of the order of $10^{-3}$. It is not possible, therefore, to fit this gamma-ray transition into the decay scheme with any certainty at this stage.

Most of the previous work on gamma rays from this isotope has been concerned with internal conversion lines when thin sources of presumably low total strength are used. The study of the photoelectron spectrum has a greater chance of bringing out weaker gamma rays, as stronger and thicker sources may be used.

The Radiochemical Center, Amersham, England, which supplied the active cesium bromide, gave us the quantitative spectrographic analysis of the material. Consideration of these data and the relevant capture cross sections for neutrons shows that no appreciable radioactive impurity can be present in the sample.

Further work on the details of the decay scheme of $Cs^{134}$ is in progress.

Our thanks are due Dr. H. J. Bhabha, F.R.S. for his keen interest in the work of installation of the new spectrometer and also in the work here described.

PHYSICAL REVIEW VOLUME 96, NUMBER 4 NOVEMBER 15, 1954

# Radiative Capture of Deuterons by $He^3$†

J. M. Blair, N. M. Hintz, and D. M. Van Patter*
*Department of Physics, University of Minnesota, Minneapolis, Minnesota*
(Received August 9, 1954)

The excitation function of $He^3(d,\gamma)$ capture radiation, measured from $E_d$=0.2 to 2.85 Mev, exhibits a broad resonance at 0.45±0.04 Mev, with a total cross section of 0.05±0.01 mb. Above this energy, the presence of nonresonant capture is observed. At $E_d$=0.58 Mev, the radiation is isotropic from 0° to 90° within ±10 percent. The measured gamma-ray energy of 16.6±0.2 Mev at resonance corresponds to a $Q$ value for the $He^3(d,\gamma)Li^5$ reaction of 16.36±0.2 Mev. The experimental radiation width at resonance is calculated to be 11±2 ev, which is compared to the Weisskopf estimate for $E1$ transitions.

## I. INTRODUCTION

THE ground states of each member of the mirror pair, $He^5$ and $Li^5$ are unstable against nucleon decay to $He^4$ by about 1.0 and 1.9 Mev, respectively, with a lifetime $\sim 10^{-21}$ sec (Fig. 1). These states have been observed chiefly as resonances in the elastic scattering of neutrons and protons[1,2] by $He^4$, although there has been some indication from other experiments.[3–5] The results of the experiment reported here give independent evidence for the existence of a virtual ground state of $Li^5$ together with a measurement of its energy.

For the case of $Li^5$, a phase shift analysis of the $p$-$He^4$ scattering data,[6] together with a measurement of the polarization of the scattered protons,[7] fixes the character of the ground state as $P_{\frac{3}{2}}$, as expected from an independent particle model with spin-orbit coupling.[8] Aside from the rather uncertain $P_{\frac{1}{2}}$ level in the vicinity of 2.5 Mev, the only other known state of $Li^5$ is the comparatively narrow level at 16.7±0.2 Mev, observed as a resonance in the $He^3(d,p)He^4$ reaction.[9–11] This has been assigned $J=\frac{3}{2}+$ on the basis of the $(d,p)$ cross section at resonance and the observed isotropy of the protons. It occurred to one of us (N.M.H.) that if these assignments are correct, it should be possible to observe radiative capture of deuterons from the state at 16.7 Mev to the virtual ground state by electric dipole transition. This is indicated by a dotted line in Fig. 1. Such a transition would be interesting to detect as it would provide an independent measurement of the ground-state energy and give some information on the character of the states involved. Radiative capture of deuterons has not been reported previously except in the case of the $D(p,\gamma)He^3$ reaction.[12]

With these considerations in mind it was decided to search for a gamma ray of energy ~17 Mev from the deuteron bombardment of a $He^3$ gas sample.

## II. EXPERIMENTAL PROCEDURE

The Minnesota electrostatic generator was used to provide a beam of deuterons or protons up to 2.8 Mev. As indicated in Fig. 2, the beam was defined by tantalum diaphragms, then passed through a thin nickel foil into the target chamber containing the enriched $He^3$ gas. The stainless steel target chamber was normally 6.17

† Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
* Present address: Bartol Research Foundation, Swathmore, Pennsylvania.
[1] Freier, Lampi, Sleator, and Williams, Phys. Rev. **75**, 1345 (1949).
[2] R. K. Adair, Phys. Rev. **86**, 155 (1952).
[3] Almqvist, Allen, Dewan, and Pepper, Phys. Rev. **91**, 1022 (1953).
[4] E. W. Titterton and T. A. Brinkley, Proc. Phys. Soc. (London) **A64**, 212 (1951).
[5] R. W. Gelinas and S. S. Hanna, Phys. Rev. **86**, 253 (1952).
[6] C. L. Critchfield and D. C. Dodder, Phys. Rev. **76**, 602 (1949).
[7] M. Heusinkveld and G. Freier, Phys. Rev. **85**, 80 (1952).
[8] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).
[9] Bonner, Conner, and Lillie, Phys. Rev. **88**, 473 (1952).
[10] Yarnell, Lovberg, and Stratton, Phys. Rev. **90**, 292 (1953).
[11] G. Freier and H. Holmgren, Phys. Rev. **93**, 825 (1954).
[12] Fowler, Lauritsen, and Tollestrup, Phys. Rev. **76**, 1767 (1949).

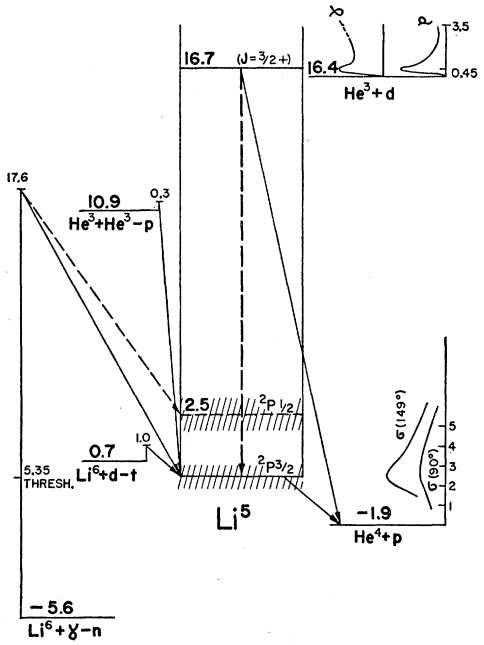


FIG. 1. Energy level diagram for $Li^5$. Dotted line shows transition reported in this paper.

cm long, with 0.050-in. thick walls. For some parts of the experiment where it was advantageous to have a shorter chamber, a target chamber 3.31 cm long was used. For measurements of the gamma radiation from the proton bombardment of lithium, the gas target chamber was replaced by a chamber which had a thick layer of LiOH at the position indicated in Fig. 2. The lithium gamma rays were used for energy and cross-section calibration.

About 3 cc of helium gas enriched to 94.5 percent $He^3$ were used in this experiment. The isotopic percentage of $He^3$ was measured before and after the experiment by mass spectroscopic analysis, and was found to be constant within 0.5 percent.[13] The enriched $He^3$ was transferred from a storage vessel to the target chamber and back by means of a mercury Toeppler pump. The storage vessel contained activated charcoal, which could be cooled by liquid nitrogen to purify the gas sample. It was demonstrated that any air contamination of the $He^3$ gas could be quickly removed by this means. To prevent mercury vapor from entering the target chamber, there was a U tube in the gas inlet line, which could be cooled by liquid nitrogen. The gas pressure was measured by means of a Bourdon gauge calibrated to within 0.2 cm Hg. Gas pressures of up to 19 cm Hg were used during the experiment.

To permit measurement of the incident beam, the target cup assembly was insulated from the target tube, and there was an insulating section in the gas inlet line. During each run, the beam current was integrated by means of a circuit developed by Dr. R. J. S. Brown for a previous experiment.[14]

The gamma-ray detector was a scintillation counter consisting of a NaI(Tl) crystal, 4.9 cm in diameter and 3 cm long, encased in a thin-walled aluminum can, having a glass window mounted with a Lucite adapter against the end of a 5819 photomultiplier tube. The pulses from the photomultiplier were amplified using a Model 100 amplifier, and analyzed by a single-channel pulse-height discriminator. During most of the experiment, the distance from the center of the target chamber to the front face of the crystal was 1.6 cm. Larger separations were used for the measurement of the absorption of the gamma rays in lead and their angular distribution.

A calibration of the bombarding energy scale was made from the $Li^7(p,n)Be^7$ threshold at the beginning and end of the experiment, and was found to remain constant within $\pm 0.15$ percent. The ratio between the measured voltage on the electrostatic analyzer and bombarding energy had been found to be constant within $\pm 0.4$ percent in an earlier experiment.[10] The thickness of the nickel entrance window was measured before and after the experiment as $185 \pm 4$ kev by observing the 441.5-kev $Li^7(p,\gamma)$ resonance, with the window inserted in the proton beam.

