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Tensor analyzing powers for ^{7}Li induced transfer breakup reactions

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The T_{20} analyzing powers have been measured for the $^{120}\mathrm{Sn}(^7\mathrm{Li},{}^8\mathrm{Be}\rightarrow 2\alpha)^{119}\mathrm{In}$ and $^{120}\mathrm{Sn}(^7\mathrm{Li},{}^6\mathrm{Li}^*\rightarrow \alpha + d)^{121}\mathrm{Sn}$ transfer breakup reactions, using a 70 MeV beam. The data exhibit excellent agreement with the results of coupled reaction channels calculations, providing an important test of these calculations when applied to the transfer breakup reaction mechanism.

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I. INTRODUCTION

Transfer breakup reactions are of particular interest because they combine two processes (the transfer of nucleons followed by breakup of the ejectile), whose individual mechanisms are well understood in isolation [1–6]. However, there has been little published on these reactions induced by the stable, lighter, heavy ions such as ^{7}Li, which are relevant to studies of nuclei with binary cluster structures, and to complementary radioactive beam studies where the projectile nuclei have a large cross section for both nucleon transfer and, in particular, fragmentation. It is important to note that radioactive beams are polarized as a result of the fragmentation process used to create them. So use of the polarized ^{7}Li beam provides a real test of a hypothetical radioactive beam experiment. If model predictions can achieve good agreement for transfer breakup reactions induced with stable nuclei, then model comparisons for radioactive beams become more meaningful.

Coupled reaction channels (CRC) calculations have historically been found to provide a very good description of cross sections and analyzing powers for elastic and inelastic scattering and transfer reactions, including specifically those induced by ^{7}Li [1,7,8]. More recently continuum discretized coupled channels (CDCC) calculations have been very successful in describing breakup reactions. In a previous publication [5] CDCC calculations were applied to $^{120}\mathrm{Sn}(^7\mathrm{Li},\alpha t)^{120}\mathrm{Sn}$ breakup analyzing powers. The α plus triton cluster structure of ^{7}Li resulted in a large breakup yield to these fragments. A detailed study was made of two mechanisms [9–11]; (i) sequential breakup following excitation of the ^{7}Li to the 4.63 MeV $(7/2^-)$ state, and (ii) the breakup into the α particle plus triton continuum. The continuum breakup, which is strong at forward angles and falls off rapidly at larger angles, can be explained by the differential strong nuclear force between the target and fragments [12] in an α particle plus triton cluster description of ^{7}Li. The good agreement between the model calculations and the measured data provided an important test of the CDCC approach.

The current challenge is to test thoroughly such coupled channels calculations with the more complex transfer breakup reactions. The aim of the current work is a measurement of the second rank (T_{20}) analyzing powers for ^{7}Li induced transfer breakup reactions, to investigate the applicability of CRC calculations to this reaction mechanism, which

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is one step more complicated than breakup alone. These analyzing powers provide a particularly sensitive test of these theoretical models. An important feature of the measured data is that they have very low background because of the coincidence imposed by the data acquisition system, combined with software selection of particle identification and measurements of the angles and energies of the fragments. The result is that the specific transfer reaction and breakup reaction can be selected without ambiguity. A preliminary report containing some data and calculations from the current work have been recently published [13]. The purpose of the current paper is to provide a more comprehensive presentation and discussion of the transfer breakup analysis.

II. EXPERIMENT

Data for the transfer breakup reactions were obtained simultaneously with those for a previously reported study of polarized ^{7}Li breakup on ^{120}Sn [5], so the experimental procedure is the same.

