Zeitschrift: Helvetica Physica Acta

Band: 34 (1961)

Heft: [6]: Supplementum 6. Proceedings of the International Symposium on polarization phenomena of nucleons

Artikel: Detection of 900 KeV vector polarized deuterons with the reaction Li6(d,)He4

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DOI: https://doi.org/10.5169/seals-513268

Detection of 900 KeV Vector Polarized Deuterons with the Reaction $Li^6(d, \alpha)He^4$

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Abstract. The existence of vector polarized deuterons after elastic scattering through 45° in the center of mass from He^4 at the 1.070 MeV resonance energy has been demonstrated by observing a right-left asymmetry in the alpha particles from the reaction $Li^6(d, \alpha)He^4$. The polarization has the correct energy dependence through the resonance. Viewing the second reaction at 45° in the lab, if we let $R = I_0(1-\varepsilon)$ and $L = I_0(1+\varepsilon)$, then for a left scattered polarized beam $\varepsilon = -0.065 \pm 0.010$. Similar measurements on $H^2(d, p)H^3$ at 45° give $\varepsilon = -0.03 \pm 0.025$.

Introduction

The possibility of producing vector and tensor polarized deuterons by using the $J = 3^+$ resonance occurring in d-He^4 elastic scattering at an incident deuteron energy of 1.070 MeV has been discussed by several authors [1, 2, 3][1]). The resonance level is only about 40 keV wide, and the recoil alpha particle absorbs more than 40 kev for deuteron scattering angles exceeding about 15° in the laboratory. Since the magnitude of the polarization drops sharply off the resonance, a double scattering experiment is impractical if deuterons are accelerated on helium gas. Polarization prediction for backward hemisphere scattering angles can be checked by accelerating alpha particles on deuterium gas and then re-scattering the deuterons in helium. The vector polarization is especially large in the forward hemisphere [3], however, and thus a measurement at a center of mass angle of 45° was considered profitable. In order to perform such a measurement, a suitable deuteron reaction on a light nucleus must be found which is sensitive to deuteron vector polarization.

Experimental limitations require a deuteron reaction with $Q > 0$ and $d\sigma/d\Omega \geqq 5$ mb/sterad. Four target nuclei used as analyzers of deuteron polarization are reported here: H^2, Li^6, B^{10}, and C^{12}. The reaction $Li^6(d, \alpha)He^4$ is indeed polarization sensitive, verifying the existence of vector polarization, but not its magnitude.

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[2]) Numbers in brackets refer to References, page 213.

Experimental Equipment

Figure 1 shows the gas scattering chamber configuration. The scattering angle in the polarizing reaction was fixed at 30°, or 45° in the center of mass. The predicted behavior of the cross section and the polarization components at this angle is given in reference [2]. The entrance and exit nickel foils were cooled by circulating the target gas through liquid nitrogen, and extracting it with a Kinney pump [4]. The target volume and gas pressure were adjusted to give a target approximately 40 keV thick. The monitor counter looked at the right scattered beam, and allowed a precise setting of the mean energy of the incident beam in the target volume by using the cross section resonance. The beam energy could be re-set to $\pm$ 10 keV, and remained constant to $\pm$ 3 keV for a run. The solid angle for the left scattered beam was 5×10^{-3} sterad, giving a polarized beam intensity on the analyzing target of the order of 10^7 particles/s. The analyzing reaction could be studied at angles of 45° and 135°. For 135° the 1/2″ × 1–1/2″ CsI(Tl) crystals were rotated about the target center. The solid angle for each counter was $\sim$ 0.10 sterad., and $\sim$ 5 counts/min were obtained in counters R and L.

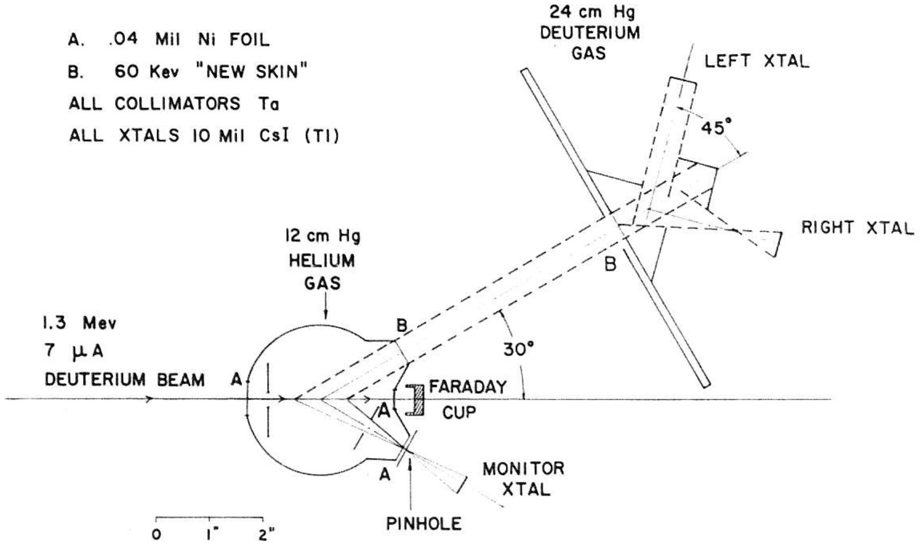

Figure 1

Double scattering chamber configuration. The 'New-Skin' windows are collodion films 60 keV thick for 900 keV deuterons.