In order to estimate the energy loss in the window for various bombarding energies, the proton energy loss curve measured by Kahn[15] was used. Since only the variation in energy loss in nickel with bombarding energy was needed, it was considered that no appreciable error would be introduced by the use of the curve for copper. For the energy loss in helium, the results of Reynolds *et al.*[16] for the atomic stopping cross section of protons in helium were used for proton energies up

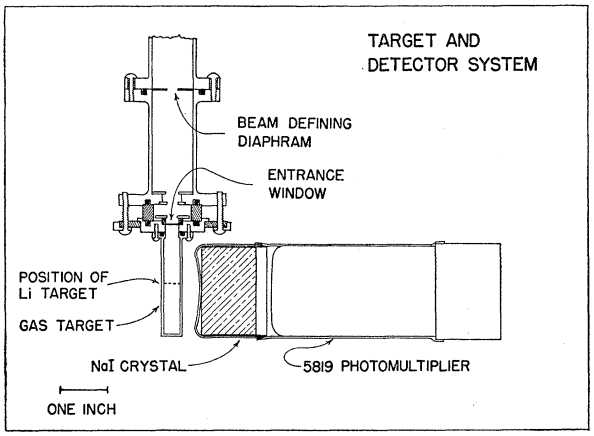


FIG. 2. Experimental arrangement of the target and detector system.

[13] The authors are indebted to Mr. Bailey Donnally of Professor A. O. C. Nier's mass spectrometer group for analyzing the samples of $He^3$.

[14] R. J. S. Brown, Rev. Sci. Instr. (to be published).

[15] D. Kahn, Phys. Rev. **90**, 503 (1953).

[16] Reynolds, Dunbar, Wenzel, and Whaling, Phys. Rev. **92**, 742 (1953).

to 0.6 Mev. For higher energies, an extrapolation was made using Bethe's formula, normalized to the experimental value at a proton energy of 0.5 Mev. After estimates of various sources of errors, it was concluded that the energy at the center of the chamber was known to ±20 kev.

## III. RESULTS

### A. Pulse-Height Distribution

When the empty target chamber was bombarded by deuterons, a large background of low-energy pulses was observed. A concerted attempt was made to locate the cause of this background, which led to the conclusion that it originated from all surfaces exposed to the beam. The background was reduced considerably after all the collimators were replaced by freshly cleaned tantalum, and all surfaces exposed to the beam were covered with 1-mil tantalum foil. In the light of later results, it is thought that most of the background of low-energy pulses could be attributed to deuteron bombardment of air adsorbed on the surfaces. In addition, a background of high-energy pulses of about 20 counts/min was observed, which remained constant when the beam was cut off at a point above the target system. This background was attributed to cosmic radiation, and was subtracted from experimental data as a time-dependent background.

A typical differential pulse distribution of the radiation observed from the $He^3$ enriched gas target bombarded by 0.54-Mev deuterons is shown in Fig. 3. The empty chamber background is shown on the same plot. For comparison, the pulse distribution due to gamma radiation from a LiOH target bombarded by 0.54-Mev protons is also shown. The $\gamma$ radiation from $Li^7+p$ at this bombarding energy consists of a monoenergetic 17.63-Mev $\gamma$ ray and a broad 14.8-Mev $\gamma$ ray, in the ratio of about 2:1.[17] The lack of resolution of the scintillation counter can be attributed to the relatively small crystal used for detection of this high-energy $\gamma$ radiation.[18]

From comparison with the pulse distribution from $Li^7+p$, it is concluded that the radiation observed from $He^3+d$ contains a high-energy component, which is not present in the empty chamber background. As will be discussed later, the rapid increase of the distribution for low pulse heights can be largely attributed to a small percentage of air contamination in the $He^3$ sample.

The end points of the $He^3+d$ and $Li^7+p$ pulse distributions were compared by similar extrapolation of the slope of steepest descent. In order to reduce effects due to gain changes in the photomultiplier and amplifier, comparisons were made as quickly as possible, usually within a few hours. Six comparisons in all were made, which gave an average energy of 16.6±0.2 Mev

