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Comparison of Energy Levels of Li^6 from Various Reactions*

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The nuclear energy levels of Li^6 of excitations less than 5 Mev were studied by using inelastic scattering of deuterons and protons and the $Be^9(p,\alpha)Li^6$ reaction. An electrostatic accelerator and a broad-range magnetic spectrograph gave high precision and resolution. Levels were observed at 2.188 ± 0.006 Mev and at 3.560 ± 0.006 Mev, the former with all three reactions and the latter with all but deuteron scattering which is forbidden by the isotopic-spin selection rule. No other levels were observed. A study of the peak shapes yields 24 kev for the half-width of the 2.188-Mev level, in agreement with previous measurements on the compound nucleus.

I. INTRODUCTION

THE Li^6 nucleus, partly because it is so light, has been the subject of a large number of experiments by many investigators. In spite of this, several uncertainties remain in the number, position, and widths of the levels below 5-Mev excitation.

The first level, known to be at 2.19-Mev excitation, has been observed by scattering of deuterons from helium,[1,2] inelastic scattering of protons,[3,4] and deuterons[4] from Li^6, the $Be^9(p,\alpha)Li^6$ reaction,[5] and the $Li^7(He^3,\alpha)Li^6$, $Li^7(d,t)Li^6$, and $Li^7(p,d)Li^6$ reactions.[3,6–8]

The experiments of high precision, namely, the deuteron scattering from helium and the (p,α) reaction, give an excitation of 2.186 Mev and agree within 2 kev of each other. Agreement concerning the width of the level is not so good, however, as the two scattering experiments give a width of 23 kev in the center-of-mass system, while the (p,α) reaction was stated to give less than 8 kev.[5] This figure, which was obtained by examination of the shape of the energy distribution of alpha particles from a thick target, is a limit on the spread in energy of the particles rather than a limit on the width of the level. The corresponding limit on the level width is 17 kev. After re-examination of this and other data on peak shapes, H. T. Richards concludes that the limit should have been set somewhat higher, as was mentioned in reference 1. Since the state can decay to He^4 plus a deuteron, an appreciable width would be expected. This decay, as well as the appearance of the state in inelastic deuteron scattering, indicates an isotopic spin of zero.

A second state of Li^6 has been observed with the $Li^7(He^3,\alpha)Li^6$ reaction,[6] the $Li^7(p,d)Li^6$ reaction,[3] and through the gamma ray to the ground state following the $Be^9(p,\alpha)Li^{6*}$ reaction.[9] The gamma-ray energy reported as 3.572 ± 0.012 Mev furnishes the only precise location of this state. The fact that gamma emission occurs in successful competition with particle emission suggests that this state has a small width, a conclusion corroborated by the observation of Li^6 recoils excited to this level in the $Li^7(He^3,\alpha)$ reaction.[6]

Previous work at this laboratory[4] failed to find inelastic deuteron scattering from Li^6 leading to the second excited state, supporting the assumption, based on location, that this state has isotopic spin 1. The gamma emission, in preference to the breakup into He^4+d, and the fact that this state is not observed in the deuteron on helium scattering also indicate $T=1$.

The scattering of deuterons from helium[2] indicates a very broad level at 4.52 Mev, and the $Li^7(He^3,\alpha)$ reaction[6] gives a suggestion of a level near 4.3 Mev. No other levels have been found below 5 Mev.

The present work uses the inelastic scattering of protons and deuterons and the $Be^9(p,\alpha)Li^6$ reaction to survey the levels in Li^6 up to 5-Mev excitation, seeking to measure positions, widths, and isotopic spins with particular interest in comparing the results from the different reactions. Of more general interest is the comparison of a level width observed in a residual nucleus with the width derived from measurements on the compound nucleus. The theory of the energy distribution of particles emitted to a state in the final nucleus has not been worked out in the general case. It appears that the technique may often provide a useful tool for the determination of the total widths of levels.