The experiment was performed using a 70 MeV polarized ^{7}Li beam from the polarized heavy ion source [14] and accelerated by the tandem Van de Graaff accelerator, at the former Nuclear Structure Facility at Daresbury Laboratory. Optical pumping [15] was used in the ion source for polarization of the beam. Ions with each of the four spin substates were selected in turn, using a high frequency transition in a magnetic field to switch between substates. The polarization states were switched every few seconds, after a specified integrated beam current was measured, to minimize systematic errors due to beam drift or polarization fluctuations. A Wien filter was used to orient the polarization symmetry axis along the beam direction at the target. The beam polarization was determined from the $^1\mathrm{H}(^7\mathrm{Li},\alpha)^4\mathrm{He}$ reaction [16] using a purpose-built, downstream polarimeter [17]. The measured magnitudes of second rank beam polarizations were typically $t_{20}=0.6$. Measurements of first and third rank polarizations resulted in magnitudes no larger than 0.05 each.

For the breakup and transfer breakup reactions a 2 mg cm^{-2} ^{120}Sn target was used. The detection system consisted of two pairs of $\Delta E.E$ detector telescopes placed symmetrically, one pair on either side of the beam. The symmetric arrangement was used so that data from both sides of the beam could be summed, thus eliminating systematic errors arising from any shift in position of the beam on target and the effects of odd rank polarization components in the beam. The telescopes comprised 230 μm thick *p-n* junction silicon ΔE detectors and 4 mm thick lithium drifted silicon E detectors. Similar detectors placed behind the E detectors acted as vetos to eliminate high energy protons, deuterons, and tritons which pass through the E detectors. The detector collimators were 8 mm wide and 6 mm high with the centers for a given pair 12 mm apart. The detectors in each pair of telescopes were mounted symmetrically above and below the beam axis and 150 mm from the target. Reaction yields were obtained for each polarization state of the beam, from which analyzing powers were determined using the same method as used in the polarized ^{7}Li breakup study [5], incorporating equations from the Madison Convention [18].

The detectors were energy calibrated using 5.486 MeV α particles from ^{241}Am sources mounted close to the detectors. Particle identification was performed using the ΔE and E signals. Fast timing was achieved by signals generated from the ΔE preamplifiers, used to start and stop a time to amplitude converter for each pair of telescopes. Data were transmitted to a computer via analog to digital converters and recorded event by event on tape.

The T_{20} data for the $^{120}\mathrm{Sn}(^7\mathrm{Li},{}^8\mathrm{Be}\rightarrow 2\alpha)^{119}\mathrm{In}$ reaction and the effective T_{20} data for the $^{120}\mathrm{Sn}(^7\mathrm{Li},{}^6\mathrm{Li}^*\rightarrow \alpha+d)^{121}\mathrm{Sn}$ reaction were obtained for a range of angles of the pairs of detector telescopes to the beam direction from 9° to 25° in the laboratory frame.

III. CALCULATIONS

CRC calculations were performed, using version FRXP.18 of the code FRESCO [19], for the $^{120}\mathrm{Sn}(^7\mathrm{Li},{}^8\mathrm{Be}\rightarrow 2\alpha)^{119}\mathrm{In}$ and $^{120}\mathrm{Sn}(^7\mathrm{Li},{}^6\mathrm{Li}^*\rightarrow \alpha+d)^{121}\mathrm{Sn}$ reactions. For the $^{120}\mathrm{Sn}(^7\mathrm{Li},{}^8\mathrm{Be}\rightarrow 2\alpha)^{119}\mathrm{In}$ reaction the entrance channel optical potential was that of Cook [20] and the exit channel optical potential was determined from single folding using an empirical $\alpha+{}^{120}\mathrm{Sn}$ optical potential [21] and $^8\mathrm{Be}=\alpha+\alpha$ cluster wave functions. A Gaussian shaped binding potential as proposed by Buck and Merchant [22] for $^7\mathrm{Be}={}^3\mathrm{He}+{}^4\mathrm{He}$ was used:

