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Spin dependence of the isospin-forbidden decay ^{8}Be($E_x = 27.5$ MeV)$\rightarrow$d$+^6$Li

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The first $T=2$ state in ^{8}Be ($E_x = 27.483$ MeV) has been studied by means of the isospin-forbidden resonance in the reaction d$+^6$Li$\rightarrow\alpha+\alpha$. Angular distributions of the cross section and of the four analyzing powers for the reaction ^{6}Li($\vec{\mathrm{d}}$,α)^{4}He have been measured at energies above, below, and on resonance. Off-resonance analyzing power measurements have also been obtained for ^{2}H($^6\vec{\mathrm{Li}}$,α)^{4}He. Because of the symmetry properties of the reaction, the number of independent collision matrix elements is fairly small, and this makes it possible to determine the matrix elements directly by fitting the data. By comparing the matrix elements, one can determine partial widths (Γ_0 and Γ_2) for decay of the ^{8}Be state into d$+^6$Li states with channel spin 0 and 2. The measured ratio of the partial widths is $\Gamma_2/\Gamma_0 = 0.322 \pm 0.091$.

I. INTRODUCTION

Experimental information about isospin mixing in nuclei can be obtained in a number of ways. One common approach is to study nuclear processes which would be forbidden if isospin were strictly conserved. Recently, Freedman *et al.*[1] have measured the partial decay widths for various isospin-forbidden decay modes of the lowest $T=2$ state of a number of $A=4N$ self-conjugate nuclei, including ^{8}Be. Very few calculations of these partial widths have been made; however, in the case of ^{8}Be Barker and Kumar[2] have performed a shell model calculation. The results of this calculation are in fair agreement with the measurements. In the calculation the Coulomb interaction is treated as a perturbation which mixes the $T=2$ state with nearby $T=0$ and $T=1$ states of the same spin and parity ($j^\pi = 0^+$). This mixing is assumed to be responsible for the isospin-forbidden decays. Isospin mixing in the final state is neglected, since in this case the nuclear states involved are generally at low excitation energies.

In this paper we will present the results of a new experimental investigation of the isospin-forbidden decay of the lowest $T=2$ state in ^{8}Be ($E_x = 27.483$ MeV). The experiment involves a detailed study of the reaction d$+^6$Li$\rightarrow\alpha+\alpha$ with polarized d and ^{6}Li beams. Although both the initial and final states of these reactions have $T=0$, the $T=2$ state in ^{8}Be can be observed as a narrow resonance in the d$+^6$Li$\rightarrow\alpha+\alpha$ cross section.[3] In the present experiment, we have used a polarized deuteron beam to measure angular distributions of the cross section $\sigma(\theta)$ and of the four analyzing powers $iT_{11}(\theta)$, $T_{20}(\theta)$, $T_{21}(\theta)$, and $T_{22}(\theta)$ for the ^{6}Li($\vec{\mathrm{d}}$,α) reaction at energies above, below, and on resonance. In addition, a polarized ^{6}Li beam has been used to measure angular distributions of the four analyzing powers at energies above and below the resonance for the reaction ^{2}H($^6\vec{\mathrm{Li}}$,α).

In a general sense, there is reason to believe that measurements of the polarization observables may turn out to be important in the study of isospin mixing. Since these measurements provide information about the spin dependence of isospin-violating processes, they allow one to distinguish between isospin mixing caused by Coulomb interactions, which are spin independent, and possible spin-dependent isospin-violating components of the strong interaction.

In the present experiment, the use of polarized beams makes it possible to completely determine the d$+^6$Li$\rightarrow\alpha+\alpha$ reaction amplitudes on and off resonance. With this information we are able to extract the separate partial widths for the decay of the $T=2$ state into various angular momentum channels of the d$+^6$Li system.

The experimental techniques used to measure the cross section and analyzing powers are outlined in Sec. II. In Sec. III we describe the analysis in which the reaction amplitudes and partial decay widths are determined from the measurements. The significance of the results is discussed in Sec. IV.

II. DESCRIPTION OF THE EXPERIMENT

A. The ^{6}Li($\vec{\mathrm{d}}$,α)^{4}He measurements

The experimental procedures used to measure analyzing powers are similar to those described in detail in Ref. 4. The cross section σ_p for a reaction induced by a polarized deuteron beam can be written as[5]

$$\sigma_p(\theta) = \sigma(\theta)[1 + 2iT_{11}(\theta)\mathrm{Re}(it_{11}) + T_{20}(\theta)t_{20} + 2T_{21}(\theta)\mathrm{Re}(t_{21}) + 2T_{22}(\theta)\mathrm{Re}(t_{22})] \,. \quad (1)$$