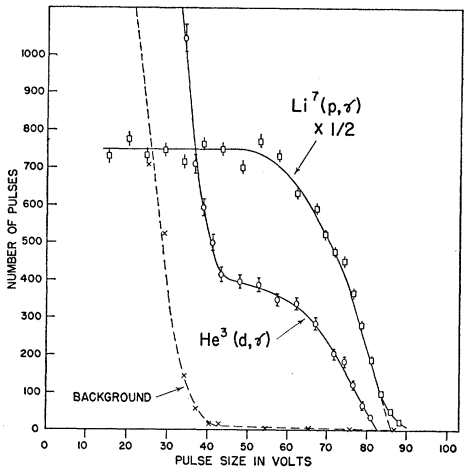


FIG. 3. Pulse-height distributions of the gamma radiation from $d+He^3$, $p+$LiOH, and $d+$empty chamber, at a bombarding energy of 0.54 Mev.

for the extrapolated end point of the $He^3+d$ pulse distribution at a deuteron bombarding energy of 0.45 Mev, assuming a linear relation between quantum energy and pulse height. The error of ±0.2 Mev represents a standard deviation obtained from the differences of the six values from the mean. An outside error of ±0.6 Mev would include all the individual determinations.

### B. Identification

Several checks were made to establish the identity of the high-energy radiation observed from enriched $He^3$ bombarded by deuterons.

(1) It was verified that the pulses observed were caused by high-energy $\gamma$ radiation emitted from the $He^3$ target, rather than from neutron capture $\gamma$ radiation in the NaI crystal. This result was obtained by comparing the absorption in lead of the $He^3+d$ radiation to the absorption of the $Li^7+p$ radiation. The decrease in the number of pulses above 50 volts was measured as a function of lead absorber thickness. The absorption curves observed for both radiations were found to be similar. The experimental results of Adams[19] were used to give the variation of the absorption coefficient in lead as a function of $\gamma$-ray energy. After taking into account the presence of the two components in the $Li^7+p$ $\gamma$ radiation, it was found that the high-energy component of the radiation from $He^3+d$ had an absorption coefficient corresponding to a $\gamma$-ray energy of 16±3 Mev.

(2) It was shown that the high-energy $\gamma$ radiation was emitted from the $He^3$ contained in the chamber gas. Pulse distributions were observed for deuteron bombardment of the chamber filled with normal helium, hydrogen, and air. In all cases, the high-energy component observed from $He^3+d$ was absent.

[17] R. L. Walker and B. D. McDaniel, Phys. Rev. **74**, 315 (1948).
[18] J. G. Campbell and A. J. F. Boyle, Australian J. Phys. **6**, 171 (1953).
[19] G. D. Adams, Phys. Rev. **74**, 1707 (1948).

(3) The possibility that the high-energy $\gamma$ radiation might originate from the capture of neutrons by $He^3$ was eliminated. The yield of the high-energy radiation was observed under the following conditions: (a) 8 lb of paraffin was placed in the vicinity of the chamber; (b) a layer of cadmium $\frac{1}{16}$ in. thick was wrapped around the target chamber. No difference within statistics (2 percent) was observed as compared to normal conditions. In addition, from the $Q$ value of the $He^3(n,\gamma)He^4$ reaction, one would expect a $\gamma$ ray of 20.5 Mev from the capture of thermal neutrons, which is considerably higher than the $16.6\pm0.2$ Mev radiation observed.

(4) An attempt was made to rule out the possibility that the high-energy $\gamma$ radiation could originate from some secondary nuclear reaction of the high-energy protons from the $He^3(d,p)He^4$ reaction. Under normal conditions, the protons passed through 1 mil of tantalum, and were stopped in the 0.050-in. stainless steel wall of the target chamber. For this investigation, the target chamber was lined with 0.038 in. of lead, so that the high-energy $He^3(d,p)$ protons were exposed only to lead. The yield of the high-energy $\gamma$ radiation from $He^3+d$ was observed to be the same as before within $6\pm5$ percent, after correction for the added absorption of the lead lining. Hence the possibility that the $\gamma$ radiation from $He^3+d$ could be attributed to a secondary reaction becomes very unlikely. Additional evidence for this conclusion comes from the fact that the excitation curve for the $He^3+d$ $\gamma$ radiation was found to differ from the known excitation curve for the $He^3(d,p)He^4$ protons.[9,10]