The electronics is shown in figure 2. The display scaler in the monitor circuit counts for one second, displays, re-sets, and repeats about every five seconds. An RIDL 256 channel analyzer split into two sets of 128 channels was used to record the pulse height spectra simultaneously from the right and left counters, which look at the analyzing reaction.

Figure 3 shows a monitor counter scan as the incident beam energy is varied through the resonance. The beam energy shown was measured

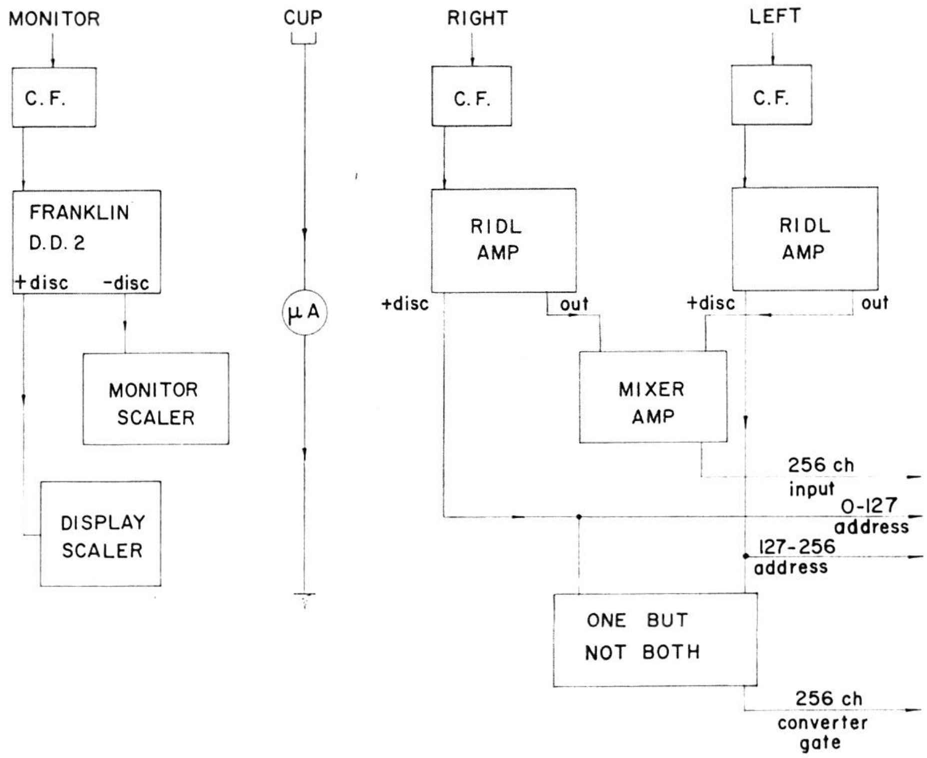

Figure 2
Block diagram of the electronics

by the Van de Graaff generating voltmeter, and therefore indicates a 230 keV loss in energy in the entrance foil and the target gas. Subsequent resonance scans have been made by measuring the excitation of the Van de Graaff bending magnet, which allows a more precise setting of relative beam energy. The uncorrected monitor counts showed a high energy tail because of background noise in the monitor counter. An integral discriminator as set to eliminate this noise at 1.20 MeV, but more background was counted as the energy increased.

Inherent asymmetries in the analyzing system were studied by using argon gas, cooled by liquid oxygen, in the first scattering chamber. At a generating voltmeter energy of 1.30 MeV and an argon pressure of 4 cm of mercury the scattered deuteron beam energy coincided with the energy normally obtained in resonance scattering from helium. This energy, after the beam left the polarizing chamber, was 900 $\pm$ 20 keV. The beam coulomb scattered from argon was normally about ten times as intense as the polarized beam. Argon runs always precede and followed helium runs to check for changes in the behavior of the experimental apparatus.

There was inherent asymmetry in the analyzer due to the intensity structure of the polarized beam, caused by the increase in the cross section towards forward angles. When the deuteron beam was coulomb scattered from argon the right side of the beam on the second target exceeded the left in intensity by about 30%. The net effect observed in over 100 argon runs, each to about 3% statistical accuracy, was that R/L for the analyzer reaction varied between 1.00 and 1.10. Thus $R/L \geq 1$, independent of such systematics checks as exchanging counters, reversing the target, turning the scattering chamber upside down, and reversing the electronics. All of these tests have been performed several times with the various targets used as analyzers.

