape; the inclusion of the exchange term increased the cross section by a factor of 1.45. By an increase of the $\Delta L = 2$ contribution, the tensor term brings the calculation into phase with the data at angles larger than 2.5°. The overprediction at smaller angles is possibly due to the neglect of the exchange part of the tensor interaction. The normalization (for $\theta_{c.m.} \geq 2.5°$) obtained for the $D+E+T$ calculation, with the Millener wave functions renormalized to give the experimental $B(GT)$ value, corresponds to a $V_{\sigma\tau}$ value of 14.4 MeV. This is acceptably close to the value of 11.7 ± 1.7 MeV obtained[23] from (p,n) studies in the same energy per nucleon range. Preliminary calculations for other nuclei at 150 and 210 MeV give similar results.[24]

In summary, a striking proportionality is found, for masses ranging from $A = 7$ to 90, between (^6Li,^6He) cross sections at the second diffraction maxium for GT transitions and the known GT strengths. This is similar to that found previously[18] for (p,n) cross sections at 120 MeV, but with the prospect of higher energy resolution. It provides a calibration curve which should be useful for the extension of the range of measured $B(GT)$ values, irrespective of the relative importance of one-step and multistep contributions. The ratios of observed cross sections for certain states in ^{14}N, as well as the reasonable description provided by one-step DWBA calculations over most of the angular range, indicate that the reaction at 210 MeV is, in fact, dominated by the one-step process. By a fit of the DWBA calculations to the data, the strengths of the $V_{\sigma\tau}$ and tensor components of the effective interaction have been determined.

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