II. EQUIPMENT AND PROCEDURE

Most of the techniques used in this experiment are those in routine use by the MIT-ONR generator group. Targets were prepared by vacuum evaporation of metallic lithium, enriched to 95% in the mass-6 isotope, or metallic beryllium onto thin Formvar backings. (The enriched lithium was obtained from the Stable Isotopes Division, Oak Ridge National Laboratory.) The lithium targets were reinforced by a thin

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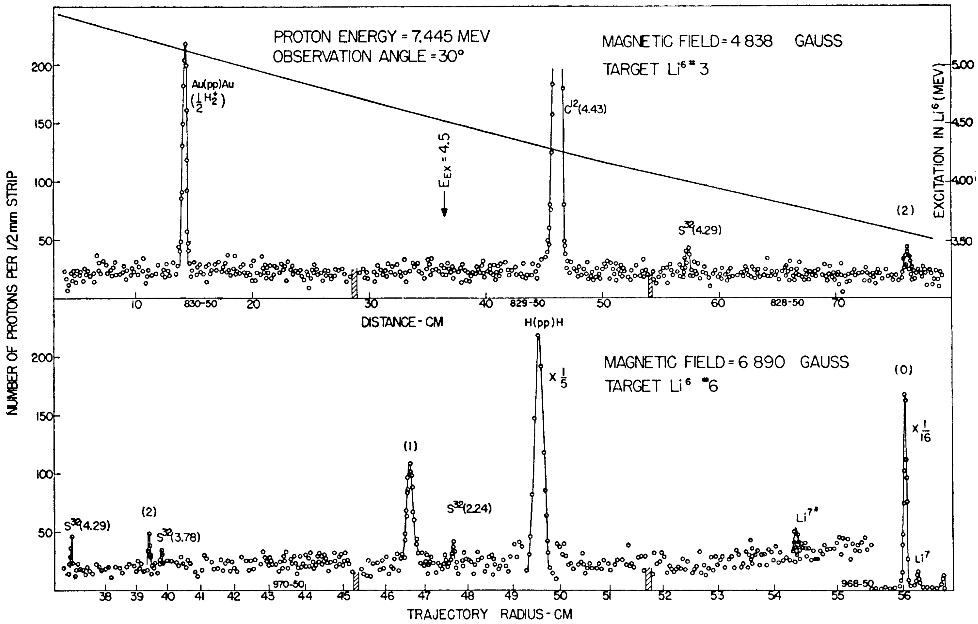

FIG. 1. Magnetic analysis of protons emitted from a Li^6 target under proton bombardment. The number of proton tracks in a $\frac{1}{2}$-mm strip across the exposed zone of the nuclear emulsions is plotted against distance along the emulsion for exposures at two magnetic fields. Polonium alpha particles were used to obtain the calibration of plate distance in terms of trajectory radius. Both abscissa scales apply to both plots. The diagonal line in the upper graph may be used to obtain the Li^6 excitation energy, read on the right-hand scale, corresponding to any plate distance on that plot.

layer of gold evaporated onto the back of the Formvar. The MIT-ONR electrostatic generator furnished protons and deuterons at bombarding energies ranging from 7.0 to 7.5 Mev, and the MIT broad-range spectograph[10] recorded the reaction products at angles ranging from 30 to 90 degrees. A survey of target materials and possible contaminations was made by observing protons elastically scattered from the target. In addition to particle groups from the target materials, groups were found from gold, oxygen, carbon, hydrogen, and a small amount of sulfur normally present in Formvar.

Analysis of the observed peak shapes to give level widths was based on the calculations and measurements of the spectrograph focal properties carried out by Zimmerman.[11]

III. SPECTRA

The spectrum of protons elastically and inelastically scattered from lithium targets was recorded at several angles with different bombarding energies. At 90 degrees with an incident energy of 7.03 Mev, the spectrum covered proton energies from 5.0 to 1.4 Mev, corresponding to excitations in Li^6 from zero to 4.1 Mev. At 60 degrees, a bombarding energy of 7.44 Mev was used, and the range of excitation covered was 3.5 to 5.2 Mev; at 30 degrees and 7.44 Mev, the range was zero to 5.4 Mev. The latter spectrum is shown in Fig. 1, where the two graphs are plots of the particle tracks on nuclear emulsions exposed at the two spectrograph fields needed to cover the 5.8-Mev range of proton energies, allowing some overlap. Particle groups are shown that arise from elastic scattering from Li^7, Li^6, and hydrogen, and from inelastic scattering from S^{32}, C^{12}, Li^7, and Li^6. The Li^6 groups are numerically labeled, starting with zero for the ground state.