Here, σ is the unpolarized-beam cross section, T_{kq} are the analyzing powers, and t_{kq} are the corresponding deuteron beam polarizations. The analyzing powers are defined according to the Madison convention.[6] From Eq. (1) one sees that the analyzing powers can be determined from measurements of ratios of cross sections for various polarization states of the incoming beam. Thus, to obtain the analyzing powers, one needs to measure only relative cross sections and the beam polarization parameters.[4]

The $T=2$ resonance in ^{6}Li(d,α)^{4}He is observed at a deuteron lab energy of 6.96 MeV[3]. Measurements by Noé *et al.*[7] indicate that the width of the resonance is 5.5±2.2

keV. The narrow width presents certain experimental difficulties. First, it is necessary to use a very thin target, and this severely limits the counting rate. In addition, one must be concerned about beam energy shifts. Since the cross section and analyzing powers vary across the resonance, a slight energy shift in the midst of an angular distribution measurement could result in systematic errors. These difficulties can be overcome, in part, by employing a large number of detectors to measure a complete angular distribution with a single run.

A schematic diagram of the experimental arrangement used for measuring the analyzing powers is shown in Fig. 1. Deuterons from the University of Wisconsin Lamb-shift polarized ion source[8] and tandem accelerator were momentum-analyzed by a 90° bending magnet and focused through rectangular slits 1.0 mm wide by 1.5 mm high at the entrance to the scattering chamber. Feedback systems were employed to keep the beam centered on the slits. α particles were detected in ten thin solid state detectors arranged as shown. In all cases, the peak of interest was free of background and was cleanly separated from other peaks in the spectrum, since the Q-value of the reaction is quite high (22.4 MeV). The target consisted of 30 $\mu g/cm^2$ ^6LiH evaporated onto a 10 $\mu g/cm^2$ carbon foil. The thickness of the ^6LiH layer corresponds to an energy loss of about 4 keV, which is comparable to the width of the resonance.

After passing through the main scattering chamber, the beam enters a $^3He(\vec{d},p)^4He$ polarimeter[9] which is used to measure the beam polarizations $Re(it_{11})$, t_{20}, $Re(t_{21})$, and $Re(t_{22})$. The uncertainty in the overall normalization of the measured polarizations is about 2%.

In order to obtain a relative measure of the integrated beam current during a run, one would ordinarily use a Faraday cup to collect the beam or employ as a monitor some reaction whose analyzing powers are well known (preferably zero). It was our original intention to use deuteron scattering from the hydrogen in the target as a beam monitor. However, this method was abandoned when it was discovered that the hydrogen-to-lithium ratio in the target was decreasing during the course of the experiment, presumably as a result of beam heating. In addition, the amount of ^6Li on the target was observed to decrease. For this reason it was necessary to monitor the target thickness in addition to the beam intensity. This was done by observing deuteron elastic scattering from ^6Li with a pair of monitor detectors placed symmetrically to the left and right of the beam at $\theta_{lab}=20°$. The disadvantage of this approach is that one needs to carry out a separate experiment to determine the T_{20} and T_{22} analyzing powers for deuteron elastic scattering. (Measurements of iT_{11} and T_{21} are not needed since the contributions from these analyzing powers cancel when the counting rates in the two monitor detectors are added.) The elastic scattering analyzing powers were measured at all relevant energies and were found to be very small ($T_{20}\approx 0.00\pm 0.006$, $T_{22}\approx -0.01\pm 0.007$). Measurements obtained at the different energies agreed to within the statistical uncertainties.

At the start of each running period, the resonance was located by measuring an excitation function of

$$\sigma(\theta_{c.m.}=15.1°)/\sigma(\theta_{c.m.}=75.4°)$$

(corresponding to lab angles of 160° and 90°). Previous measurements[3] show that $\sigma(15.1°)$ increases on resonance whereas $\sigma(75.4°)$ decreases, so that the ratio is sensitive to the resonance position. A typical excitation function is shown in Fig. 2. In all cases, the peak of the resonance was observed when the 90° analyzing magnet was set for a deuteron energy of 6.96 MeV.

Measurements were taken at the resonance energy 6.96 MeV, above the resonance at 7.04 MeV, and below the resonance at 6.88 MeV. At each energy the analyzing powers were determined by taking runs for several different polarization states of the incident beam (see Ref. 4). To check for possible systematic errors (e.g., errors resulting from beam energy shifts) the entire set of measurements was taken two times at 6.88 and 7.04 MeV and four times at 6.96 MeV. In all cases observed deviations were consistent with expected statistical fluctuations. The results reported here are weighted averages of the individual measurements.

