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(${}^6\text{Li}, {}^6\text{He}$) AT INTERMEDIATE ENERGIES

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Résumé - Les noyaux de ${}^7\text{Li}$, ${}^{12,14}\text{C}$, ${}^{26}\text{Mg}$ et ${}^{90}\text{Zr}$ ont été étudiés en réaction d'échange de charge (${}^6\text{Li}, {}^6\text{He}$), aux énergies incidentes de 35, 25 et 14 MeV/A. Les rapports de sections efficaces observés pour certains états dans ${}^{14}\text{N}$ et ${}^7\text{Be}$ semblent indiquer que le mécanisme de réaction est dominé par le processus à une étape à 35 MeV/A, avec une contribution croissante du transfert séquentiel aux énergies incidentes plus faibles. Les calculs DWBA à une étape à 35 et 25 MeV/A sont en bon accord avec les données expérimentales. Une bonne proportionnalité entre les sections efficaces GT mesurées et les éléments de matrice β correspondants est observée.

Abstract - Angular distributions have been measured for the (${}^6\text{Li}, {}^6\text{He}$) reaction on targets of ${}^7\text{Li}$, ${}^{12,14}\text{C}$, ${}^{26}\text{Mg}$ and ${}^{90}\text{Zr}$ at bombarding energies of 35, 25 and 14 MeV/A. The ratios of observed cross sections for states in ${}^{14}\text{N}$ and ${}^7\text{Be}$ suggest that the reaction mechanism is predominantly one-step at 35 MeV/A with an increasing contribution from sequential transfer at lower energies. One-step DWBA calculations at 35 and 25 MeV/A are consistent with the data. Good proportionality is observed between the measured cross sections for Gamow-Teller transitions and the corresponding β -decay matrix elements.

The heavy-ion charge-exchange reaction (${}^6\text{Li}, {}^6\text{He}$) is potentially a very useful probe of spin-flip strength in nuclei because, providing that the reaction mechanism is one-step, the spins and parities of ${}^6\text{Li}$ and ${}^6\text{He}$ impose a spin transfer of $\Delta S=1$. Then at forward angles, where $\Delta L=0$ transfers are strong, Gamow-Teller (GT) strength may be measured, whilst at more backward angles, higher multipolarity spin-flip excitations may be observed. The main reason why (${}^6\text{Li}, {}^6\text{He}$) has not been exploited to date is the uncertainty at previously available bombarding energies ($E/A < 15$ MeV) over whether the one-step (π -exchange) mechanism dominates the competing sequential nucleon transfer processes, involving e.g. ${}^6\text{Li} + {}^7\text{Li} \rightarrow {}^6\text{He}$. Such second-order processes are expected /1/ to become less important as the bombarding energy is increased, which was the motivation for the present exploratory survey of GT transitions induced by the (${}^6\text{Li}, {}^6\text{He}$) reaction at $E/A = 14, 25$ and 35 MeV. A related issue is whether the measured GT cross sections are proportional to known β -decay matrix elements, as has been found /2/ in (p,n) reactions above 100 MeV.

Measurements were performed with the NSCL S-320 spectrograph and its focal plane detector. The targets studied were ${}^7\text{Li}$, ${}^{12}\text{C}$, ${}^{14}\text{C}$ (for all bombarding energies), ${}^{26}\text{Mg}$ ($E/A = 35$ MeV only), and ${}^{90}\text{Zr}$ ($E/A = 25$ and 35 MeV). Figure 1 shows a

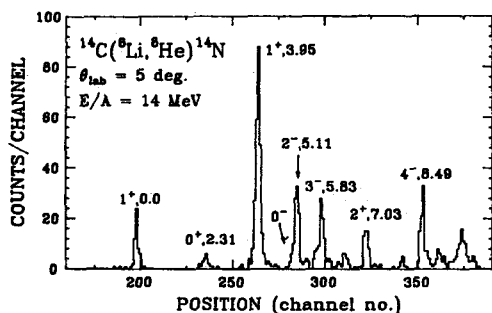


Fig. 1 - Spectrum of $^{14}\text{C}(^6\text{Li},^6\text{He})^{14}\text{N}$ for $E(^6\text{Li})/A = 14$ MeV. States in ^{14}N are indicated with the excitation energy given in MeV. The observed resolution is 140 keV.