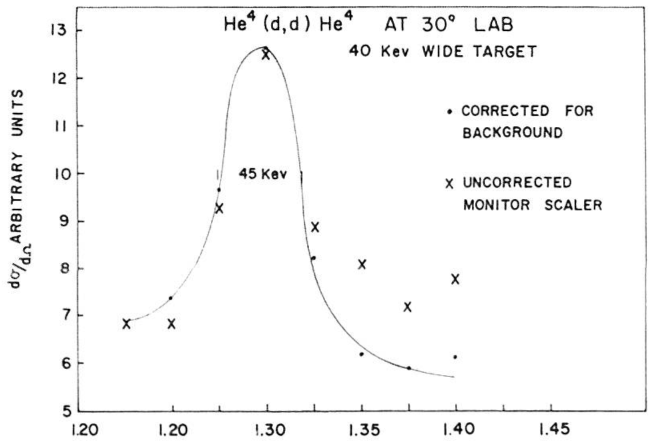

Figure 3

Typical scan of the scattering resonance with the monitor counter. The uncorrected tail represents low energy noise in the counter spectrum. The energy scale is the potential of the Van de Graaff dome.

The 130 keV thick deuterium gas analyzer is shown in figure 1. To study Li^6, B^{10}, or C^{12} as an analyzer a solid target of about 1 mg/cm^2 thickness was placed at the center of the gas target volume, and the «New Skin» window and defining slits were removed. Solid targets were prepared on 0.02 mil nickel foil backing; C^{12} and B^{10} were deposited by evaporating the water from a «dag» suspension. Li^6 was evaporated on the nickel foil in metallic form.

The technique for observing a polarization effect involved measuring R/L at the analyzer for deuteron energies on, above, and below the polarizing resonance, and using the argon R/L as a relative normalization. An «on-resonance minus off-resonance» difference in the asymmetry indicated both a polarized beam and a sensitive analyzer.

Results

Figure 4 shows a typical set of helium resonance runs with Li^6 as the analyzer at angles of 45° and 135° in the lab. The energy is set 10 keV below the peak rate determined as in figure 3, to correspond to the

