Deformation Effects in ^{6}Li

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The asymptotic D- to S-state ratio η for the $\langle d\alpha \,|\, ^6\text{Li}\rangle$ bound-state overlap is determined from measurements of the tensor analyzing powers for $(^6\vec{\text{Li}}, d)$ reactions on medium-heavy targets. The reactions are described by the distorted-wave Born approximation assuming a direct α-particle transfer reaction mechanism. The calculations provide good agreement with cross section and vector analyzing power data. A best fit to the tensor analyzing power data results in a new value of $\eta = +0.0003 \pm 0.0009$, much smaller than previous experimental and theoretical determinations. [S0031-9007(98)06789-1]

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One way to quantify nuclear deformation effects in light nuclei is by the ratio of the D- and S-state asymptotic normalization constants η [1]. The quantity η is a measure of the relative strength of the D-state component in the asymptotic region of the wave function, where the nuclear potential is not significant. A D-state component in the wave function of a nucleus is manifested directly by a nonzero D- to S-state ratio and/or a nonzero quadrupole moment. The value of η for the deuteron $\eta(d)$ has been determined to within a few percent [2] while for the $A = 3$ systems values of $\eta(t)$ and $\eta(^3\text{He})$ have been established to within 10% [2,3]. Even the $d + d$ configuration of the α particle is nonspherical, with a measure of its deformation established to within about 20% [4]. The D-state components of the wave functions of s-shell nuclei are generated by tensor forces which are responsible for a large part of the binding energy in these light nuclei [5].

In the case of ^{6}Li, much less is understood. Cluster configurations of a $d + \alpha$ or a $t + {}^3$He can combine to form $L = 0$ or 2 states and still allow $J^\pi = 1^+$ for the ^{6}Li ground state. Most of the previous theoretical and experimental investigations into the ^{6}Li ground state have focused on the $d + \alpha$ configuration because the large binding energy of the α particle and the small separation energy between the α particle and the deuteron (1.47 MeV) suggest that this configuration has a large probability [1]. Unlike the D-state component in the overlaps of s-shell nuclei which are generated solely by tensor forces, the D state in the $d + \alpha$ configuration of ^{6}Li can also result from its p-shell structure. As a consequence there is no model-independent relation between η and the ^{6}Li quadrupole moment ($Q = -0.083$ fm^2 [6]) as is the case for the deuteron [5]. Therefore a measurement of η yields additional physical information about the structure of ^{6}Li. An important practical application of this information is the determination of the neutron polarization when ^{6}Li is used as a polarized neutron target [7].

Contrary to the lighter nuclei mentioned above, η for ^{6}Li is not well determined, even as to its sign. Three-body (αnp) models assuming different forms of the nuclear potential have generated predictions of $\eta = +0.0194$ and $+0.0169$ [2]. These models give excellent agreement with several properties of the ^{6}Li ground state but, in each case, predict $Q > 0$ and unavoidably result in predictions of $\eta > 0$ [8]. Recently, a variational Monte Carlo solution to the six-body problem, using realistic nuclear forces, has been used to calculate the $\langle d\alpha \,|\, ^6\text{Li}\rangle$ bound-state overlap [9]. They estimate $\eta = -0.07 \pm 0.02$ and predict $Q = -0.8 \pm 0.2$ fm^2, an order of magnitude larger than the experimental value [6].

Experimentally, the S-state and D-state asymptotic normalization constants were determined in a forward dispersion relation analysis of $d - \alpha$ scattering [10] from which η is found to be $+0.005 \pm 0.017$. In Ref. [11], the D-state amplitude of the wave function was adjusted to reproduce Q and yielded a value of $\eta = -0.014$. In an analysis of the tensor analyzing powers (TAPs) from the $^6\text{Li}(\vec{d}, \alpha)\alpha$ reaction it was found that a value of η between -0.010 and -0.015 gave the best agreement with the data [12]. This analysis was found to be very sensitive to the D state of ^{4}He and thus was limited by the uncertainty in $\eta(^4\text{He})$. To reproduce T_{20} data from the breakup of $^6\vec{\text{Li}}$ at 4.5 GeV, a small positive value of η was indicated

[13]. In an analysis of $^{6}\vec{\mathrm{Li}} + {}^{58}\mathrm{Ni}$ scattering at 70.5 MeV assuming a coupled channels reaction mechanism, it was concluded that a negative value of η, similar in magnitude to that of Ref. [11], gave the best reproduction of the TAP data [14]. A reanalysis of these data, however, assuming a different coupling mechanism, suggested that a smaller value for η (half that of Ref. [14]) provided the best agreement with the data [15].