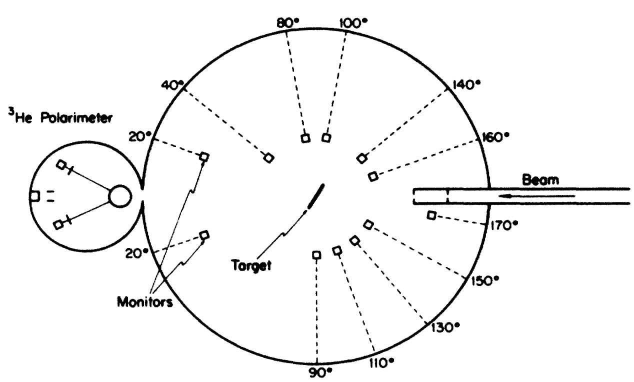

FIG. 1. Experimental setup for the $^6Li(\vec{d},\alpha)^4He$ measurements.

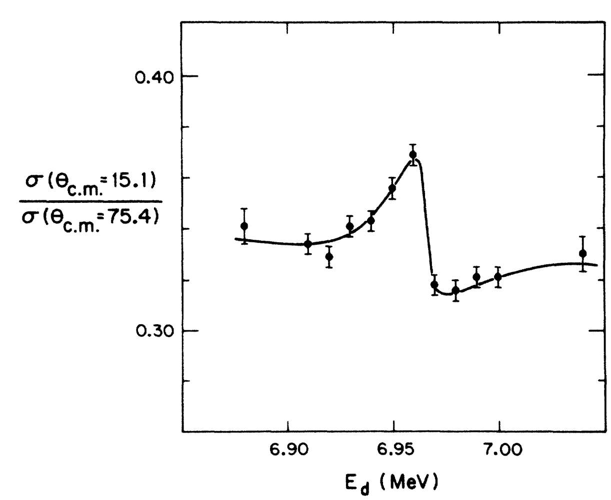

FIG. 2. Typical excitation function of $\sigma(\theta_{c.m.}=15.1°)/\sigma(\theta_{c.m.}=75.4°)$ for $^6Li(d,\alpha)^4He$. The curve is a guide to the eye.

From the polarized-beam measurements one obtains, in addition to the analyzing powers, information on the variation of the cross section with energy. However, no information is obtained about the angular dependence of $\sigma(\theta)$. In principle, one could obtain the angular distribution by measuring the relative solid angles of the various detectors in Fig. 1; however, this was not attempted. Instead, angular distributions of the relative cross sections were measured in a separate experiment using an unpolarized beam and a single detector. The overall normalization of $\sigma(\theta)$ was fixed by normalizing the data to existing cross section measurements[10] at 7 MeV.

The measurements are shown in Fig. 3. Since the final state involves identical particles, the cross section and analyzing powers must be either symmetric or antisymmetric about 90° in the c.m. frame, and therefore measurements are shown only for the forward hemisphere. The measurements designated as "off resonance" are averages of the measurements taken above and below the resonance.

It is interesting to note that while the resonance has relatively little effect on the cross section (σ changes by at most 8.6%), the analyzing powers are quite different on and off resonance. This is particularly true for T_{20} at forward angles.

The error bars shown in Fig. 3 include counting statistics, the statistical uncertainties in the measurements of the beam polarization, and the uncertainty in the monitor reaction analyzing powers. The error bars on the cross sections include an estimate of systematic errors associated with the measurement of the off-resonance angular distributions. In addition to the errors shown in the figure,