(5) The remaining possibility to be eliminated was that the high-energy $\gamma$ radiation might originate from an excited state of $He^4$ formed from the $He^3(d,p)He^4$ reaction rather than from the $He^3(d,\gamma)$ capture process. This possibility can be readily investigated, since the energy of a $\gamma$ ray emitted from an excited state of a product nucleus should be independent of deuteron bombarding energy. On the other hand, one expects the energy of the $He^3(d,\gamma)$ capture radiation observed at 90° to depend on deuteron bombarding energy in the following manner:

$$\Delta E_\gamma = \Delta E_d m_{He^3}/(m_{He^3}+m_{D^2}) = 0.6E_d.$$

The end point of the $\gamma$-ray pulse distribution from $He^3+d$ was measured at deuteron energies of 2.59 and 0.58 Mev. The resultant shift was found to be $5.8\pm1.0$ volts, corresponding to a change in $\gamma$-ray energy of $1.3\pm0.2$ Mev. The expected change for $He^3(d,\gamma)$ capture radiation is 1.21 Mev. The quoted error in the energy shift comes from estimates of the errors involved in locating the extrapolated end points of the two distributions, and does not take into account any gain change while the machine energy was being lowered. If this error is not underestimated, then this result indicates that the $\gamma$ radiation can only originate from deuteron capture on a very light element. For instance, the expected shift in $\gamma$-ray energy for $C^{12}(d,\gamma)$ would be 1.71 Mev. Since the high-energy radiation was not observed with hydrogen, $He^4$ or air in the chamber, and one would not expect Li, Be, or B in the chamber, the observed $\gamma$-ray energy shift indicates that the only possible assignment is to the $He^3(d,\gamma)$ capture.

An attempt was made to observe the Doppler shift of the $\gamma$-ray energy, which would have unambiguously assigned the $\gamma$ radiation to a reaction involving a very light element. However, with the experimental arrangement used, it was found to be impossible to make a reliable measurement of the Doppler shift, because of difficulties caused by background and gain instability.

It was concluded that most of the rapid rise for pulses below 40 volts (see Fig. 3) could be attributed to air contamination of the $He^3$ gas. In the case of the $He^3(d,\gamma)$ results shown in Fig. 3, a pressure increase of up to 5 percent was observed, which was attributed to an air leak. The yield of $\gamma$ radiation from a known amount of air in the target chamber was compared to the $He^3+d$ pulse distribution, after subtraction of the pulses due to the high-energy component. The rapid rise of low-energy pulses could be well fitted by assuming that the pressure increase was caused by air leaking into the target chamber. In another run of 6.5 hours, when there was no indication of an air leak, the low-energy pulses from $He^3+d$ could be accounted for by the presence of $0.9\pm0.3$ percent of air contamination. At the end of the experiment, a sample of $He^3$ gas was extracted from the target chamber after a two-hour run. Analysis of this sample by a mass spectrometer indicated an air contamination of 0.27 percent to 0.54 percent. It was concluded that an air contamination of this magnitude could account for the low-energy pulses observed from $He^3+d$, for runs without known air leaks, within the reliability of the data. Evidently this air contamination originated from the outgassing of the target chamber walls and gas inlet, since the $He^3$ was free from air contamination when first inserted in the chamber. However, because of the high yield of $\gamma$ rays of energy less than 9 Mev from air contamination, one cannot rule out the possibility that a $He^3(d,\gamma)Li^{5*}$ $\gamma$ ray of less than 9 Mev may be present with an intensity comparable to that of the high-energy component.

### C. Excitation Curve

The yield of the high-energy $He^3(d,\gamma)$ radiation was measured from 0.2 to 2.85 Mev, using the experimental arrangement of Fig. 2. Later, an improved collimating system was inserted which gave current collection reliable to $\pm3$ percent, and the excitation curve was remeasured using the 3.31-cm target chamber for bombarding deuteron energies from 0.17 to 2.42 Mev. The results of this are shown in Fig. 4. From the lowest to the highest bombarding energy, the energy loss in the entrance window varied from 260 to 130 kev,

while the loss in the $He^3$ gas varied from 100 to 25 kev. The energy scale plotted in Fig. 4 represents the estimated deuteron energy at the center of the chamber, considered reliable to $\pm 20$ kev.

Most of the data for the excitation curve were obtained by counting all the pulses greater than 55 volts (see Fig. 3). However, at energies above 1.7 Mev, it was found that some pulses were being recorded from the tail of the rapid increase of low-energy pulses, amounting to 18 percent at the highest bombarding energy. In order to eliminate this source of uncertainty, pulses above 65 volts were also counted for the higher bombarding energies. After the highest energy point was obtained, repeat runs were made at $E_d=0.91$ and 0.41 Mev, in order to estimate any possible gain changes. No gain change was observed within the combined statistical errors of $\pm 4$ percent.