The variation of dispersion with position on the plate is seen in the difference of spacing between the lithium second excited-state group and the S^{32} group appearing on both the upper and lower plots. The group at a radius of about 41 cm on the top plot is produced by the elastic scattering of protons from the gold target backing. These protons originate from the molecular beam of half-energy which momentarily passes through the deflecting magnet as the generator energy falls after a spark or at the end of a run.

It is seen that the first state gives a broad intense group, the second state gives a weak narrow group, and no higher levels are observed. In examining the peak widths, it should be recalled that the spectrograph dispersion increases markedly for the larger trajectory radii. The apparent energy width of the elastic group from hydrogen is caused by the rapid change in energy over the $\frac{1}{4}$-degree range of acceptance angle of the spectrograph. The background observed comes from slit-edge scattering in the input-beam slit system.

Deuteron spectra were recorded at 7.01 Mev and

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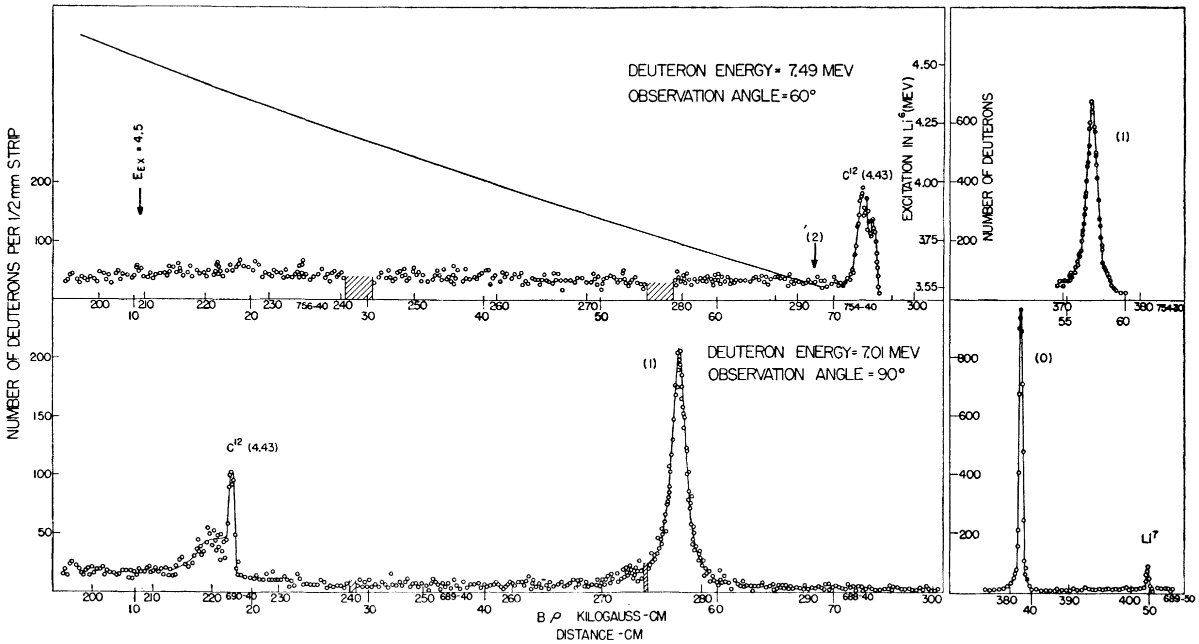

FIG. 2. Magnetic analysis of deuterons emitted from a Li^6 target under deuteron bombardment. The arrow marked (2) in the upper graph indicates the position calculated for a group of deuterons corresponding to the second excited state of Li^6.