$$V(r) = V_o \exp\left[-\left(\frac{r}{R_o}\right)^2\right]. \qquad (1)$$

The parameter R_o was chosen so as to reproduce the rms radius of the matter distribution of ^{8}Be, 2.62 fm, predicted by Patra [23]. The ^{8}Be ground state was assumed to be weakly bound, by just 0.01 MeV, and the potential depth, V_o, was adjusted to reproduce this. For the $^{120}\mathrm{Sn}(^7\mathrm{Li},{}^6\mathrm{Li}^*\rightarrow \alpha+d)^{121}\mathrm{Sn}$ reaction the entrance channel optical potential was that of Cook [20] and the exit channel optical potential was determined from single folding using empirical $\alpha+{}^{120}\mathrm{Sn}$ [21] and $d+{}^{120}\mathrm{Sn}$ [24] optical potentials and $^6\mathrm{Li}=\alpha+d$ wave functions [25] calculated using the $\alpha+d$ binding potential proposed by Kubo and Hirata [26]. Spectroscopic amplitudes were obtained from Cohen and Kurath [27] and Turkiewicz *et al.* [28]. The coupling schemes used are shown in Figs. 1 and 2. The CDCC technique was used to generate the $^8\mathrm{Be}(2^+)$ and $^6\mathrm{Li}(3^+)$ resonance wave functions. In order that the calculations are manageable, ^{7}Li breakup is not included. This approach is justified because second rank tensor analyzing powers for elastic scattering are mainly generated by ^{7}Li ground state reorientation and coupling to the ^{7}Li first excited state [29]. These are consequently the two entrance channel effects incorporated into the CRC calculations.

To make a reasonable comparison of data with prediction, the detector configuration used for the breakup fragments needs to be considered. The ^{8}Be case is the simplest because the ^{8}Be is in its ground state so the fragment relative angular momentum is $L=0$ for the breakup. The $L=0$ breakup gives an isotropic distribution of α fragment directions in the center of mass frame of the ^{8}Be. A direct measurement of T_{20} for the transfer breakup reaction is consequently made because it

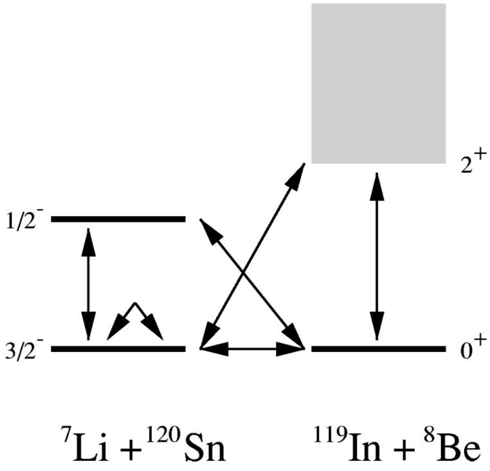

FIG. 1. Coupling scheme for ^{120}Sn(^{7}Li, ^{8}Be$\rightarrow 2\alpha$)^{119}In CRC calculations. The spins and parities refer to the projectile/ejectile.

does not matter where the detectors are placed relative to the reaction plane. The ^{6}Li* case is somewhat more complicated because the ^{6}Li* is in the 2.19 MeV 3$^+$ excited state. This is known to be a pure $L=2$ ($\alpha+d$) cluster state, so $L=2$ breakup of the state with no $L=4$ admixture can be assumed to a very good approximation. The $L=2$ breakup will result in an anisotropic fragment distribution and a consequent phase space effect due to detector positions. The analyzing powers measured for the ^{120}Sn(^{7}Li, ^{6}Li$^*\rightarrow\alpha+d$)^{121}Sn reaction are consequently effective T_{20} which include a detector phase space effect. A technique was therefore developed to take this into account in calculating effective analyzing powers to compare with the data, by which the measured analyzing powers T_{kq} are modeled by a combination of the calculated polarization transfer coefficients $X_{kq,k'q'}$, which may be calculated from amplitudes generated by the FRESCO code, with tensors $I_{k'q'}$ which are related to the detector geometry. This technique, which is described in detail in a previous publication [5], was applied to the transfer breakup via ^{6}Li*. This involved the use of a probability function for the spatial distribution of the breakup fragments, calculated using a Monte Carlo simulation code [30] in which the collimator positions for the coincidence detection were defined.

