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Measurement and Miscroscopic Analysis of the Reactions $^6Li(^6Li, ^6Li^*(3.56))^6Li^*(3.56)$ and $^6Li(^6Li, ^6He)^6Be$†

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Angular distributions and an excitation function have been measured for the reactions $^6Li(^6Li, ^6Li^*(3.56))^6Li^*(3.56)$ and $^6Li(^6Li, ^6He)^6Be$ at laboratory bombarding energies between 28 and 36 MeV. A microscopic distorted-wave Born-approximation analysis which includes the tensor interaction and exchange gives good agreement with the data, except at forward angles, and predicts the correct magnitude of the cross sections. Estimates of the strengths of the effective Majorana and spin-tensor isospin interactions are given.

The reactions $^6Li(^6Li, ^6Li^*)^6Li^*$ and $^6Li(^6Li, ^6He)^6Be$ proceed to three members of the same $T=1$ isospin multiplet. Naive charge independence would predict identical differential cross sections, but Coulomb distortions and other effects produce significant differences. (Here $^6Li^*$ indicates the $T=1$, $J^\pi=0^+$ state at 3.56 MeV excitation in ^6Li.) The wave functions[1] of the isomultiplet states have a configuration which is nearly identical to the ^6Li ground state except for a different spin-isospin coupling of the $1p$-shell nucleons, and it is expected that these reactions are quasielastic.[2-4] Thus such reactions can be analyzed microscopically to obtain information on the spin-isospin–dependent effective nucleon-nucleon interaction in finite nuclei, in the same spirit as similar analyses of inelastic and charge-exchange reactions such as (p,p'), (p,n), and $(^3He, t)$.[5] In the present work we have studied these Li + Li induced reactions, measuring angular distributions and excitation functions at laboratory bombarding energies between 28 and 36 MeV, and have analyzed the data with distorted-wave Born-approximation (DWBA) calculations employing microscopic form factors, as will be discussed below.[2]

The experiment was performed using $^6Li^{+++}$ beams from the FN tandem Van de Graaff incident upon self-supporting targets of 80–300 $\mu g/cm^2$ thickness. The two reactions were measured simultaneously by observing both ^6He and ^6Li in the same ΔE-E detector telescope. The $^6Li^*$, which is detected after it undergoes photon decay, is required to be in fast coincidence with the recoil $^6Li^*$ detected in a recoil counter. To assure a high coincidence efficiency, a major problem at forward angles, the recoil-detector solid angle was chosen as large as 0.045 sr which was up to 1000 times the telescope solid angle. Before and after each measurement the coincidence efficiency for the elastic scattering was measured at the same recoil energy as in the measurement of $^6Li(^6Li, ^6Li^*)^6Li^*$; the recoil energies were chosen to be equal so that we could accurately monitor the multiple scattering of the recoil ^6Li in the target. This was important for recoil energies less than 3 MeV. We then did a series of calculations using our measured elastic coincidence efficiency to determine our inelastic coincidence efficiency. The differences between the two efficiencies arose solely from kinematics and the decay of each $^6Li^*$ which were known exactly. The calculated inelastic efficiencies varied between 70% and 99.9% and were greater than 90% at nearly all angles greater than $\theta_{c.m.}=20°$. The absolute cross sections were obtained by normal-

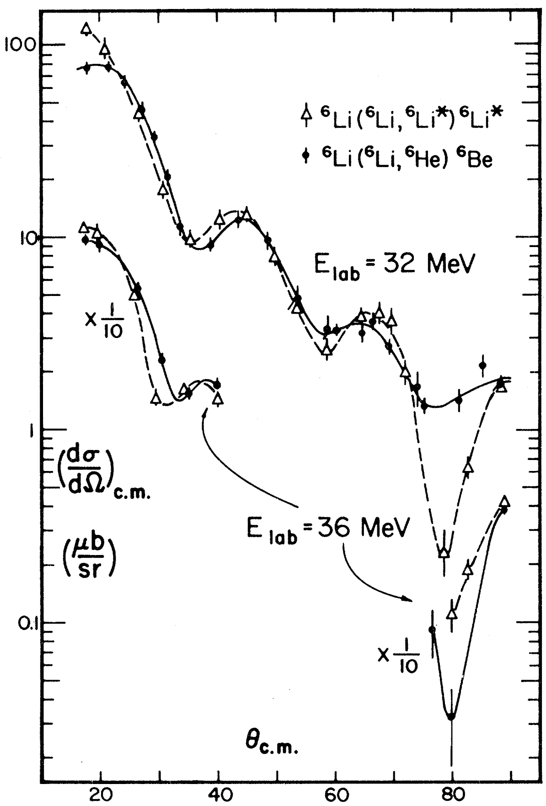

FIG. 1. Angular distributions for the reactions ^{6}Li(^{6}Li, ^{6}Li*)^{6}Li* and ^{6}Li(^{6}Li, ^{6}He)^{6}Be at bombarding energies of 32 and 36 MeV. At 32 MeV, they have been fitted by an even Legendre polynomial expansion up to polynomials of order 16 for the reaction ^{6}Li(^{6}Li, ^{6}Li*)^{6}Li* (dashed line) and up to order 18 for the reaction ^{6}Li(^{6}Li, ^{6}He)^{6}Be (solid line). The lines through the 36-MeV data are freely drawn.

izing our elastic-scattering data to the data of Fortune, Morrison, and Siemssen.[6]

The cross sections are shown in Fig. 1. The data on ^{6}Li(^{6}Li,^{6}Li*)^{6}Li* have been corrected for efficiency loss and divided by 2 to account for there being two indistinguishable particles in the final state. The measured cross sections for ^{6}Li(^{6}Li,^{6}Li*)^{6}Li* given here differ at forward angles from those of Nagatani *et al.*[3] presumably because the latter work did not include multiple scattering effects in the efficiency corrections.