90 degrees and 7.49 and 60 degrees and covered excitations from zero to 3.4 Mev and 1.7 to 4.6 Mev, respectively. Parts of the spectra are shown in Fig. 2. The only groups seen are those from the elastic scattering from Li^6 and the inelastic scattering from the first excited states in Li^6 and in C^{12}. The position at which the second excited-state group would appear is marked by an arrow near the C^{12} inelastic group. As in the case of the protons, the width of the first excited-state group is caused by the natural level width, while the width and asymmetry of the C^{12} inelastic group is caused by straggling in the target backing. Again, the background arises from slit-edge scattering. A triton group, not shown in Fig. 2, was also found. It corresponded to the Li$^7(d,t)$ reaction proceeding to the first excited state of Li^6. The identification was confirmed by a bombardment of a natural lithium target. No attempt was made to observe the triton group leading to the ground state. A group leading to the second excited state would have been obscured by an intense alpha-particle group from the O$^{16}(d,\alpha)$N^{14} reaction.

Alpha-particle spectra recorded at 30 degrees with 7.31-Mev protons incident and at 60 degrees with 7.25-Mev bombardment are shown in Fig. 3. In addition, runs were made at 30 degrees and 7.32 and 7.48 Mev. Two sets of beryllium targets were used, neither of which was entirely satisfactory. The first had a thin, reasonably uniform, layer of beryllium, but contained a considerable amount of impurity in the backings. The second set was relatively free of impurity but had a small amount of beryllium on the reverse side of the backing, giving a double peak for each particle group, as may be noted in the upper portion of Fig. 3.

Three groups of alpha particles are seen, corresponding to the ground and first two excited states of Li^6. A background of alpha particles from the three-particle reaction giving a deuteron and two alphas rises with decreasing momentum from its threshold, which is marked by an arrow to the right of the first excited-state group in the upper spectrum. A group of triply charged Li^6 recoil nuclei from the reaction leading to the ground state is seen at the left of the spectra. The recoil nuclei have a range very close to that of alpha particles at this momentum and were not distinguished from them in counting the plate. Of course, the shift of the peak with energy and angle confirms the identification. Again, groups corresponding to only two excited levels are seen.

IV. FIRST EXCITED STATE

Several determinations of the half-width of this level were made using each of the reactions at various bombarding energies, angles of observation, and with different input and spectrograph slit settings. The best results are those from proton and deuteron scattering, because here energy loss in the target was negligible.

Factors other than the natural level width contributing to the observed peak widths are a spread in energy of the incoming beam, variation in energy loss in the target, finite size of the target spot, and aberration of the spectrograph. The relative effect of each