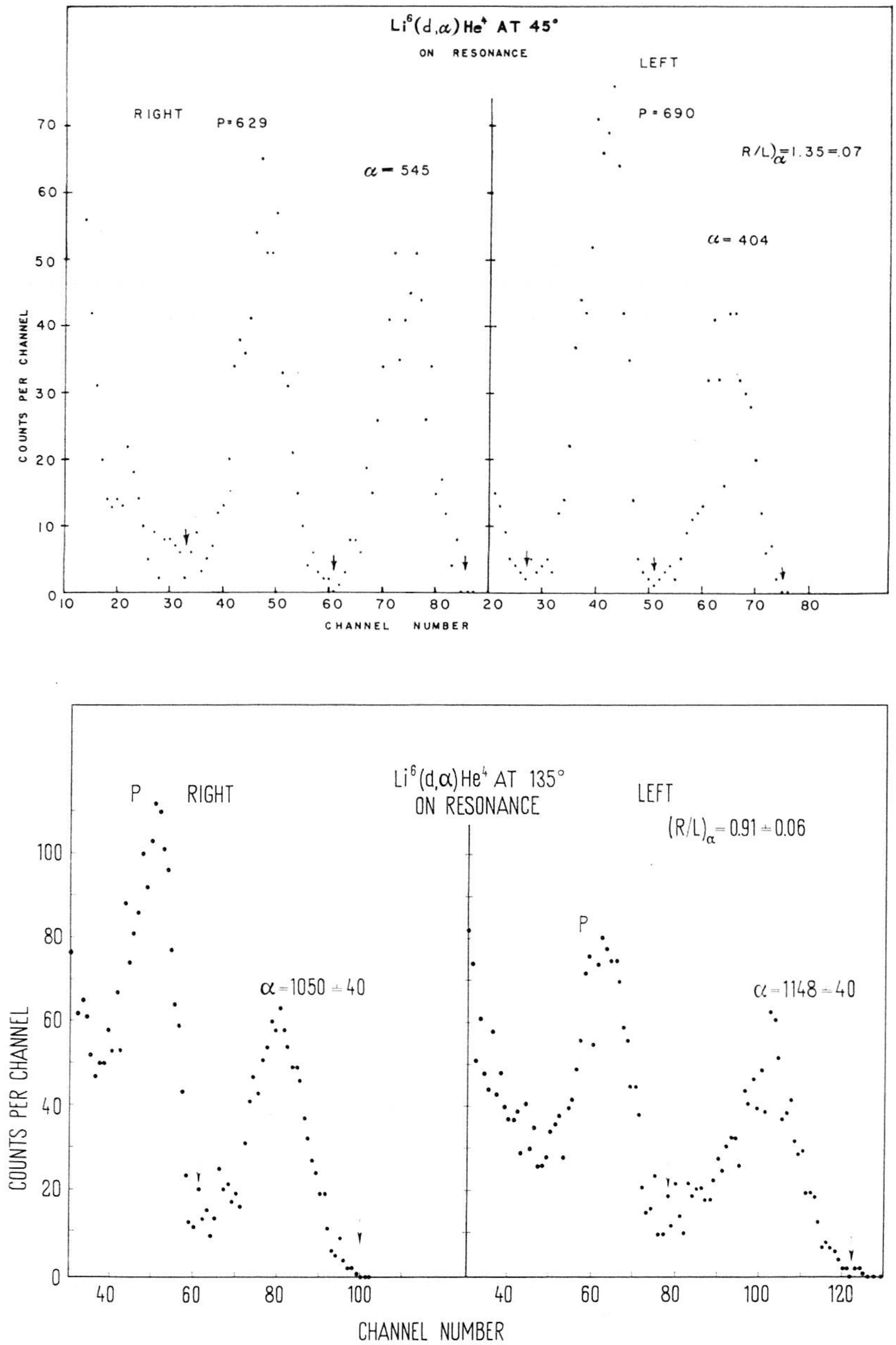

Figure 4

Typical pulse height spectra obtained from the asymmetry counters for $Li^6(d, \alpha)He^4$ at 45° and 135° with the polarized deuteron beam. 'On resonance' refers to the polarizing reaction energy.

expected position of the maximum polarization, as described in reference [2]. The low energy peak of each counter shown in figure 4 represents the two unresolved proton groups from $Li^6(d,p)Li^7$ and $Li^6(d,p)Li^{7*}$, where Li^{7*} is the first excited state, at 0.478 MeV. [6]. The 135° run lasted three hours; the 45° run lasted 70 minutes. Because the counters were much closer to the incident beam at 135°, the proton peaks appear on a large background. The second peak in each spectrum is alpha particles from $Li^6(d,\alpha)He^4$. The background is completely negligible for both protons and alphas at 45°, and only represents about 3% of the alpha rate at 135°. Since this 3% is essentially the same in both R and L, it is ignored in computing R/L. The poor separation between protons and alphas at 135° is therefore a resolution problem, and not due to background. Error in estimating this separation is included in the errors for 135° asymmetries.

Table I gives a resume of all of the helium runs performed with Li^6 as an analyzer. E refers to the energy of the incident beam at the center of the helium target. Both targets were about 1 mg/cm², or 400 keV thick for 900 keV deuterons, neglecting the stopping power of the unknown

Table I

R/L for $Li^6(d, p)Li^7$ and $Li^6(d, \alpha)He^4$ with deuterons initially scattered from helium gas

Li^6 TGT	E	θ'	$R/L)\alpha$	$R/L)_p$
A	1.07	45°	1.26 ± 0.07	0.95 ± 0.05
A	1.07	45°	1.08 ± 0.06	1.04 ± 0.04
A	1.07	45°	1.19 ± 0.05	1.02 ± 0.04
A	0.97	45°	1.37 ± 0.07	1.07 ± 0.06
B	0.97	135°	1.00 ± 0.07	—
B	1.06	135°	0.92 ± 0.06	—
B	1.06	135°	0.89 ± 0.06	—
B	1.06	135°	0.91 ± 0.05	—
B	1.17	135°	1.02 ± 0.07	—
B	1.17	135°	1.03 ± 0.06	—
B	0.97	135°	1.09 ± 0.11	—
B	0.97	135°	0.98 ± 0.11	—
B	1.06	45°	1.40 ± 0.10	1.10 ± 0.07
B	1.10	45°	1.10 ± 0.07	0.97 ± 0.06
B	0.97	45°	1.16 ± 0.07	1.10 ± 0.06
B	1.17	45°	1.02 ± 0.06	1.09 ± 0.05
B	0.97	45°	1.06 ± 0.06	1.03 ± 0.05
B	1.06	45°	1.35 ± 0.07	0.91 ± 0.06
B	1.06	45°	1.16 ± 0.05	1.02 ± 0.04
B	0.97	45°	1.05 ± 0.05	1.02 ± 0.05
B	1.17	45°	1.07 ± 0.07	1.09 ± 0.06

quantity of oxygen contamination. Table II gives the weighted average helium results, and the average normalization results obtained by replacing the helium in the first scattering chamber with argon. Each argon number represents about ten runs, but an error of 3% is nevertheless assigned because of possible systematic effects when windows are changed or pressures varied slightly. Both parameters could effect the beam structure, and have never been studied to better than 3%. Window changes occurred quite frequently during a series of runs. R/L for protons at 135° is not recorded because of the background. The essential features to note are that the argon runs in all cases result in $R/L)_\alpha \sim R/L)_p \sim 1.04$, and that $R/L)_p \sim 1.00$ for a helium scattered beam at the resonance energy, while $R/L)_\alpha \sim 1.15$ for $\theta' = 45°$ and $R/L)_\alpha \sim 0.90$ for $\theta' = 135°$ with the same resonant scattered beam.