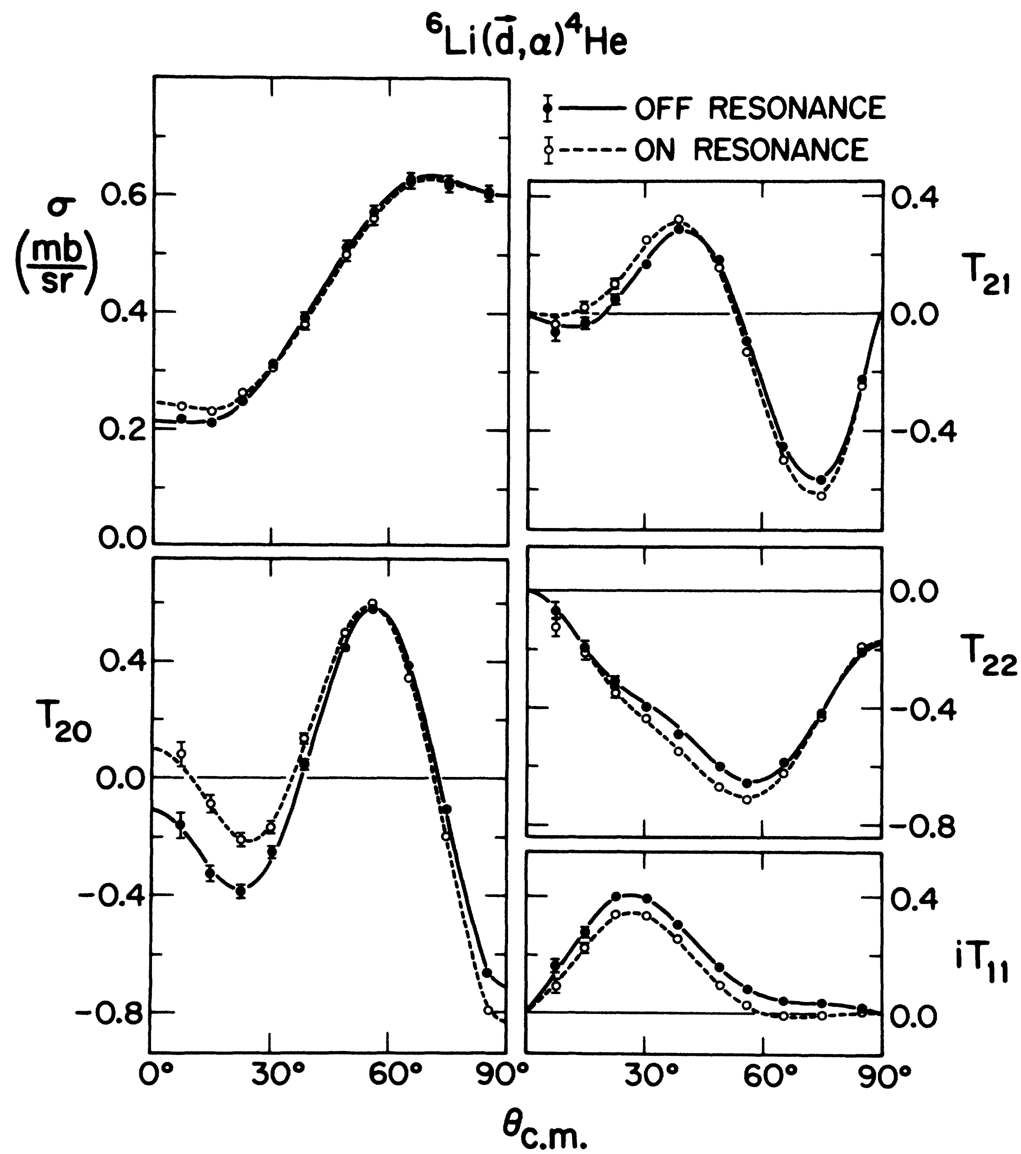

FIG. 3. Angular distributions of the cross section and analyzing powers for ^{6}Li($\vec{d}$,α)^{4}He, at and near the resonance energy for the lowest $T=2$ state in ^{8}Be. The off-resonance data are averages of measurements taken above and below the resonance. The curves are least-squares fits to these data and the measurements shown in Fig. 5.

the measurements are subject to an overall normalization uncertainty of 2% for the analyzing powers and 10% for the cross sections.

B. The ^{2}H($^6\vec{\mathrm{Li}}$,α)^{4}He measurements

The analyzing powers iT_{11}, T_{20}, T_{21}, and T_{22} for the reaction ^{2}H($^6\vec{\mathrm{Li}}$,α)^{4}He have been measured at a total of six angles. Only off-resonance data were obtained for this case. A schematic diagram of the experimental arrangement is shown in Fig. 4. A ^{6}Li beam from the University of Wisconsin crossed-beams polarized ion source[11] was accelerated and focused into the same scattering chamber used for the deuteron analyzing power measurements. The target consisted of a 2 cm diameter gas cell filled with deuterium gas at a pressure of approximately 760 Torr. The entrance and exit foils were 2.5 μm thick Havar. α particles were detected with a total of six thin solid state detectors arranged in symmetric pairs to the left and right of the beam. Each detector was equipped with a slit system which intercepts reaction products produced in the gas cell foils. A measure of the integrated beam current was provided by a Faraday cup located at the back of the scattering chamber.

The $T=2$ resonance in ^{2}H(^{6}Li,α)^{4}He is located at a ^{6}Li lab energy of 20.79 MeV. Measurements were taken below the resonance at 20.55 MeV and above the resonance at 21.03 MeV, corresponding to deuteron energies of 6.88 and 7.04 MeV, respectively, for the ^{6}Li(d,α)^{4}He reaction.

Measurement of the analyzing powers was complicated by the fact that no polarimeter was available for ^{6}Li beams. The polarization of the incident beam was determined periodically throughout the experiment by making use of the fact that for a given c.m. angle and energy, the analyzing power A_{yy} $(=-T_{20}/\sqrt{2}-\sqrt{3}T_{22})$ must be the same for the reactions ^{6}Li($\vec{\mathrm{d}}$,α) and ^{2}H($^6\vec{\mathrm{Li}}$,α) (see, for example, Ref. 12). By orienting the spin-alignment axis of the beam along the y axis, where we have adopted the coordinate frame of the Madison convention,[6] one may thus determine the tensor beam polarization parameter, τ_{20}. The beam polarization was typically $\tau_{20}=0.63$ (approximately 89% of the theoretical maximum), and was measured to an accuracy of approximately $\pm 3.5\%$ [including statistical errors and the uncertainty in the ^{6}Li($\vec{\mathrm{d}}$,α) A_{yy} values].