In the present work, we determine η by an analysis of the TAPs observed in $(^{6}\vec{\mathrm{Li}}, d)$ transfer reactions. We will show that the magnitude of the TAPs scales with the magnitude of η. Similar methods have proven successful in D-state studies of the $A = 2 - 4$ systems [3,4,16]. In this Letter, we report measurements of the vector analyzing power (VAP) and TAPs for the $^{58}\mathrm{Ni}(^{6}\vec{\mathrm{Li}}, d)^{62}\mathrm{Zn}$ and the $^{40}\mathrm{Ca}(^{6}\vec{\mathrm{Li}}, d)^{44}\mathrm{Ti}$ reactions leading to the 0^+ ground state (g.s.) and the 2^+ first excited state for each reaction. These data represent the first analyzing power measurements for $(^{6}\vec{\mathrm{Li}}, d)$ reactions on any target heavier than $^{12}\mathrm{C}$.

The experiments were performed using the optically pumped polarized lithium ion source [17] at Florida State University. The $^{6}\vec{\mathrm{Li}}$ ions were accelerated to 34 MeV with the Super FN Tandem accelerator into an 85-cm-diameter scattering chamber. Two pairs of ΔE-E Si detector telescopes were placed symmetrically on each side of the beam. The telescopes consisted of 4 to 6 mm of Si with 1- or 2-mm Si ΔE detectors preceded by a Ta foil to stop elastically scattered $^{6}\mathrm{Li}$ ions. A small detector was placed at 135° with respect to the incident beam direction to monitor the target and was used to normalize yields for cross section measurements. The $^{58}\mathrm{Ni}$ targets ($>$99.76% enriched) were self-supporting rolled foils ranging in thickness from 0.8 to 2.0 $\mathrm{mg/cm^2}$. The $^{40}\mathrm{Ca}$ targets consisted of 0.9 $\mathrm{mg/cm^2}$ of $^{\mathrm{nat}}\mathrm{Ca}$ sandwiched between 0.3-$\mathrm{mg/cm^2}$ layers of Au. After passing through the target the beam entered a secondary scattering chamber where the polarization was monitored via $^{4}\mathrm{He}(^{6}\vec{\mathrm{Li}}, {}^{4}\mathrm{He})^{6}\mathrm{Li}$ scattering, as described in Ref. [18]. Typical beam polarizations on target were $p_z, p_{zz} \approx -0.6, -1.1$.

In Figs. 1 and 2 we show the cross section and analyzing power data for the $^{58}\mathrm{Ni}(^{6}\vec{\mathrm{Li}}, d)^{62}\mathrm{Zn}$ reaction at $E(^{6}\mathrm{Li}) = 34$ MeV. Relative cross section data were determined by taking the ratio of the counts in the chamber detectors with the counts in a gate set on the breakup spectrum in the fixed monitor detector and were normalized to that of Ref. [19]. The $^{40}\mathrm{Ca}(^{6}\vec{\mathrm{Li}}, d)^{44}\mathrm{Ti}$ analyzing power data (not shown) were taken over a similar angular range and are of comparable quality. In addition, we have used $^{40}\mathrm{Ca}(^{6}\mathrm{Li}, d)^{44}\mathrm{Ti}$ cross section data at $E(^{6}\mathrm{Li}) = 32$ MeV [20] to supplement the present data in establishing a theoretical description of the reaction.