Several corrections were applied to the original data to obtain the excitation curve plotted in Fig. 4. A background correction, averaging 5 percent, was made, estimated from the background observed from the empty chamber. To the three highest energy points, taken at the integral bias setting of 55 volts, corrections of up to 18 percent have been subtracted to eliminate the contribution of the low-energy rise mentioned above. A correction was also made for the change of the $He^3+d$ capture $\gamma$-ray energy with bombarding energy, since the bias setting was not changed for the measurement of the excitation curve.

In addition, a correction was applied for the effect of multiple scattering in the entrance window. The root-mean-square spatial angle was calculated using Molière's theory[20] and was found to be 10° at the lowest bombarding energy. The effective reduction of deuteron path length in the target was estimated by numerical integration, taking the finite area of the beam into account. This resulted in a correction of $+18\pm 5$ percent to the lowest point on the excitation curve; however, this correction rapidly decreased to only $+2$ percent at $E_d=0.49$ Mev. Hence, multiple scattering caused very little effect on the general shape of the observed excitation curve.

The data obtained for pulses greater than 65 volts have been normalized to the points for pulses greater than 55 volts, essentially using the ratio observed at $E_d=0.41$ Mev. In addition to the data shown in Fig. 4, earlier measurements of the excitation curve were made at about 100-kev intervals to a maximum bombarding energy of 2.85 Mev. These data indicate that the yield varied smoothly between the points plotted in Fig. 4, but because of gain changes which occurred during these measurements, the earlier data are not considered to be as reliable as the data shown. A maximum is observed in the excitation curve at a bombarding energy of $0.45\pm 0.04$ Mev.

[20] G. Molière, Z. Naturforsch. **3A**, 78 (1948); W. C. Dickenson and D. E. Dodder, Rev. Sci. Instr. **24**, 428 (1953).

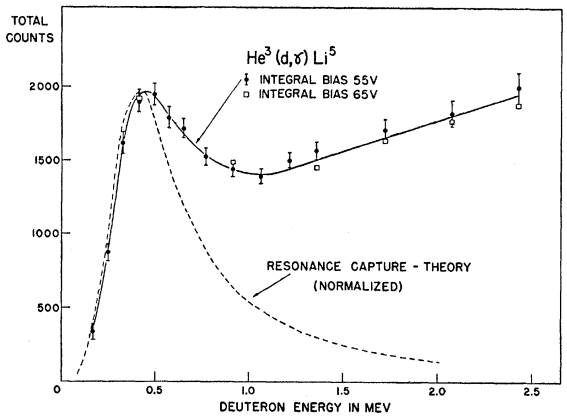


FIG. 4. Excitation curve for the $He^3(d,\gamma)Li^5$ reaction. The solid curve was drawn through the experimental points. The dotted curve shows the contribution expected from resonance capture alone, calculated using dispersion theory with level parameters found for the $He^3(d,p)$ $He^4$ reaction.

### D. Angular Distribution

A rough angular distribution of the high-energy $He^3(d,\gamma)$ radiation was measured using a 66-kev target at $E_d=0.585$ Mev, slightly above the peak of the excitation curve. Measurements were made at laboratory angles of 0°, 45°, and 90° with an angular resolution of about 25°. Corrections were made for the effect on the average value of $1/r^2$ due to the extended target and finite size of the crystal, resulting in a net correction of only 3 percent between points taken at 0° and 90°. The largest uncertainty in the measurements ($\pm 5.5$ percent) came from the uncertainty of the gain stability during the run, which was estimated from pulse distributions measured immediately following the angular distribution. The total errors, including statistics (3 percent), amounted to about $\pm 9$ percent. From this data, the angular distribution from 0° to 90° appeared to be isotropic within $\pm 10$ percent.

### E. Absolute Cross Section

The absolute cross section for production of the high-energy $He^3(d,\gamma)$ capture $\gamma$ radiation at $E_d=0.45$ Mev has been computed from the observed yield of $\gamma$ rays in two ways.

(1) The first method was based on a comparison with the yield of $\gamma$ rays from the $Li^7(p,\gamma)$ reaction.[21] To obtain the relative number of $\gamma$ rays counted from the two reactions, differential pulse distributions for both the $He^3(d,\gamma)$ and $Li^7(p,\gamma)$ reactions were measured (Fig. 3). In each case the total number of $\gamma$ rays producing pulses in the NaI crystal was estimated from the observed integral count above a convenient bias level and the shape of the differential pulse distri-

[21] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 248 (1948); and revision by W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).

bution curves (obtained with a 3-volt discriminator channel). In the case of the $He^3(d,\gamma)$ radiation, this involved an extrapolation by a factor of 3 due to the presence of a large amount of lower-energy radiation.