spectrum for $^{14}\text{C}(^6\text{Li},^6\text{He})^{14}\text{N}$ at $E/A = 14$ MeV. Typically, a resolution of $\Delta E/E \approx 1/600$ was obtained. For the lower bombarding energies, the absolute resolution is thus significantly better than in state-of-the-art intermediate-energy (p,n) experiments.

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 the residual nuclei. Three states in ^{14}N are of interest for this purpose. The 1^+ ground state has a $B(\text{GT})$ value from β -decay only about 10^{-5} of that for the strong 3.95 MeV 1^+ level, and in the (p,n) reaction at 160 MeV the ratio of cross sections is observed to be 0.01. For $(^6\text{Li},^6\text{He})$, the ratios (taken at $q \approx 100$ MeV/c) are 0.11, 0.15 and 0.21 at $E/A = 35$, 25 and 14 MeV, respectively; other work /3/ shows the ratio continues to increase to 0.30 at $E/A = 10$ MeV. However, tensor and exchange terms in the interaction may account for the differences between the various reactions and the dependence of the ratios for $(^6\text{Li},^6\text{He})$ on energy. A better test of the contribution of two-step processes is the ratio of the 0^+ isobaric analog state (IAS) at 2.31 MeV to the 3.95 MeV state, because a $0^+ \rightarrow 0^+$ transition can only be mediated by the non-local part of the exchange interaction in a one-step process. This ratio is 0.05 at $E/A = 35$ and 25 MeV, 0.08 at $E/A = 14$ MeV and 0.1 for the $E/A = 10$ MeV data /3/. The fact that the IAS is suppressed by a factor of two at $E/A = 35$ and 25 MeV compared with the lower bombarding energies, suggests that multi-step processes are much less significant at the higher energies.

A similar test to the above is to compare the ratio of $\Delta L=0$ cross sections for the ground and 0.43 MeV excited states of ^7Be with the ratio, 1.18, of $B(\text{GT})$ values known from β -decay. The ratios for the smallest angles studied ($\approx 2.5^\circ$) are 1.08 ± 0.06 , 1.34 ± 0.07 and 1.78 ± 0.05 for $E/A = 35$, 25 and 14 MeV, respectively. Thus only at $E/A = 35$ MeV is the $(^6\text{Li},^6\text{He})$ ratio in agreement with the $B(\text{GT})$ ratio. There is a trend away from this value as the bombarding energy is reduced, which suggests a similar conclusion as for the ^{14}N IAS comparisons above.

A second class of tests of the reaction mechanism is to compare the data with one-step distorted wave Born approximation (DWBA) calculations. In Fig. 2, angular distributions are shown for the calculations completed so far; others are in progress. The DWBA code used is a modified version /4/ of DWUCK which allows for the finite size of the projectile system and includes direct (V_{OT}) + exchange + tensor terms in the interaction. Optical potentials obtained /5/ from 150 MeV ^6Li elastic scattering data were used. The $E/A \approx 35$ MeV calculations for ^{14}N and ^{12}N overpredict the data at small angles, possibly because of the lack of appropriate optical model potentials or the neglect of the exchange part of the tensor interaction. The normalizations of the curves required to fit the data (excluding points for $\theta < 4^\circ$), with a Yukawa interaction of 1 fm range and with the single-particle wave functions renormalized to give the experimental $B(\text{GT})$ value, correspond to V_{OT} values ranging from 7 to 14 MeV. These are to be compared with the average value of 11.7 ± 1.7 MeV obtained /6/ from (p,n) studies at similar energies/nucleon. A tensor force of strength ≈ 1.5 MeV gives the best reproduction of the data.