We use the distorted-wave Born approximation (DWBA), assuming a direct α-particle transfer process, to model the reactions. The calculations were performed using the computer code FRESCO [21]. To constrain the entrance channel parameters for the $^{58}\mathrm{Ni}(^{6}\vec{\mathrm{Li}}, d)^{62}\mathrm{Zn}$ calculations, we measured the cross section and VAP for $^{6}\vec{\mathrm{Li}} + {}^{58}\mathrm{Ni}$ elastic scattering at 34 MeV and found that the optical model (OM) parameters derived from a global parametrization of $^{6}\mathrm{Li}$ elastic scattering [22] slightly

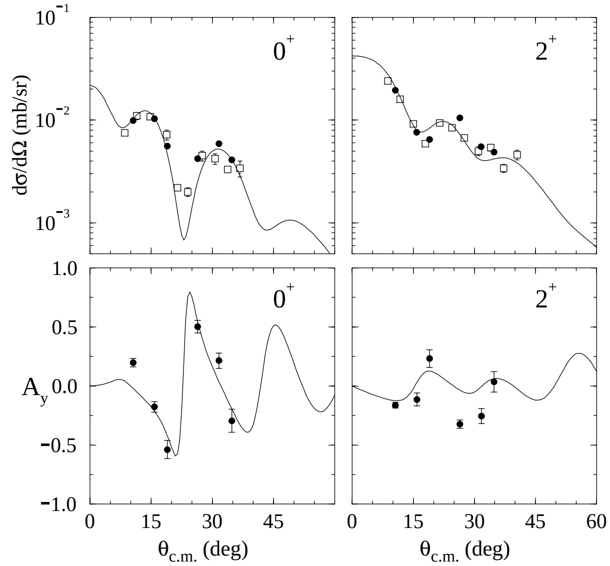

FIG. 1. Angular distributions of $d\sigma/d\Omega$ and A_y for the $^{58}\mathrm{Ni}(^{6}\vec{\mathrm{Li}}, d)^{62}\mathrm{Zn}$ reaction at $E(^{6}\mathrm{Li}) = 34$ MeV leading to the 0^+ g.s. and the 2^+ first excited state. The open squares (□) are from Ref. [19]. The solid curves are the results of finite-range DWBA calculations described in the text.

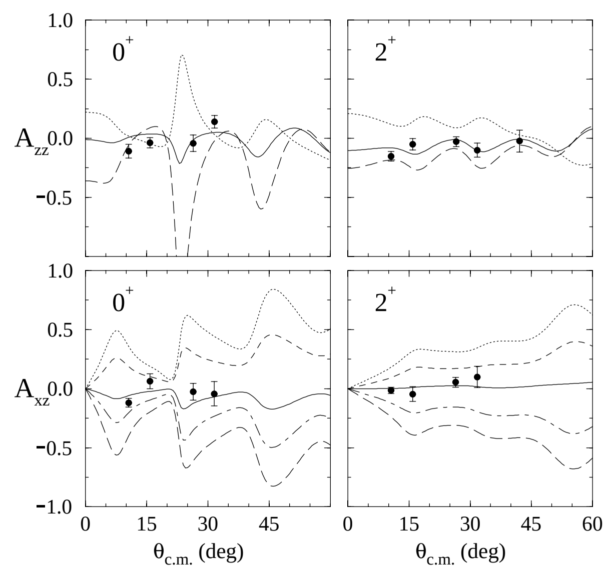

FIG. 2. Angular distributions of A_{zz} and A_{xz} for the $^{58}\mathrm{Ni}(^{6}\vec{\mathrm{Li}}, d)^{62}\mathrm{Zn}$ reaction at $E(^{6}\mathrm{Li}) = 34$ MeV. The solid curves assume a value of η that results in the best fit to that analyzing power (see Table I). The long-dashed (dotted) curves correspond to calculations with $\eta = +0.015$ (-0.015), while the dotted-dashed (short-dashed) curves, shown only for A_{xz}, correspond to $\eta = +0.0075$ (-0.0075).

underpredicted the cross section. To improve the agreement with the data we performed a search on these parameters with the results being used in the DWBA calculations. A spin-orbit potential with $V_{LS} = 3.0$ MeV, $r_{LS} = 1.26$ fm, and $a_{LS} = 0.65$ fm, as defined in Ref. [23], was included in the entrance channel and gave the best description of the elastic scattering VAP data. For the $^{40}\mathrm{Ca}(^{6}\vec{\mathrm{Li}}, d)^{44}\mathrm{Ti}$ calculations, no changes were made from the global parametrization [22] describing $^{6}\mathrm{Li} + {}^{40}\mathrm{Ca}$ elastic scattering.