In obtaining the $He^3(d,\gamma)$ cross section from the relative yield, several other factors had to be taken into account. The average solid angle subtended by the crystal was greater at the LiOH target than at the elongated $He^3$ gas target. The sensitivity of the NaI crystal was calculated to be the same for the $Li^7(p,\gamma)$ $\gamma$ rays, which are a mixture of 14.8- and 17.6-Mev radiation, as for the 16.6-Mev $\gamma$ radiation from the $He^3(d,\gamma)$ reaction.[17,22] The absolute thick target yield for the 441-kev $Li^7(p,\gamma)$ resonance quoted in reference 21 was adjusted for the contribution of nonresonant radiation to the thick target yield, since the $Li^7(p,\gamma)$ yield in this experiment was measured at a proton energy of 0.54 Mev.

The $He^3(d,\gamma)$ radiation was assumed to be isotropic, in accordance with our rough measurements. On this basis, the total cross section for production of high-energy $He^3(d,\gamma)$ capture radiation at the peak of the excitation curve is calculated to be $(0.57\pm0.10)\times10^{-28}$ cm$^2$. Individual determinations of this value were consistent to within 10 percent; however, because of uncertainties in the extrapolation of the differential pulse distribution, and in the estimation of the relative solid angle subtended by the crystal at the targets, a larger estimate of error is quoted.

(2) As a check on the first method, a calculation was also made of the absolute sensitivity of the NaI crystal for 16.6-Mev $\gamma$ rays. This calculation was based on the $\gamma$-ray cross sections contained in reference 22. Therefore, it does not depend on the absolute value of the $Li^7(p,\gamma)$ yield, but does contain the same solid angle calculation and extrapolation of the pulse-height distribution to zero pulse height. This method results in a maximum cross section for the $He^3(d,\gamma)$ high-energy $\gamma$ radiation of $(0.37\pm0.10)\times10^{-28}$ cm$^2$. Two experimental determinations of this value were consistent to 5 percent, but a larger error is estimated for the same reasons as for the other method.

## IV. CONCLUSIONS

The radiative capture of deuterons by $He^3$ seems to be well estabilshed. The total cross section is measured to be $(0.5\pm0.1)\times10^{-28}$ cm$^2$ at $E_d=0.45$ Mev. The energy of the $\gamma$ ray is $16.6\pm0.2$ Mev at this deuteron energy. A rough measurement of the angular distribution indicates isotropy to within $\pm10$ percent slightly above the resonance energy. This is consistent with the formation of the state by $s$-wave deuterons as is also indicated by the isotropy of the protons from the $(d,p)$ reaction at the same deuteron energy.[10]

[22] C. M. Davisson and R. D. Evans, Revs. Modern Phys. **24**, 79 (1952).

### A. Contribution from Resonance Capture

The contribution to the $He^3(d,\gamma)Li^5$ reaction to be expected from resonance capture from the 16.7-Mev level to the $P_{\frac{3}{2}}$ ground state has been calculated using the Wigner-Eisenbud dispersion theory.[23] The parameters $a$, $E_\lambda$; $\gamma_d^2$, $\gamma_p^2$ have been selected to give a good fit to the $(d,p)$ reaction data of Yarnell *et al.*[10] and Freier and Holmgren[11] in the vicinity of the resonance for this reaction ($E_d=0-1$ Mev). The parameters are:

$$a=7.6\times10^{-13}\text{ cm},\quad \gamma_d^2=5.0\times10^{-10}\text{ kev cm},$$
$$E_\lambda=195\text{ kev},\quad \gamma_p^2=12.8\times10^{-12}\text{ kev cm}.$$

These are the same as used by Bonner *et al.*[9] to fit their $He^3(d,p)He^4$ measurements except for a slightly larger $\gamma_p^2$, which was needed to give a total cross section of 0.9 barn at resonance as measured by Freier and Holmgren[11] with somewhat better experimental geometry. Only $s$-wave deuterons were considered in the calculation. The outgoing protons must be $d$ wave for the breakup of a $J=\frac{3}{2}+$ state. In calculating the level shifts $\Delta_\lambda$ and the total width $\Gamma_\lambda$, the contribution from the radiative width was neglected. For the radiative width $\Gamma_\gamma$, an energy dependence of the form $(\text{const}\times E_\gamma^3)$ was assumed, the constant being adjusted to give a calculated cross section equal to the experimental at $E_d=0.45$ Mev. The calculated resonance contribution to the $(d,\gamma)$ reaction is plotted as a broken line in Fig. 4.