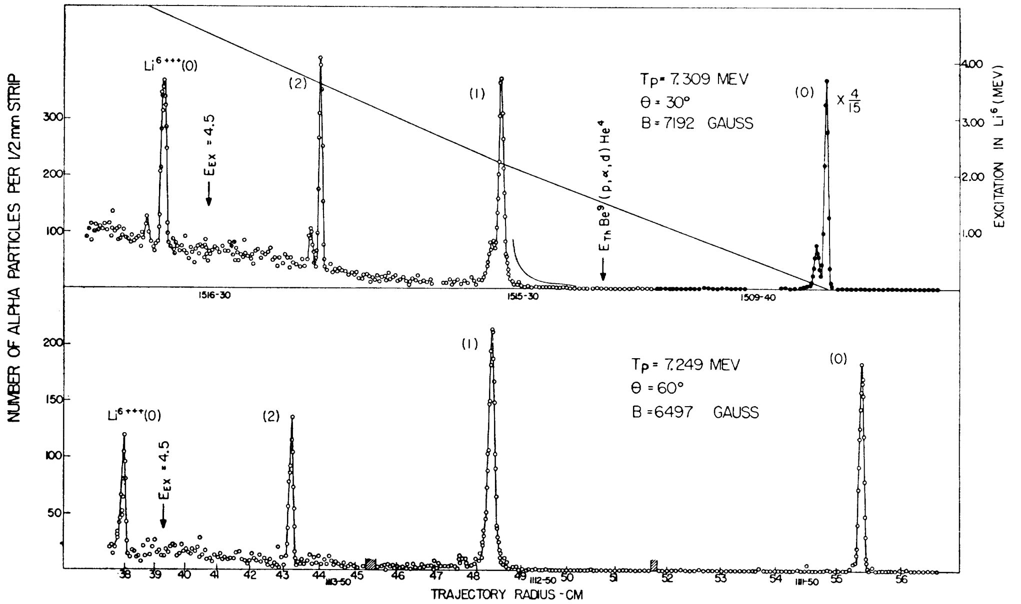

FIG. 3. Magnetic analysis of alpha-particles from a beryllium target bombarded by protons of energy 7.309 Mev (upper graph) and 7.249 Mev (lower graph). The solid curve at a radius of 49 to 50 cm on the upper graph is the alpha-particle count from a longer exposure showing that the observed background approaches the calculated three-particle threshold as the exposure is increased.

of these depends, among other things, on the dispersion and magnification of the spectrograph. In order to check the estimate for the magnitude of each factor, two runs were made with a narrow ($\frac{1}{4}$-mm) 7.03-Mev proton beam spot, a small spectrograph acceptance angle, and narrow beam analyzing magnet slits. The spectrograph was set at 90 degrees, and the field was adjusted to place first the elastic group and then the inelastic group at a given position along the plate. The position chosen was near the upper end of the focal surface where the dispersion is high. These results are shown on the lower portion of Fig. 4. At these two settings, an inelastic peak corresponding to the first excited state and one from the narrow second excited state also appeared at a point near the bottom end of the focal surface where the dispersion is lower. The latter two peaks are shown in the upper part of Fig. 4. In these plots, equal distance intervals correspond to equal energy intervals to within 5%, and the abscissa may be taken as essentially linear in energy.

TABLE I. Widths of the first excited state.

Reaction	Bombarding energy (Mev)	Angle of observation (degrees)	Source size (mm)	ΔQ (kev)
(p,p')	7.03	90	$\frac{1}{2}$	25
	7.03	90	$\frac{1}{2}$	27
	7.03	90	$\frac{1}{4}$	22
	7.03	90	$\frac{1}{4}$	27
	7.44	30	$\frac{1}{2}$	26
(d,d')	7.01	90	$\frac{1}{2}$	25
	7.49	60	$\frac{3}{4}$	24
(p,α)	7.32	30	$\frac{3}{4}$	31
	7.48	30	$\frac{1}{2}$	27
	7.25	60	$\frac{3}{4}$	30
(d,t)	7.49	60	$\frac{3}{4}$	<27

From the known aberration and magnification, it may be calculated that aberration and source size contribute a very small amount to the observed peak widths. The major factors that determine the shape of these peaks are the input energy spread, the variation of energy loss in the target, and the distribution in energy ascribed to the natural width of the level. For a level as narrow as the first excited state here, the true shape should be given by the resonance formula, in which the variation of the partial widths across the level may be neglected. Within the statistical error of the present measurement, the resonance shape is indistinguishable from a Gaussian curve. Since the natural width is large compared to either of the spreads from the remaining instrumental factors, it is considered a good approximation to assume that the observed width is the square root of the sum of the squares of the natural width and the instrumental energy spread.

The combined effects of the instrumental factors are exemplified in Fig. 4 by the narrow peaks, which are associated with levels presumed to have zero natural width. These measurements are not accurate enough to separate the effect of input energy spread from the effect of target thickness. Since the former should contribute equal energy increments to both peaks, the increase in stopping power as energy decreases should render the lower energy peak wider. However, the opposite is observed. Nevertheless, an upper limit for the variation of energy loss in the target is set by the observed width of the second excited-state group by assuming all the energy spread to come from this effect. Then, using the ratio of stopping powers for the energies of this group and the elastic group, it is found that target thickness contributes a negligible amount to the observed width of the elastic peak. If this is the case, the width of the elastic peak must be ascribed wholly to energy spread in the beam. The figure obtained is higher than the estimate obtained from the slit settings of the beam-analyzing magnet, so that it must be assumed that, for the run giving the elastic peak, there was a slight drift of the magnetic field. By using the observed width of the elastic peak and assuming the variations to be caused entirely by beam energy spread, the contribution to energy width of the first excited-state group was calculated. This was then subtracted as the square root of the sum of the squares from the observed width to find the spread in energy caused by the level width. The result is 19 kev. This is quite insensitive to the assumptions regarding the origin of the observed width of the peak from elastic scattering, because the total width of this peak is only about one-third the width of the peak from inelastic scattering.