Table II
Weighted average results for $Li^6(d, \alpha)He^4$

Li TGT	E	θ'	$R/L)_\alpha$	$R/L)_p$	Gas
A	1.070	45°	1.17 ± 0.03	1.00 ± 0.03	He
A	0.970	45°	1.37 ± 0.07	1.07 ± 0.06	He
A	1.070[a]	45°	1.04 ± 0.03	1.04 ± 0.03	Argon
B	1.060	135°	0.91 ± 0.03	—	He
B	0.970	135°	1.02 ± 0.04	—	He
B	1.170	135°	1.03 ± 0.04	—	He
B	1.070[a]	135°	1.02 ± 0.03	—	Argon
B	1.060	45°	1.25 ± 0.04	1.01 ± 0.03	He
B	0.970	45°	1.08 ± 0.04	1.06 ± 0.04	He
B	1.103	45°	1.10 ± 0.07	0.97 ± 0.06	He
B	1.170	45°	1.04 ± 0.05	1.09 ± 0.04	He
B	1.070[a]	45°	1.09 ± 0.03	1.07 ± 0.03	Argon

[a]) The argon energy is adjusted to give a scattered beam energy equal to the energy of the beam scattered from helium on the resonance, or 1.070 MeV. This scattered energy is 900 keV after leaving the gas target.

Simple kinematics requires that in the center of mass system every alpha particle appearing at θ', ϕ' must be accompanied by an alpha at $\pi - \theta'$, $\pi + \phi'$, regardless of initial polarization. Thus if we observe a right-left asymmetry ε, defined at $\theta' = 45°$ by

$$R = (1 - \varepsilon) \qquad \frac{R}{L} \cong 1 - 2\,\varepsilon \tag{1a}$$

$$L = (1 + \varepsilon)$$

then the asymmetry at $\theta' = 135°$ must have the form

$$R = (1 + \varepsilon)$$
$$L = (1 - \varepsilon) \qquad \frac{R}{L} \cong 1 + 2\,\varepsilon\ . \tag{1b}$$

Hence $\theta = 45°$ and $\theta' = 135°$ measure the same asymmetry parameter, and the R/L ratio must be less than unity at 135° by the same amount by which it exceeds unity at 45°, or the converse.

Using the notation of Lakin [6], the differential cross section in the center of mass system for a reaction initiated by vector polarized deuterons is

$$I\,(\theta, \phi') = I_0(\theta') + i\langle T_{11}\rangle\, C(\theta') \sin\theta' \cos\phi' \tag{2}$$

where $i\langle T_{11}\rangle = -\,i\sqrt{3/2}\,\langle S_x + i S_y\rangle$ for the incident deuteron beam, $I_0(\theta')$ is the unpolarized cross section, and $C(\theta')$ is a polynomial in $\cos\theta'$ with a maximum power $(\cos\theta')^{2L-1}$, L being the highest incoming orbital angular momentum participating in the reaction. Since a state which decays into two alpha particles can have only even orbital angular momentum, let us assume for $Li^6(d,\alpha)He^4$ that $L = 2$. Then the two alpha particle final state requires

$$C(\theta') = (a + b\cos^2\theta')\cos\theta' \tag{3}$$

or

$$I(\theta', \phi') = I_0(\theta') + i\langle T_{11}\rangle\,(a + b\cos^2\theta')\sin\theta'\cos\theta'\cos\phi'. \tag{4}$$

Therefore ε defined by equations (1) is given by

$$\varepsilon = i\langle T_{11}\rangle\,(a + \tfrac{1}{2}\,b)/2\,I_0\,(45°) \tag{5}$$

for s and d waves contributing to the reaction. The coordinate systems for this experiment are shown in figure 5 for $\theta' = 45°$. The center of mass to lab transformation amounts to a 3° change in angle, which produces no appreciable effect because of the $\sin\theta' \cos\theta'$ factor in equation (4).

Figure 6a shows a plot of the weighted averages of $(R/L - 1)$ from table II, where each number has been normalized to the corresponding average argon number. From the above discussion we see that we can combine all of the results into one graph of ε versus $E - E_0$ if we divide each $(R/L - 1)$ by two, and change the sign of each 135° datum. This has been done in figure 6b. Since $R/L > 1$ at 45°, ε is negative. The predicted form of the polarization from reference 2 with the experimental target width folded in is also sketched in figure 6b. The height of the polarization curve is normalized to the maximum value of ε; no energy shift in the prediction has been made. The finite resolution decreases