IV. RESULTS

Details concerning the general techniques used for production of spectra and extraction of analyzing powers are provided in the previous ^{7}Li breakup study [5], so only the key points relevant to the transfer breakup reactions of current interest are summarized here. An energy resolution of 0.4 MeV was obtained for the reaction particles. For the ^{120}Sn(^{7}Li, ^{8}Be$\rightarrow 2\alpha$)^{119}In reaction spectra were reconstructed corresponding to breakup via the 0$^+$ ground state of ^{8}Be. The unresolved ground 9/2$^+$ and 0.31 MeV 1/2$^-$ first excited states of ^{119}In were found to be populated strongly in these spectra. These are $1g_{9/2}$ and $2p_{1/2}$ single hole shell model states, respectively. For the ^{120}Sn(^{7}Li, ^{6}Li$^*\rightarrow\alpha+d$)^{121}Sn reaction spectra were reconstructed corresponding to breakup via the 2.18 MeV 3$^+$ state of ^{6}Li. These latter spectra were observed to contain three strong structures corresponding to the unresolved ground 3/2$^+$, 0.006 MeV 11/2$^-$ first excited and 0.06 MeV 1/2$^+$ second excited states and many unresolved states around 1.2 and 2.7 MeV in ^{121}Sn. The three states comprising the lowest excitation energy structure are the $2d_{3/2}$, $1h_{11/2}$, and $3s_{1/2}$ single particle shell model states, respectively. Many of the states contributing to the two higher excitation energy structures have uncertain or unknown spin-parities, rendering calculations for these particular data impossible.

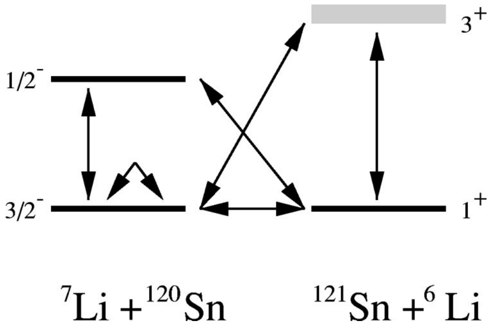

FIG. 2. Coupling scheme for ^{120}Sn(^{7}Li, ^{6}Li$^*\rightarrow\alpha+d$)^{121}Sn CRC calculations. The spins and parities refer to the projectile/ejectile.

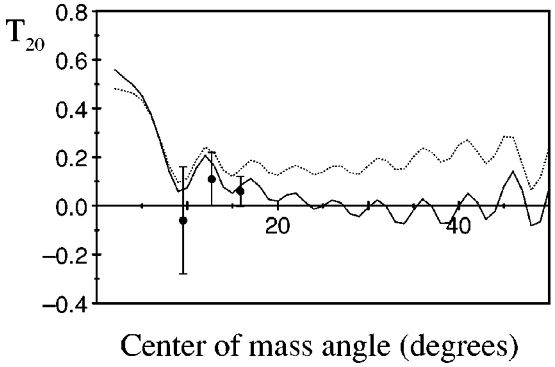

FIG. 3. Results of CRC calculations for the ^{120}Sn(^{7}Li, ^{8}Be$\rightarrow 2\alpha$)^{119}In ground state reaction compared with data (ground and 0.31 MeV states in ^{119}In are unresolved). The dotted line excludes ^{7}Li reorientation and excitation while the solid line is for the full coupling scheme of Fig. 1.