For the exit channel we used a global set of deuteron OM parameters derived from elastic scattering [23]. In order to reproduce the positions of the maxima and minima better in the cross section and VAP angular distributions for the $(^{6}\vec{\mathrm{Li}}, d)$ reactions, it was necessary to decrease the radius parameter for the deuteron real Woods-Saxon (WS) potential by $\approx 12\%$. This change improved the agreement between the calculations and the experimental data for each transition considered here. It was also found that both deuteron and ^{6}Li OM tensor potentials, which are poorly known and difficult to constrain, had very small effects on the calculated angular distributions and therefore were not included in the final calculations. However, an estimate of their effects on the extracted value of η has been obtained, as discussed below.

The bound-state wave functions were calculated using a WS effective potential to bind the α particle to the deuteron in the entrance channel and to the target nucleus in the exit channel. The α + target bound-state geometry was parametrized by $R = 1.25 A_T^{1/3}$ fm and $a = 0.65$ fm, with the depth of the potential well adjusted to reproduce the correct binding energy. To describe the $\langle d\alpha \mid {}^{6}\mathrm{Li} \rangle$ bound-state overlap, we used the parametrization first suggested in Ref. [24] with $R = 1.9$ fm and $a = 0.65$ fm for both the S-state and D-state wave functions.

The overall very good agreement between the cross section and VAP data and the direct-transfer calculations is a strong indication that multistep processes are weak for these transitions and do not affect the DWBA predictions. Therefore we consider only the channel couplings in the entrance channel that are implicitly included in the OM potentials.

The value of η was the only quantity varied in obtaining final fits to the TAP data. As can be seen in Fig. 2, the DWBA calculations of the TAPs A_{zz} and A_{xz} are very sensitive to the magnitude and sign of η. The magnitude of the predicted TAPs scales with the magnitude of η, and the sign of the predicted TAPs tends to be opposite that of η. This statement is particularly evident for A_{xz}. For each TAP angular distribution, a best-fit value for η was determined via χ^2 minimization. In this way, we have extracted eight independent measurements for η, as summarized in Table I. The solid curves shown in Fig. 2 correspond to the best-fit η values for each analyzing power.

The uncertainty $\Delta\eta$ of each determination arises from a combination of statistical uncertainties and uncertainties in the DWBA parameters. The statistical uncertainty depends on the errors of the data points as well as the sensitivity of the calculation to changes in the value of η. This uncertainty was taken to be the difference between the value of η for χ^2_{min} and the value of η for $\chi^2_{\mathrm{min}} + 1$. However, since the chi-square per degree of freedom χ^2_ν for six of the individual results was >1 we chose to multiply those uncertainties by $\sqrt{\chi^2_\nu}$. The resulting statistical uncertainties are reported in Table I as $\Delta\eta_s$.

The uncertainties in the DWBA parameters are more difficult to estimate. A systematic investigation of changes in the OM parameters showed that very few significantly affected the description of the cross section and VAPs for the $(^{6}\mathrm{Li}, d)$ reactions. In addition, since these reactions take place above the Coulomb barrier, the elastic scattering observables are very sensitive to changes in the OM parameters. Therefore, the OM parameters were held fixed as described above. The potential binding the α particle to the target nucleus has previously been set by a variety of criteria (see, for example, Refs. [20,25]). The calculated TAPs were influenced by the geometry of this potential. To reflect this sensitivity and to account for the differences in the geometry parameters found in the literature, we assigned them an overall uncertainty of $\pm 15\%$. Incidentally, changes in the bound-state geometry by more than $\pm 15\%$ began to destroy the agreement with the cross section and the VAP data. The difference between the best value of η for the geometry parameters given above and the best value of η when each parameter was changed by $\pm 15\%$ was added in quadrature and is reported in Table I as $\Delta\eta_{\mathrm{BS}}$.