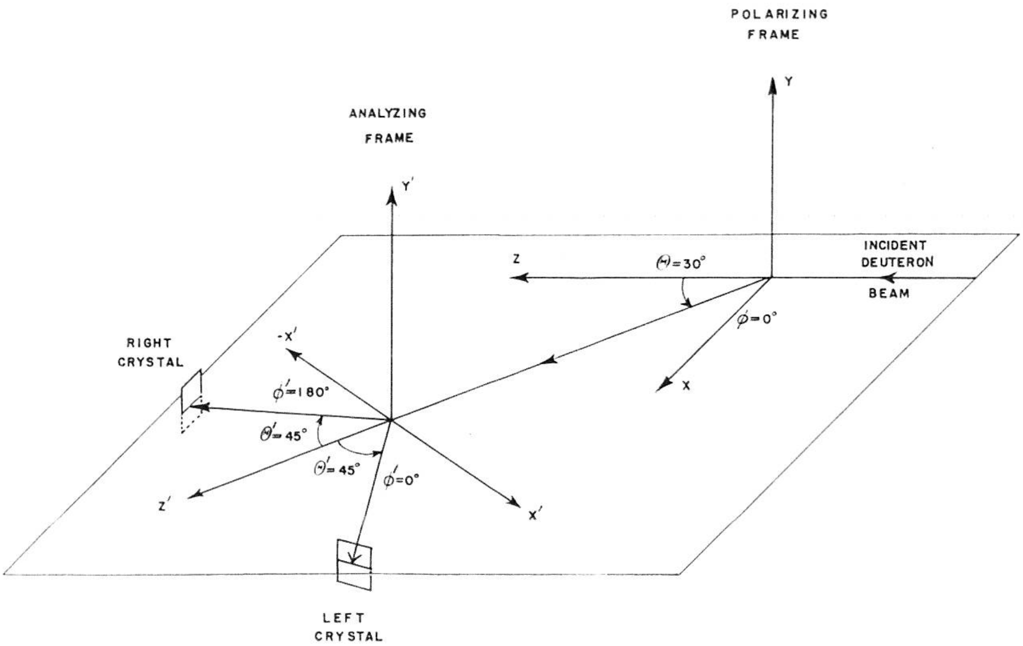

Figure 5

Diagram of the two coordinate systems for the double scattering. The analyzer angle is shown at 45°.

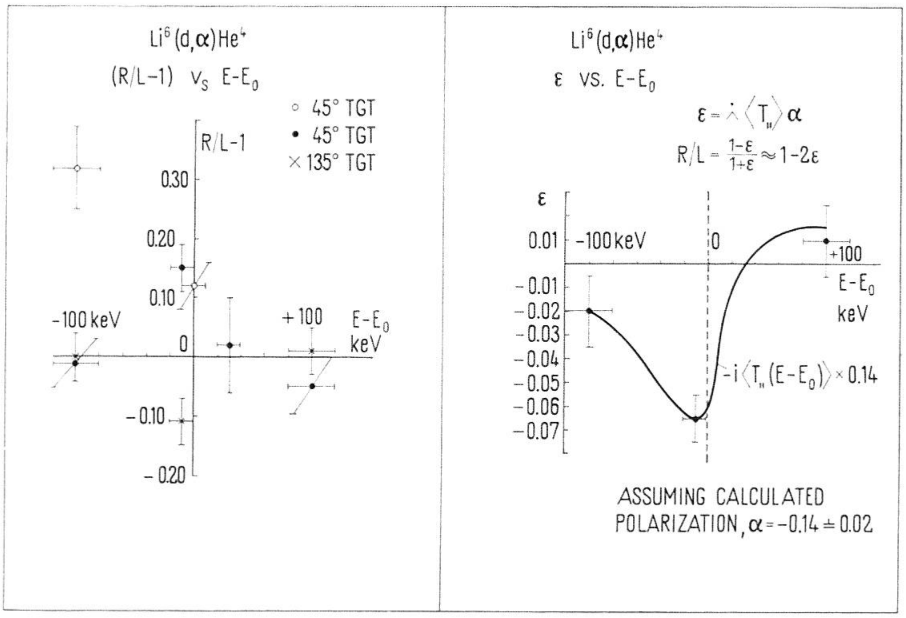

Figure 6

Final weighted average results for $Li^6(d, \alpha)He^4$ asymmetry as a function of the deuteron energy on the polarizing target. $E_0 = 1.070$ MeV. The quantity ε is defined in the text.

the predicted maximum of the polarization from 0.57 to 0.47. Using 0.47 as the maximum, $\varepsilon = -0.065 \pm .01$ from figure 6b gives