The effect of the coupling schemes used for the calculations was investigated. Calculations showing the effect of ^{7}Li reorientation and coupling to its first excited state are shown with the data for the ^{120}Sn(^{7}Li, ^{8}Be$\rightarrow 2\alpha$)^{119}In ground state reaction in Fig. 3. The sensitivity of T_{20} to the entrance channel is shown to be weak at the forward angles, although it can be concluded that the calculation using the full coupling scheme of Fig. 1 best reproduces the data. Calculations, using the full coupling scheme, for the ^{120}Sn(^{7}Li, ^{8}Be$\rightarrow 2\alpha$)^{119}In reaction are compared with the data in Fig. 4. The calcuations for the transfer breakup reactions leading to the ground and first excited states of ^{119}In are very different. This shows how sensitive analyzing powers are to the reaction mechanism and spectroscopic factors. The data agree very well with the calculation assuming population of the ^{119}In ground state. The calculation assuming population of the ^{119}In first excited state does not reproduce the data. This indicates that only the ground state is significantly populated by the reaction and illustrates the usefulness of analyzing

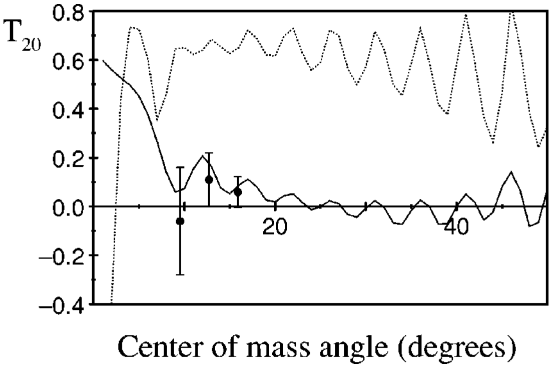

FIG. 4. Results of CRC calculations for the ^{120}Sn(^{7}Li, ^{8}Be $\rightarrow 2\alpha$)^{119}In reaction compared with data (ground and 0.31 MeV states in ^{119}In are unresolved). The solid and dotted lines assume population of the ^{119}In $9/2^{+}$ ground state and 0.31 MeV $1/2^{-}$ first excited state, respectively.

powers in distinguishing reactions to the unresolved states. The strong population of the ^{119}In ground state can be understood in simple shell model terms. The ^{120}Sn target nucleus has proton shells filled to the $1g_{9/2}$ shell inclusive. The $1g_{9/2}$ shell contains ten protons while the $2p_{1/2}$ shell contains two protons. The incoming ^{7}Li picks up a proton. It would be expected from numbers of available protons to be five times more likely to pick up a $1g_{9/2}$ proton, leaving ^{119}In ground state, than to pick up a $2p_{1/2}$ proton, leaving ^{119}In first excited state. Also, the $1g_{9/2}$ shell model level is at a higher energy than the $2p_{1/2}$ level, albeit by not very much, which could serve to increase the likelihood of ^{119}In ground state population further.

Calculations *without* the detector phase space correction for the ^{120}Sn(^{7}Li, ^{6}Li$^{*} \rightarrow \alpha + d$)^{121}Sn reaction assuming population of the ground $3/2^{+}$, 0.006 MeV $11/2^{-}$, and 0.06 MeV $1/2^{+}$ states are shown with the unresolved data in Fig. 5. Good agreement is not achieved, although it could be argued on the basis of these calculations alone that the calculation for the $1/2^{+}$ state, being predominantly negative, represents the data better than the calculations for the other two states, which are predominantly positive.

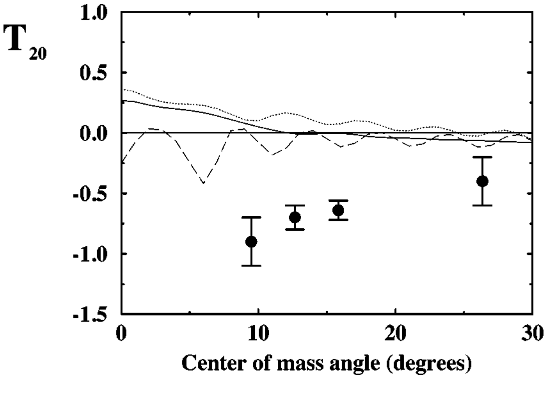

FIG. 5. Results of CRC calculations without detector phase space correction for the ^{120}Sn(^{7}Li, ^{6}Li$^{*} \rightarrow \alpha + d$)^{121}Sn reaction. The data shown are effective T_{20}. The dotted, solid, and dashed lines assume population of the ^{121}Sn $3/2^{+}$ ground state, the $11/2^{-}$ state at 0.006 MeV and the $1/2^{+}$ state at 0.06 MeV, respectively.