The ^{6}Li ground state has $J^\pi = 1^+$ so that the channel spin S (the vector sum of the individual spins) is 0, 1, or 2 in the ^{6}Li + ^{6}Li channel. According to Bose-Einstein statistics and parity conservation, only the $S=0$ and 2 channels contribute to the reaction ^{6}Li(^{6}Li,^{6}Li*)^{6}Li*. Central forces between the two nuclei can contribute to the reaction only from the $S=0$ channel and tensor forces can contribute only from the $S=2$ channel. Tensor forces may mix channel spins 0 and 2 in the initial channel but otherwise channel spin is a good quantum number and the central and tensor forces contribute nearly incoherently to the reaction.

DWBA calculations are performed with the form factors obtained microscopically. The nuclear states are described as good L-S coupled states[1] and the interaction between the p-shell nucleons, indexed by i and j in each nucleus respectively, is

$$\sum_{i,j} V_{11}(r_{ij})(\vec{\sigma}_i \cdot \vec{\sigma}_j)(\vec{t}_i \cdot \vec{t}_j) + \sum_{i,j} V_{T1}(r_{ij})(\vec{t}_i \cdot \vec{t}_j)S_{12}.$$

These are the only parts of the central and tensor N-N interactions, respectively, which contribute to the reactions in a one-step process. Exchange contributions, in which the full N-N interaction contributes, are included by assuming a Serber potential. Form factors are obtained assuming either "knock-on" (K.O.) exchange, in which only the two interacting nucleons may be exchanged, or full exchange, in which the p-shell nucleons in both nuclei are completely antisymmetrized with each other. Recoil corrections for the exchange terms are not included. The Majorana interaction is taken from the long-range part of the Hamada-Johnston potential with the radial cutoff at 1.05 F. The tensor potential is chosen to have the one-pion exchange potential form with a strength of 3.7 MeV obtained from the pion-nucleon coupling constant, 0.08. The r^{-3} singularity in $V_{T1}(r)$ presents no difficulty since the tensor force contributes as $r^4V(r)$ at small interaction distances. Ten sets[7] of optical potentials are obtained using Woods-Saxon shapes with widely varying parameters, and all sets give fair fits to the elastic scattering data between laboratory energies of 16 and 36 MeV.

Figures 2 and 3 show some of the calculations. The magnitude of the calculated cross section is determined by the strength of the N-N interaction but can be different by factors of 2 or possibly more for different optical potentials. Within this variation there is good agreement with the magnitude of the experimental cross sections. The inclusion of exchange terms involving noninteracting nucleons ("full exchange") increases the cross section by nearly a factor of 2 over the cross section obtained with just K.O. exchange terms. Traditionally most calculations include only K.O. exchange terms. The tensor force

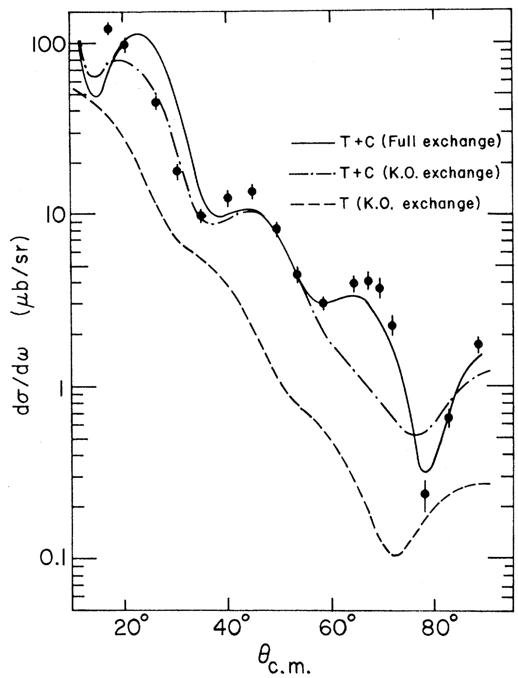

FIG. 2. The DWBA calculation of the reaction ^{6}Li(^{6}Li, ^{6}Li*)^{6}Li* at 32 MeV using the optical potential which best describes the elastic scattering data. The contribution of the tensor force (dashed line), and the incoherent sum of the tensor and central forces with (K.O.) exchange and with full exchange are shown.