$$(a + 1/2\, b)/2\, I_0 = -0.14 \pm 0.02\,. \qquad (6)$$

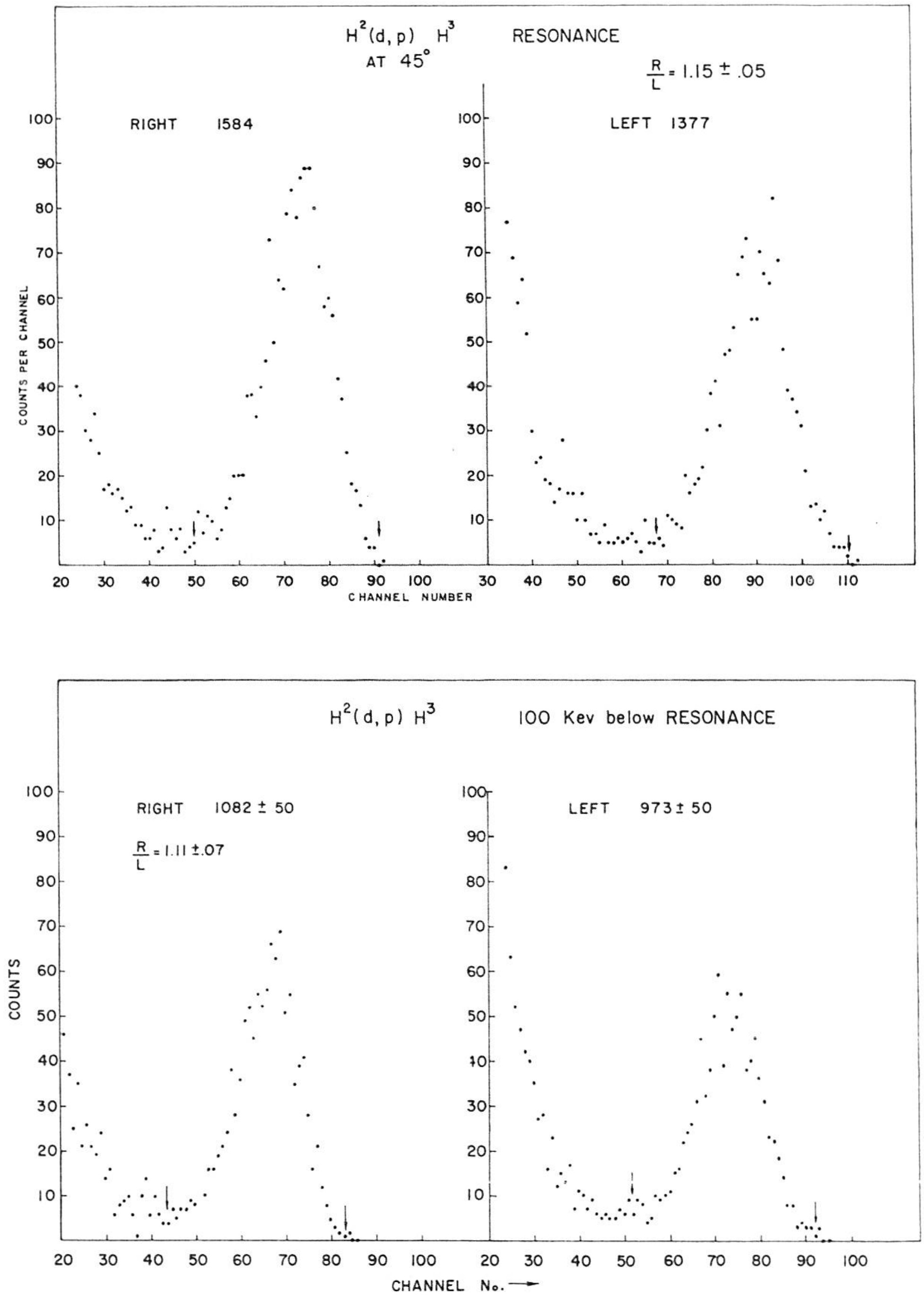

Figure 7

Typical pulse height spectra for $H^2(d, p)H^3$ on and off the polarizing resonance at 45°

This result represents an average value for incident deuteron energies from 900 keV to 500 keV, since the target is approximately 400 keV thick. Figure 6b can be interpreted as indicating, however, that a, b, and I_0 are slowly varying functions of energy in this range, since the energy