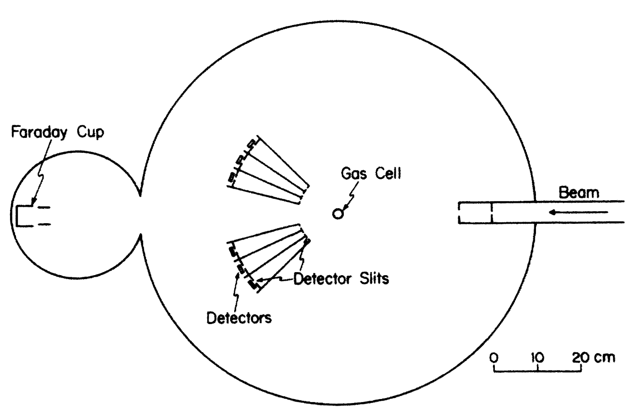

FIG. 4. Experimental setup for the ^{2}H($^6\vec{\mathrm{Li}}$,α)^{4}He measurements.

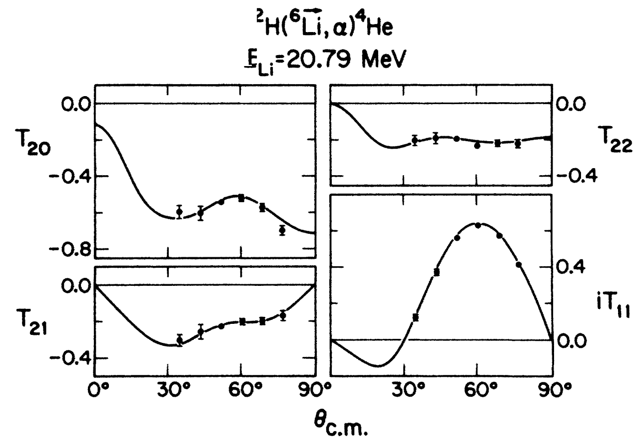

FIG. 5. Angular distributions of the off-resonance analyzing powers for ^{2}H($^6\vec{\mathrm{Li}}$,α)^{4}He. The data are averages of measurements taken above and below the resonance. The curves are least-squares fits to these data and the measurements shown in Fig. 3.

Four separate runs were taken at each energy and angle setting to measure the four analyzing powers. In each case the spin-alignment axis of the beam was oriented to maximize the beam moment of interest ($\hat{s}$ along $\hat{z}$ for T_{20}, along the line $x=z$ for T_{21}, along $\hat{x}$ for T_{22}, and along $\hat{y}$ for iT_{11}). This procedure reduces the sensitivity of the measurements to errors in the orientation of the spin. For the measurement of iT_{11} a purely vector polarized beam was used. Since a direct measurement of the vector beam polarization was not possible, it was assumed that the degree of depolarization was the same as for the tensor beam; i.e., the polarization was taken to be $\tau_{10}=0.73$, which is 89% of the theoretical maximum. For each run a fast spin-switching cycle, which included states with positive, negative, and zero polarization, was employed. Since it is possible to determine the analyzing powers by combining the unpolarized data with the data from either the + or − spin state, the full data set provides two measurements of each analyzing power.

The measurements are presented in Fig. 5. The error bars shown include only the statistical errors. In addition to the statistical errors, the measurements are subject to an overall normalization uncertainty which arises from the uncertainty in the beam polarization. This is taken to be $\pm 3.5\%$ for the tensor analyzing powers and $\pm 5\%$ for iT_{11}.

III. ANALYSIS

A. Determination of the matrix elements

The cross section and analyzing power measurements contain enough information about the $\mathrm{d}+{}^6\mathrm{Li}\rightarrow\alpha+\alpha$ reaction to allow an empirical determination of the collision matrix elements. The first step in the analysis is to derive an expression which gives the observables in terms of the matrix elements of the reaction. According to Lane and Thomas,[13] the transition amplitudes for any nuclear reaction can be expressed in terms of a set of collision matrix elements $U^{j}_{ls,l's'}$, where l and s (l' and s') are, respectively, the orbital angular momentum and the channel spin in the entrance (exit) channel, and where j is the total angular momentum.

Since the final state of the $d+{}^6Li \rightarrow \alpha+\alpha$ reaction consists of two identical spin-zero particles, $s'=0$ and $j=l'$. Symmetry requires l' to be even, and by parity conservation l must also be even. The allowed values of s are 0, 1, and 2. These restrictions greatly reduce the number of nonzero matrix elements.