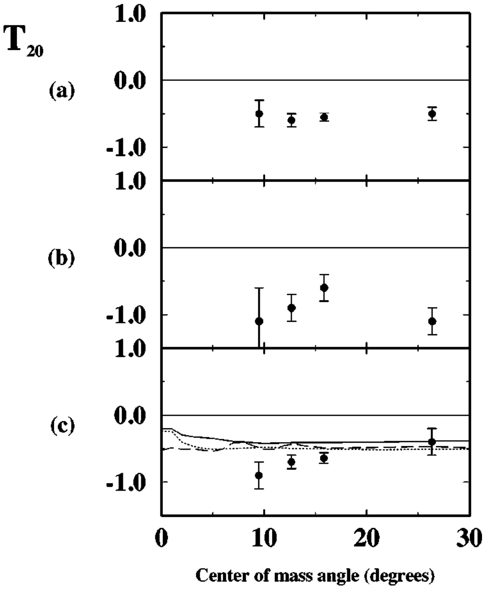

FIG. 6. Results of CRC calculations including detector phase space correction for the ^{120}Sn(^{7}Li, ^{6}Li$^{*} \rightarrow \alpha + d$)^{121}Sn reaction to ^{121}Sn (a) states around 2.7 MeV, (b) states around 1.2 MeV, and (c) unresolved ground, 0.006 and 0.06 MeV states. The data shown are effective T_{20}. The dotted, solid, and dashed lines assume population of the ^{121}Sn $3/2^{+}$ ground state, the $11/2^{-}$ state at 0.006 MeV, and the $1/2^{+}$ state at 0.06 MeV in ^{121}Sn, respectively.

Calculations *with* the detector phase space correction included are shown in Fig. 6, together with all the ^{120}Sn(^{7}Li, ^{6}Li$^{*} \rightarrow \alpha + d$)^{121}Sn data. These illustrate the importance of the correction, included in the calculations of Fig. 6(c), which leads to far better agreement between the calculations and the data than obtained without the correction in Fig. 5. They also lead to a different conclusion than that arrived at from the uncorrected calculations alone, because once the correction is included all three calculations are very similar and agree with the data equally well. This means the relative contributions from the three states to the data are not important in assessing the success of the calculations.

V. CONCLUSIONS

Analyzing power angular distributions have been measured for the ^{120}Sn(^{7}Li, ^{8}Be$\rightarrow 2\alpha$)^{119}In and ^{120}Sn(^{7}Li, ^{6}Li$^{*} \rightarrow \alpha + d$)^{121}Sn transfer breakup reactions, using a 70 MeV beam. The results show that good coincidence transfer breakup measurements are possible and that CRC calculations do very well in reproducing T_{20} and effective T_{20} analyzing power data for the respective reactions in one of the first tests of these calculations for transfer breakup reactions. It is therefore expected that CRC calculations can provide a good foundation for the study of nuclear reactions of considerable complexity, especially those induced using radioactive beams. In particular, the theoretical and data analysis techniques developed and applied in the current work can be well utilized with data from radioactive beam induced reactions which involve fragmentation and provide a sound basis for such studies. Because of the sensitivity of analyzing powers to details of what occurs during a reaction, they can be of use in determining reaction mechanisms and spectroscopic amplitudes of states populated in reactions. This would be particularly beneficial in radioactive beam studies where reactions of considerable complexity are likely. Measurements of analyzing powers for reactions induced by radioactive beams are therefore strongly encouraged in the future.

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