From the inelastic peak at the position of lower dispersion and the peak from the second excited state, similar calculations give an energy spread of 23 kev.

Estimates of the level width were made in a similar way from all the peaks observed with the three reactions. The results are tabulated in Table I in the column marked ΔQ. For the (p,α) and (d,t) reactions, the target thickness was a larger factor, and the results are considered less accurate. The fact that there is good agreement between the runs taken under different conditions gives confidence that the number obtained actually represents the level width.

The determine the position to be used in calculating the energy of a group having a natural width, a procedure must be used that is somewhat different than that used for a narrow group. Normally, the observed peak shape arises from target and instrumental effects only, and the point on the peak whose position is least sensitive to those, namely the point at one-third maximum, is chosen to represent the peak position on the plate distance scale. This point is obviously unsuitable for the present case, where the observed width arises mainly from natural level width. The procedure used was to determine the position of the center of the peak and to add to this the distance from the center to the third-height point for the polonium alpha-particle peaks used to calibrate the spectrograph.

As the energy equivalent of the half-width of the calibration peaks is of the order of 2 kev, the error involved in this transformation of calibration from third-height position to peak position should be less than this. There is an uncertainty in determining the center of the observed inelastic group because of the slight asymmetry of the peak; however, it may be seen from Fig. 4 that, for the proton scattering, this error is small, and the midpoint of the half-height of the peaks lies on the center of the Gaussian that gives the best fit to the points. In the case of the $Be^9(p,\alpha)Li^6$ reaction, the ground-state Q-value determined from the same exposure was used with the excited-state Q value to give the excitation energy. These values are somewhat less accurate because of the greater stopping for alphas

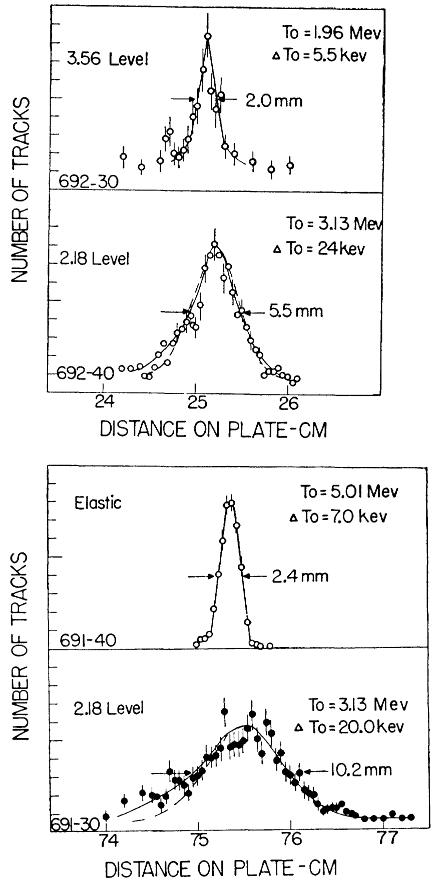

FIG. 4. Sharp and broad proton groups from Li^6 examined at two positions on the spectrograph focal surface in order to display the width of the first excited state. The observed energies (T_0) of the groups and their full widths at half-maximum (ΔT_0) are given.

TABLE II. Q values and excitation for first excited state.

Reaction	Bombarding energy (Mev)	Angle of observation (degrees)	Q-value (Mev)	Excitation (Mev)
(p,p')	7.028	90	−2.186	2.186
	7.028	90	−2.189	2.189
	7.031	90	−2.189	2.189
	7.031	90	−2.187	2.187
(d,d')	7.012	90	−2.186	2.186
(p,α)	7.318	30	−0.079	2.190
	7.485	30	−0.058	2.191
	7.249	60	−0.069	2.194

TABLE III. Energy of the second excited state.