It is straightforward to show that the cross section and analyzing powers for ${}^6Li(\vec{d},\alpha){}^4He$ can be expressed as

$$\sigma=\tfrac{1}{9}(|A_{00}|^2+2|A_{11}|^2+|A_{20}|^2+2|A_{21}|^2+2|A_{22}|^2)\,, \quad (2)$$

$$iT_{11}=\frac{1}{9\sigma}\mathrm{Im}(-2A_{11}A_{00}^{*}+A_{11}A_{20}^{*}/\sqrt{2}+3A_{21}A_{20}^{*}/\sqrt{2}-\sqrt{3}A_{22}A_{11}^{*}+\sqrt{3}A_{22}A_{21}^{*})\,, \quad (3)$$

$$T_{20}=\frac{1}{9\sigma}\mathrm{Re}(2A_{20}A_{00}^{*}-|A_{20}|^2/\sqrt{2}-|A_{11}|^2/\sqrt{2}+3\sqrt{2}A_{11}A_{21}^{*}-|A_{21}|^2/\sqrt{2}+\sqrt{2}|A_{22}|^2)\,, \quad (4)$$

$$T_{21}=\frac{1}{9\sigma}\mathrm{Re}(2A_{21}A_{00}^{*}-A_{21}A_{20}^{*}/\sqrt{2}-3A_{11}A_{20}^{*}/\sqrt{2}-\sqrt{3}A_{22}A_{21}^{*}+\sqrt{3}A_{22}A_{11}^{*})\,, \quad (5)$$

$$T_{22}=\frac{1}{9\sigma}\mathrm{Re}(2A_{22}A_{00}^{*}+\sqrt{2}A_{22}A_{20}^{*}-\sqrt{3}|A_{11}|^2/2-\sqrt{3}A_{11}A_{21}^{*}-\sqrt{3}|A_{21}|^2/2)\,, \quad (6)$$

where

$$A_{s\nu}(\theta)=\frac{-i\sqrt{\pi}}{k}\sum_{l,j}(2l+1)^{1/2}\langle s\nu,l0\,|\,j\nu\rangle U_{l,s,j}Y_j^{\nu}(\theta,0)\,. \quad (7)$$

Similar expressions can be obtained for the ${}^6\vec{Li}$ analyzing powers. The formulas in this case are identical to Eqs. (3)–(6), except that the sign of A_{11} is changed wherever it occurs.

Of particular interest in our analysis are the matrix elements with $j=0$. Since the $T=2$ state in ${}^8Be$ has $j^{\pi}=0^{+}$, only these matrix elements may resonate. Two $j=0$ matrix elements occur: one with $l=s=0$, referred to as the "non-spin-flip" amplitude, and a second with $l=s=2$, referred to as the "spin-flip" amplitude. The purpose of our analysis is to determine how these two matrix elements change in crossing the resonance. This will make it possible to obtain the separate partial widths for decay of the $T=2$ state into the non-spin-flip and spin-flip channels of the $d+{}^6Li$ system.

In order to determine the collision matrix elements, a computer program incorporating a nonlinear regressions routine was written. In this program the matrix elements are treated as free parameters which are varied to produce the optimum fit to the data. This is done in the usual way by minimizing the quantity

$$\frac{\chi^2}{N}=\frac{1}{n-m}\sum_{i=1}^{n}\left[\frac{f_i-y_i}{\Delta y_i}\right]^2. \quad (8)$$

Here the quantities y_i (f_i) represent the measured (calculated) values of the cross section and analyzing powers, while Δy_i is the corresponding experimental uncertainty. The quantity n is the number of data points, and m is the number of adjustable parameters.

In the fitting program the on- and off-resonance data sets are analyzed simultaneously. On resonance the two $j=0$ matrix elements are written as a sum of a background term $U^{\mathrm{bkg}}_{l,s,j}$, and a resonant term $U^{\mathrm{res}}_{l,s,j}$, while for the off-resonance data only the background term is retained. The remaining matrix elements are constrained to be identical for the two data sets. All matrix elements with $l \le 6$ were included in the analysis.

Our initial attempts to fit the data in the manner just described did not lead to acceptable χ^2 values. In these initial fits the uncertainties used in the calculation of χ^2 were just the errors shown in Figs. 3 and 5. This neglects two important sources of error. The overall normalization uncertainty in the measurements and the error which results from uncertainty in the setting of the detector angles can both be comparable in magnitude to the statistical error.