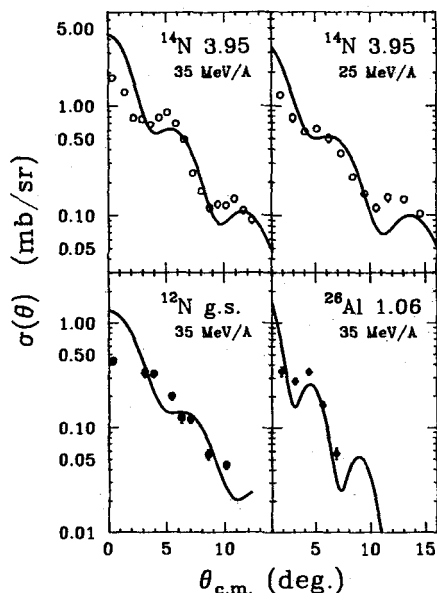


Fig. 2 - Angular distributions for the (${}^6\text{Li}, {}^6\text{He}$) reaction with the final state nucleus and excitation energy indicated for each case. The curves are DWBA calculations normalized to the data.

We have investigated how closely the observed forward-angle $\Delta L=0$ cross sections measure Gamow-Teller strength. Wharton and Debevec /7/ have shown that even at $E({}^6\text{Li}) = 34$ MeV, where multistep processes are known to give sizeable contributions, there is still some correlation between (${}^6\text{Li}, {}^6\text{He}$) $\Delta L=0$ cross sections and the corresponding β -decay matrix elements within a given nucleus. Their data do show a marked mass dependence, however. Our results, which cover a mass range from 7 to 90, are shown in Fig. 3 as a plot of cross section at $qR/R({}^{14}\text{C}) = 100$ MeV/c, where q is the linear momentum transfer and $R/R({}^{14}\text{C})$ is the sum of the projectile and target radii divided by that of ${}^6\text{Li}+{}^{14}\text{C}$. At $E/A = 14$ MeV the overlap of equivalent qR values is too limited for comparison, but at 25 and 35 MeV/nucleon there is a high degree of proportionality for all final states measured.

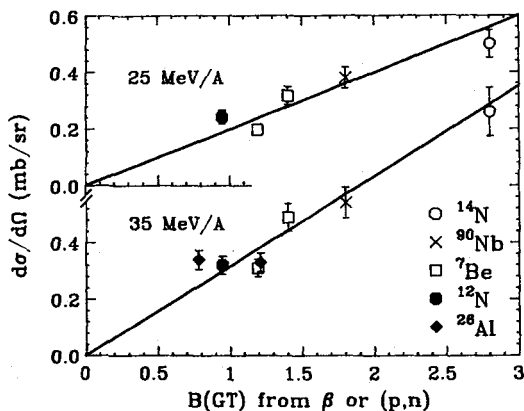


Fig. 3 - Plot of cross sections at $qR/R({}^{14}\text{C}) = 100$ MeV/c for various GT transitions induced by (${}^6\text{Li}, {}^6\text{He}$) at 25 and 35 MeV/nucleon. The final states, with excitation energies in MeV, are: ${}^{14}\text{N}(3.95)$, ${}^{90}\text{Nb}(2.3)$, ${}^{12}\text{N}(0.0)$, ${}^7\text{Be}(0.0$ and $0.43)$, and ${}^{26}\text{Al}(1.06$ and $1.85)$.

In summary, the ratios of observed cross sections for certain states in ${}^{14}\text{N}$ and ${}^7\text{Be}$ indicate that the contribution to the (${}^6\text{Li}, {}^6\text{He}$) reaction from higher-order processes is increasingly noticeable as the bombarding energy is reduced. One-step

DWBA calculations give a reasonable account of the data at $E/A = 35$ and 25 MeV. The most pleasing result, however, is the observed proportionality between the cross sections for GT transitions and β -decay matrix elements at $E/A = 35$ and 25 MeV. The reaction may still be a useful probe of spin strength in nuclei at even lower energies.

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