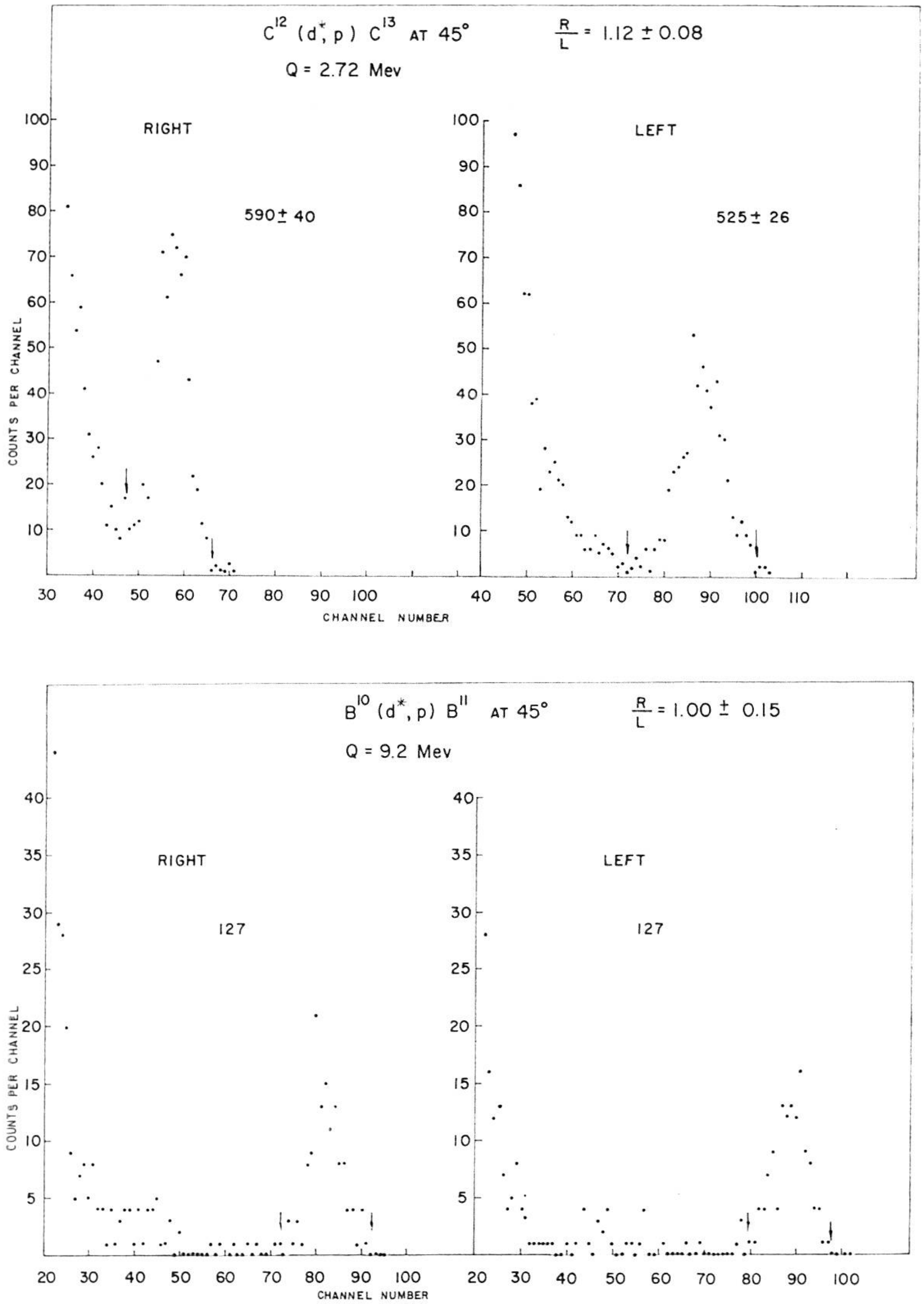

Figure 8

Typical pulse height spectra for $B^{10}(d, p)B^{11}$ and $C^{12}(d, p)C^{13}$ at 45° with the polarized beam on resonance.

dependence of $i\langle T_{11}\rangle$ completely accounts for the observed energy dependence of ε.

Figure 7 shows typical results of similar asymmetry runs made on and off the polarizing resonance with deuterium gas as the analyzing target. Defining ε as in equation (1a), the final results for $H^2(d,p)H^3$ at $\theta' = 45°$ and resonance scattered deuterons are

$$\varepsilon = -\,0.03 \pm 0.025\,. \tag{7}$$

Figure 8 shows resonance runs on $C^{12}(d,p)C^{13}$ and $B^{10}(d,p)B^{11}$. These reactions have not been carefully studied, for there has never been any indication of a positive effect. Our results at 45° on resonance are as follows:

$$B^{10}(d,\,p)\,B^{11}, \quad \varepsilon = +\,0.02 \pm 0.07 \tag{8a}$$

$$C^{12}(d,\,p)\,C^{13}, \quad \varepsilon = -\,0.02 \pm 0.04 \tag{8b}$$

Conclusions

The reaction $Li^6(d,\alpha)He^4$ has a broad resonance at 600 keV incident deuteron energy, which is attributed to a resonant state of Be^8 occurring at $E_d = 350$ keV with $\Gamma \simeq 500$ keV [5, 7]. The energy spread of the polarized beam across the target, from 900 to 500 keV, brackets the peak of this resonance [7], which is consistent with an analyzer sensitivity which varies slowly with energy. It seems likely, therefore, that it is this level which is sensitive to the vector polarization. Hence unless there is interference with some neighbouring level with spin two, this level cannot have spin zero, but must have spin of at least $J = 2^+$.

Further studies of this reaction are contemplated. It is hoped that the energy dependence of the polarization can be studied in detail. Confidence in the correct magnitude of the vector polarization can be strengthened by checking the magnitude of the predicted tensor polarization with the reaction $He^3(d,p)He^4$ [8]. There is a weak indication from these data that the protons from $Li^6(d,p)Li^7$, Li^{7*} show a small positive ε. Since the ground state of Li^7 is $J = 2/3^-$ and the first excited state is $J = 1/2^-$ [5], one might except opposite proton asymmetries from the two levels, and hence a cancellation effect on the total peak asymmetry. The two peaks can be resolved with this apparatus if a thinner Li^6 target is used, about 0.2 mg/cm².

We have profited by discussions with Dr. R. E. Segel and Dr. J. W. Olness during all phases of this work. Thanks are due to Mr. Dave Breitenbecher for efficient maintenance of the 2 MeV Van de Graaff accelerator.

Note added in proof: The authors have recently measured the polarization component $\langle T_{20} \rangle$ produced by this d-He^4 scattering resonance using $He^3(d, p)He^4$ as an analyzer (Physical Review, to be published). This component was found to have the correct magnitude and sign. A term $3/8 \sqrt{2} \langle T_{20} \rangle B(\theta)$ should appear in the R-L asymmetry expression, equation (2) above. It was ignored because $3/8 \sqrt{2} \langle T_{20} \rangle = -0{\cdot}12$, only 25% of the magnitude of $i \langle T_{11} \rangle$. The conclusion $J \geqq 2^+$ for the 22·6 MeV state of Be^8 is slightly weakened, for $B(\theta) \sim \cos\theta$ if $J = 0^+$. However, for $J = 0^+$ the observed asymmetry would have to come exclusively from $B(\theta) \sin\theta / I_0(\theta) \sim 0{\cdot}8$, an improbably large sensitivity.

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