One way to include the effects of the angle uncertainty would be to increase each of the Δy_i by adding in quadrature a contribution proportional to the angle uncertainty times the slope of the analyzing power. However, this approach does not properly account for the fact that all the analyzing power measurements at a given angle are subject to the same angle error. In order to include these correlations properly, we treat each of the 16 detector angles (ten angles for the deuteron data, six for the ${}^6Li$ data) as a measured quantity with an uncertainty $\Delta\theta$, and allow for the possibility that the true value of the angle can differ from the measured value. This is done by incorporating into the fitting program 16 new adjustable parameters which represent the true detector angles. In addition, we modify the formula for χ^2/N to include 16 new terms in which f_i is the true angle, y_i the measured angle, and Δy_i the uncertainty. The angle uncertainties were taken to be $\pm 0.1°$ in the lab frame.

The same approach was used to include the overall normalization uncertainties. In this case we added six adjustable renormalization parameters (one for each of the four deuteron analyzing powers, one for the ${}^6Li$ vector analyzing power, and one common parameter for the three ${}^6Li$ tensor analyzing powers). Correspondingly, we included six additional terms in the calculation of χ^2/N. The normalization uncertainties were taken to be $\pm 2\%$ for the deuteron analyzing powers, $\pm 3.5\%$ for the ${}^6Li$ tensor analyzing powers, and $\pm 5\%$ for the ${}^6Li$ vector analyzing power.

With these modifications we were able to obtain a fit which has an acceptable χ^2. The best fit, which is shown by the curves in Figs. 3 and 5, has $\chi^2/N=1.07$ (corresponding to a confidence level of 0.32).

The problem of fitting the matrix elements to the measurements produces a complicated χ^2/N surface which, quite likely, has a number of local minima. In order to determine whether the fit shown in Figs. 3 and 5 does in fact give the true overall χ^2/N minimum, the search was repeated many times using different starting points and different fitting procedures. In all, over 100 searches were made, and roughly 10 different local minima were found. Three of these local minima had reasonably low χ^2/N values (1.07, 1.09, and 1.10). Since these three fits have virtually the same χ^2, there is no way to be certain which one corresponds to the correct physical solution. Fortunately, the existence of these multiple solutions is not a serious problem, because the extracted partial widths are approximately the same for all three cases (see Sec. III B). All of the remaining local minima had $\chi^2/N \geq 1.36$ (corresponding to confidence levels of less than 2%) and may safely be disregarded.

The results of our analysis indicate that the $T=2$ resonance couples to both the spin-flip and the non-spin-flip channels. In both cases, the resonant matrix element, $U^{\rm res}_{l,s,j}$, is several error bars away from zero. To demonstrate the resonant behavior of the spin-flip matrix element, the analysis was repeated with $U^{\rm res}_{2,2,0}$ constrained to be zero. The resulting best fit had $\chi^2/N=1.71$, which corresponds to a confidence level of 1.7×10^{-5}.

Although there is a significant improvement in the fit to the data when one allows the spin-flip amplitude to resonate, one might still argue that the reduction in χ^2/N is possibly the result of including more free parameters in the analysis. To address the question of whether adding more parameters will produce a significant decrease in χ^2/N, we performed a number of calculations in which $U^{\rm res}_{2,2,0}$ was constrained to be zero while one of the $j\neq0$ amplitudes was allowed to "resonate." In this way we introduce into the analysis a free parameter, $U^{\rm res}_{l,s,j}$. Since this parameter should be zero, there should be no improvement in χ^2/N when the parameter is included. This test calculation was carried out separately for 15 different $j\neq0$ matrix elements. On the average, χ^2/N dropped from 1.71 to 1.63, and the lowest χ^2/N value obtained was 1.44. These results support the conclusion that the $T=2$ compound nucleus state does, in fact, couple to the spin-flip channel.

B. Determination of the partial widths

Using the results described in the preceding section, we may now determine the partial widths for decay of the $T=2$ state into the spin-flip and non-spin-flip channels. Since we have an isolated resonance in the presence of a smooth background, the resonant part of each collision matrix element can be written as a simple Breit-Wigner term,

$$U^{\rm res}=-ie^{i(\phi_a+\phi_b)}\frac{(\Gamma_a\Gamma_b)^{1/2}}{E-E_R+i(\Gamma/2)} . \tag{9}$$

In this expression the subscripts a and b refer to the incident channel (d+^{6}Li) and the outgoing channel ($\alpha+\alpha$), respectively. The quantity E_R is the resonance energy, Γ is the total width, Γ_a and Γ_b are the partial widths, and ϕ_a and ϕ_b are the phases for each channel.