contributes less than 30% of the cross section. If the strength of the tensor potential were increased to about 6 MeV, the deep minimum at 80° in the ^{6}Li(^{6}Li,^{6}Li*)^{6}Li* angular distribution would be filled in. This is taken as evidence against a strong tensor interaction, such as that used to analyze the reaction ^{54}Fe(^{3}He, t)^{54}Co.[8]

Most of the calculated angular distributions using the various optical potentials give good agreement with the data at center-of-mass angles greater than 35°, but all calculations do poorly at forward angles, giving a minimum at 15° (c.m.), whereas the experimental cross section is still rising at 17° (c.m.). The disagreement is more severe at 32 MeV than at 36 MeV and is similar to the anomaly found in the angular distributions of (^{3}He, t) reactions.[9] The experimental and theoretical excitation functions near 90° (c.m.) are in good agreement. Differences between the shapes of the ^{6}Li(^{6}Li,^{6}Li*)^{6}Li* and the ^{6}Li(^{6}Li,^{6}He)^{6}Be angular distributions (calculations not shown) are also explained[10] by the DWBA theory. Much of the difference is due to the unequal Q values for the two reactions. However, the experimentally determined ratio of magnitudes for the two reactions integrated over an angular range of 20° to 90° (c.m.) agrees with the theoretical value to only about 20 or 30% depending on the choice of optical parameters.[7]

The DWBA calculations have also been performed using a Yukawa potential of range 1.0 fm for V_{11}, with the strengths adjusted to match the magnitudes of the cross sections. The values

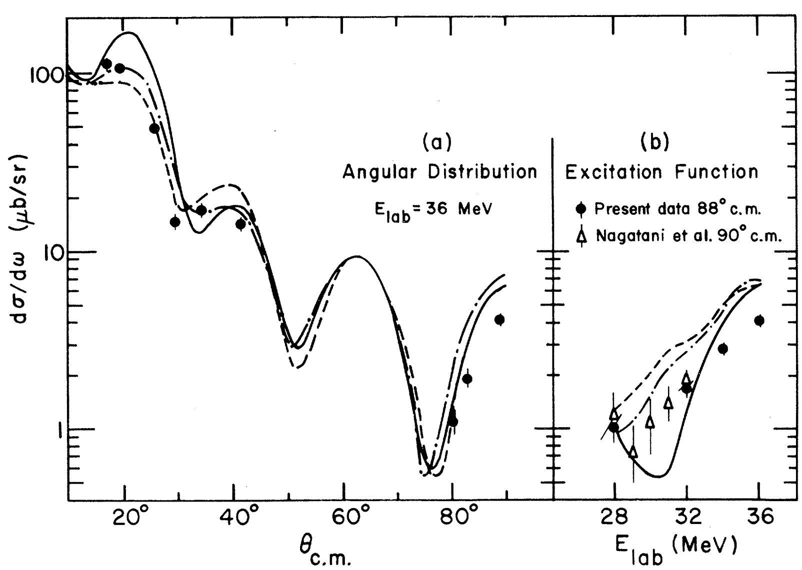

FIG. 3. The DWBA calculations of the reaction ^{6}Li(^{6}Li, ^{6}Li*)^{6}Li* using three different optical potentials are compared to the data at 36 MeV and the excitation function near 90° (c.m.). The calculations are made with the optical potential used in Fig. 2 and full exchange (solid line), or two other optical potentials and knock-on exchange (dashed and dash-dotted lines, respectively).

obtained for V_{11} are

$$V_{11} = 7.0 \text{ MeV with full exchange,}$$

$$V_{11} = 10.0 \text{ MeV with K.O. exchange,}$$

$$V_{11} = 20.0 \text{ MeV with no exchange.}$$

The uncertainty in these numbers is 20% or larger[10] and is primarily due to uncertainties in the optical potential. The values of V_{11} obtained from calculations of the (p, p') reactions using K.O. exchange vary from 9 to 14 MeV[11] and agree with the present results. This agreement is an indication that the use of microscopic form factors with an effective N-N interaction will eventually provide a consistent description of many inelastic and charge exchange reactions.

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Measurement of the Neutron Polarization from D(p, n)2p †

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The polarization of breakup neutrons from the reaction D(p,n)2p has been measured at E_p = 21.5 MeV as a function of neutron energy with accuracy of approximately ± 0.01. The high-energy neutrons (E_n > 14 MeV) show a small but significant positive polarization (P_n ~ 0.015), in disagreement with the prediction (P_n = 0) of the Amado model and also in disagreement with expectations if the dominant process were simple quasifree p-n scattering.

During the past few years, three-body calculations have been performed with more and more realistic NN forces, and predictions now are in fairly good quantitative agreement with all available three-body observables measured up to 30 MeV. These include the differential cross sections[1-3] and vector and tensor polarizations[2,3] for elastic scattering and the inelastic differential cross sections.[4] Since calculations for the elastic channel have shown that the polarization observables are more sensitive to details of the NN force than are the cross sections,[1-3] it is exceptionally interesting to extend the three-body measurements to include inelastic polarization phenomena. Polarization effects in the breakup channel can be studied either using polarized beams to measure asymmetries in the breakup cross section[5] or by measuring the polarization