To estimate the uncertainty due to OM tensor potentials, we separately included deuteron and ^{6}Li tensor potentials in the calculations. The deuteron-nucleus tensor potential was adopted from the results of 30 MeV deuteron scattering from neighboring nuclei [26]. The ^{6}Li tensor potential was derived from ^{6}Li scattering from ^{12}C at 30 MeV [18]. The TAPs changed only slightly with the inclusion of each of these potentials. The important result, however, was that the extracted value of η did not change significantly at all. The uncertainty assigned to η due to the tensor potentials came from the difference in the best value of η with and without the tensor potentials. These results are reported in Table I as $\Delta\eta^{d}_{\mathrm{tens}}$ and $\Delta\eta^{\mathrm{Li}}_{\mathrm{tens}}$.

The final uncertainty for each of the eight determinations of η results from adding each of the individual uncertainties ($\Delta\eta_s$, $\Delta\eta_{\mathrm{BS}}$, $\Delta\eta^{d}_{\mathrm{tens}}$, $\Delta\eta^{\mathrm{Li}}_{\mathrm{tens}}$) in quadrature and is given in the right-most column in Table I. To obtain a final value for η, we took the average value of all eight determinations, weighted by the inverse square of the overall uncertainty for each determination, with the

TABLE I. Values of η and the associated uncertainties extracted from the tensor analyzing power measurements of $(^6\vec{\text{Li}}, d)$ reactions. The uncertainties have been multiplied by 10^3.

Target	State	TAP	η	χ^2_ν	$\Delta\eta_s$	$\Delta\eta_{\text{BS}}$	$\Delta\eta^d_{\text{tens}}$	$\Delta\eta^{\text{Li}}_{\text{tens}}$	$\Delta\eta$
^{58}Ni	0^+	A_{zz}	−0.0020	3.39	3.7	2.1	0.3	1.3	4.5
		A_{xz}	+0.0021	2.20	1.5	0.7	<0.1	0.2	1.7
	2^+	A_{zz}	+0.0063	1.63	2.6	8.6	0.6	0.1	9.0
		A_{xz}	−0.0007	0.83	1.2	0.3	<0.1	0.5	1.3
^{40}Ca	0^+	A_{zz}	+0.0024	1.44	4.4	4.1	0.1	1.7	6.3
		A_{xz}	−0.0017	2.80	5.4	5.8	<0.1	0.2	7.9
	2^+	A_{zz}	+0.0114	0.73	1.7	13.0	0.3	0.1	13.1
		A_{xz}	−0.0003	5.53	2.6	0.7	0.1	1.0	2.9

result being

$$\eta = +0.0003 \pm 0.0009 .$$

This result is generally in agreement with the results of Ref. [10], given the uncertainty placed on their determination of η. However, the upper limit on the value of η obtained here is an order of magnitude smaller than several previous determinations [2,11,12,14]. Using the overlap wave function obtained by the variational method of Ref. [9] in the DWBA calculations with the same OM potentials, we find large discrepancies between the calculations and the large oscillatory VAP data and the small TAP data. This confirms that the value of $\eta = -0.07$ is not compatible with the present experimental results.

By attributing the negative quadrupole moment Q to the D-state component of the $d + \alpha$ wave function and the deuteron quadrupole moment, it has been argued [11] that $\eta < 0$. However, calculations based on the three-body (αnp) models give systematically $\eta > 0$ and $Q > 0$ [2,8]. The very small value of η obtained here challenges these simple correlations between η and Q and indicates that η is influenced by complicated exchange effects in different components of the ^{6}Li wave function, which the variational methods are still unable to reproduce. This smaller value of η implies a smaller total D-state probability in the wave function of the ^{6}Li ground state. It, therefore, influences the determination of the neutron polarization when ^{6}Li is used as a polarized neutron target such as the ^{6}LiD target used at SLAC [7,27].

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