For the d+^{6}Li channel there are two partial widths: one for the non-spin-flip channel (denoted Γ_0) and one for the spin-flip channel (denoted Γ_2). On the other hand, the same outgoing-channel partial width appears in both $U^{\rm res}_{0,0,0}$ and $U^{\rm res}_{2,2,0}$, since the two matrix elements correspond to reactions leading to the same final-state angular momentum channel. In addition, we note that $U^{\rm res}_{0,0,0}$ and $U^{\rm res}_{2,2,0}$ have the same energy denominator. Thus, it is straightforward to obtain the ratio of the d+^{6}Li partial widths in terms of the ratio of the measured resonant matrix elements, i.e.,

$$\frac{\Gamma_2}{\Gamma_0}=\frac{|U^{\rm res}_{2,2,0}|^2}{|U^{\rm res}_{0,0,0}|^2} . \tag{10}$$

It is important to note that this expression is valid for any energy E (provided, of course, that E is sufficiently close to E_R to allow a measurement of $U^{\rm res}$), and that it remains valid even if the matrix elements used are averages taken over a range of energies. Thus the determination of Γ_2/Γ_0 is not complicated by the fact that the energy loss in the target used for the on-resonance measurements was comparable to Γ.

Using Eq. (10) and the values of $U^{\rm res}_{0,0,0}$ and $U^{\rm res}_{2,2,0}$ which correspond to the $\chi^2/N=1.07$ fit, we obtain

$$\frac{\Gamma_2}{\Gamma_0}=0.322\pm0.091 . \tag{11}$$

The uncertainty in Γ_2/Γ_0 was found by determining the curvature of the χ^2 surface at the minimum. This was done by carrying out a series of calculations in which Γ_2/Γ_0 was fixed at some value and the remaining parameters varied to minimize χ^2. The quoted error is the amount by which Γ_2/Γ_0 must be changed to increase the total χ^2 by 1. The results obtained from the alternate fits, which have $\chi^2/N=1.09$ and 1.10, are $\Gamma_2/\Gamma_0=0.357\pm0.091$ and $\Gamma_2/\Gamma_0=0.325\pm0.071$, respectively.

By combining the result in Eq. (11) with the measured value of the partial width for decay into the d+^{6}Li system (obtained from Ref. 1), we may determine Γ_0 and Γ_2 separately:

$$\Gamma_0=1165\pm185 \text{ eV}, \quad \Gamma_2=375\pm96 \text{ eV} . \tag{12}$$

IV. DISCUSSION

We have now seen that the measurements allow a determination of the partial widths Γ_0 and Γ_2. *A priori*, one would expect the partial width for the $s=2$ channel to be small. In the $T=2$ state the nuclear spins should all be paired off [i.e., the state is the analog of the ^{8}He ground state which has a shell-model configuration of $(1s_{1/2})^2$ for the protons and $(1s_{1/2})^2(2p_{3/2})^4$ for the neutrons], and since the mixing of this state with the $T=0$ d+^{6}Li channels is presumably caused by spin-independent Coulomb interactions, one would expect the decay to occur primarily to states with channel spin zero.

It is indeed found that Γ_2 is small; however, it is not zero. One is therefore led to ask if the observation of a nonzero Γ_2 can be taken as evidence for the existence of isospin-violating forces which are spin dependent and thus of nuclear rather than electromagnetic origin.

It is rather easily seen that decay into the $s=2$ channel is allowed even if the isospin-mixing forces are spin independent. To see this, it is convenient to introduce two spin operators. The first, $\mathbf{s}$, is taken to be the sum of the deuteron and ^{6}Li spins (i.e., the channel spin), while the second, $\mathbf{s}_N$, is defined as the sum of the eight individual nucleon spin operators. These two spin operators differ in that $\mathbf{s}$ contains the orbital angular momentum associated with the internal motion of the nucleons in the deuteron and in ^{6}Li.

Now the issue is whether Coulomb forces can mix the $T=2$ state in ^{8}Be, which is primarily a state with $s_N=0$, with an $s=2$ state of the d+^{6}Li system. Clearly, this can occur in a number of ways. First, the $s=2$ state of the d+^{6}Li system certainly contains small components with $s_N=0$. For example, in the deuteron D state the nucleon spins are antiparallel to the deuteron spin vector. Second, the wave function of the $T=2$ state in ^{8}Be is presumably not a pure $s_N=0$ state, but may well contain $s_N=2$ components. Third, we note that in the collision matrix formalism, the quantum numbers l and s refer to the properties of the scattering state in the asymptotic region. If the effective d+^{6}Li nuclear interaction contains terms which do not conserve channel spin, these interactions may introduce small $s=0$ components into the state which asymptotically has $s=2$ and $l=2$.

It is therefore clear that a measurement of Γ_2 does not provide direct evidence for the existence of spin-dependent isospin-violating interactions. Nevertheless, the present measurement does provide us with a potentially valuable piece of information about the spin dependence of the isospin-forbidden decay. In order to take full advantage of this information, it will be necessary to carry out a detailed calculation to determine whether the observed partial widths are consistent with what one would expect based on the assumption that the mixing results from the Coulomb interactions only. Such a calculation would require the use of realistic wave functions for the deuteron, ^{6}Li, and the ^{8}Be $T=2$ state, as well as scattering wave functions to describe the relative motion of the d+^{6}Li system.

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