Reaction	Bombarding energy (Mev)	Angle of observation (degrees)	Q-value (Mev)	Excitation (Mev)
(p,p')	7.028	90	-3.559	3.559
	7.031	90	-3.559	3.559
	(7.447)	60	(-3.561)	(3.561)
(p,α)	7.318	30	-1.453	3.564
	7.485	30	-1.442	3.566
	7.249	60	-1.428	3.553

TABLE IV. Upper limit of intensity for a nonobserved sharp state.

Reaction	Bombarding energy (Mev)	Angle of observation (degrees)	Intensity limit	
			Percent of first excited state	Percent of second excited state
(p,p')	7.45	30	<3	<50
	7.45	60	<3	<50
(d,d')	7.49	60	<1	...
(p,α)	7.30	30	<5	<5

and also because the incident protons passed through the targets.

Table II lists the excitations found for this level. The agreement with previous values is remarkable, particularly for a broad level.

The strong inelastic deuteron scattering to this level confirms the expectation that $T=0$.

In summary, the present experiment gives the excitation energy of the first excited state of Li^6 as 2.188±0.006 Mev, with a width of 24 kev and isotopic spin of 0. The deuteron on helium scattering experiments[1,2] show this level to have spin 3 and even parity and the "pickup" reactions[7,8] give results consistent with these values.

V. 3.56-MEV LEVEL

Data for the position of this level are given in Table III. The weighted average of 3.560±0.006 Mev agrees within the errors with the gamma-ray energy of 3.572 ±0.012 previously determined.[9] Since the gamma-ray energy was uncorrected for any Doppler shift, the agreement in position shows that the state is relatively long-lived. The sharp peaks obtained with the proton scattering indicate that the width of this level cannot be more than a few kilovolts.

The assumption of $T=1$ is confirmed by the lack of inelastic deuteron scattering to this level. At 7.49 Mev and 60-degree observation angle, an upper limit of 0.9% of the first excited-state intensity is found.

In summary, this experiment shows the second level in Li^6 to be at 3.560±0.006 Mev with a width less than 5 kev and with $T=1$. Other experiments[9,12,13] are consistent with a 0^+ assignment or a $T=1$ assignment or both.

VI. OTHER LEVELS

No other levels below 5-Mev excitation are seen with any of the three reactions studied. Intensity limits for a state less than about 100 kev in width are listed in Table IV.

The upper limit is given as a percentage of the intensity of the first and second excited-state groups. In the case of the proton scattering, the high ratio to the second state reflects the very low intensity of that group.

A level with a width of the order of 1 Mev would be much more difficult to observe, because the reaction products would be spread out over most of the nuclear plate and would be indistinguishable from instrumental background.

For the proton scattering at 7.45 Mev and 30 degrees, a total number of tracks greater than three times the number of tracks in the first excited-state group would have been seen, provided that they were spread out over about 1-Mev excitation energy. The narrower the group, the lower this limit would be, down to that listed for a sharp state. For the proton run at 7.45 Mev and 60 degrees, there is a very slight indication of an apparent rise and fall of the "background" from a point below the second excited-state group down to a point corresponding to around 5-Mev excitation. From the deuteron scattering, it is felt that a group 1 Mev wide, with a total intensity greater than twice that of the first state group would have been seen. The spectrum from the (p,α) reaction shows only a smooth rise of the number of alpha particles from the three-particle reaction.

The level at 4.52±0.08 Mev seen in the deuteron on helium scattering[2] is evidently at least 1 Mev wide, so that reaction products from this state are probably indistinguishable from the background in the present experiment. This wide level may be the one reported at 4.3±0.02 Mev with uncertain width from the $Li^7(He^3,\alpha)Li^6$ reaction.[6] If this is the case, all recent experiments are in complete agreement, and the characteristics of the levels of Li^6 up to 5-Mev excitation are now well known.

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