From Fig. 4 it is apparent that there is a large contribution to the $(d,\gamma)$ reaction from nonresonant capture above $E_d=0.45$ Mev. As pointed out by Thomas,[24] this is to be expected for such light nuclei, because the large reduced widths of the initial and final states result in a large contribution to the capture cross section from the external region. In fact, the usual perturbation calculation gives an infinite result for the external contribution to the dipole matrix element. This is because both the initial and final state wave functions extend to infinity for virtual states.[25] Further theoretical work is necessary to find a way around this difficulty.

### B. Size of the Dipole Matrix Element

The experimental radiative width at the resonance energy deduced from the measured $(d,\gamma)$ and $(d,p)$ cross sections is $\Gamma_\gamma=11\pm2$ ev. In comparing with the Weisskopf[26] estimate for $E1$ transitions, it is necessary to divide the experimental width by a statistical weight factor of $\frac{1}{5}$ for a $J=\frac{3}{2}\rightarrow\frac{3}{2}$ transition.[27] The

[23] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947); R. G. Thomas, Phys. Rev. **81**, 148 (1951).
[24] R. G. Thomas, Phys. Rev. **88**, 1109 (1952).
[25] We are indebted to R. G. Thomas for an informative discussion on this point.
[26] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, New York, 1952).
[27] D. J. Hughes, Phys. Rev. **94**, 740 (1954).

experimental $\Gamma_\gamma$ then corresponds to an electric dipole matrix element 0.043 times the Weisskopf estimate for a radiative transition to the ground state of $Li^5$. This is of the same order of magnitude as $E1$ matrix elements for other light nuclei.[28] In using Weisskopf's formula, a conventional radius of $R=1.45\times10^{-13}\ A^{\frac{1}{3}}$ cm was used. However, the formula depends on $R^2$; if $R=a=7.6\times10^{-13}$ cm is used, the experimental $\Gamma_\gamma$ is equal to the Weisskopf estimate. In any case, it is not expected that a single-particle model, as used by Weisskopf, would give the correct transition probability for a $(d,\gamma)$ reaction on such a light nucleus. This is especially true as the 16.7-Mev state of $Li^5$ appears to be due to an excitation of the $\alpha$ core[8] while the ground state is more nearly a single-particle state.

Transitions from the 16.7-Mev state of $Li^5$ to a possible $P_{\frac{3}{2}}$ state in the vicinity of 2.5 Mev, relative to transitions to the ground state, should occur in a ratio of $\sim(14.1/16.7)^3\times5=3$ (including the statistical weight factors).[26,27] However, because of the poor resolution inherent in a small NaI crystal and the large background below 9 Mev due to air contamination, nothing can be said experimentally about possible radiative transitions to this $P_{\frac{3}{2}}$ state. It would be interesting to repeat the experiment with a very large NaI crystal and with greater precautions against contamination.

### C. The Mass of $Li^5$

From the measured $\gamma$-ray energy, $E_\gamma=16.6\pm0.2$ Mev at $E_d=0.45$ Mev, the $Q$ for the $He^3(d,\gamma)Li^5$ reaction is calculated to be $Q=16.36\pm0.2$ Mev. Using the mass values tabulated by Li *et al.*,[29] this gives the $Li^5$ ground state at an energy of $1.95\pm0.2$ Mev above $He^4+p$. The measurements of Almqvist *et al.*[3] on the $He^3(He^3,p)Li^5$ reaction give $1.99\pm0.15$ Mev for the $Li^5-(p+He^4)$ mass difference. The phase-shift analysis of the low-energy $p+He^4$ scattering data[2,6] gives $E_{res}=2.1\pm0.1$ Mev for the energy at which the $P_{\frac{3}{2}}$ phase shift passes through 90°. The $Li^6(\gamma,n)Li^5$ reaction[4,30] gives a somewhat lower value of the $Li^5-(p+He^4)$ difference ($1.6\pm0.2$ Mev), but because of the difficulty of interpreting these measurements, they should perhaps be given less weight than the aforementioned. A preliminary report on the $Li^6(d,t)Li^5(p)He^4$ reaction[31] gives a $Li^5-(p+He^4)$ energy difference of $1.6\pm0.1$ Mev. It seems reasonable to adopt a value of $1.9\pm0.2$ Mev for the $Li^5-(p+He^4)$ energy difference. This corresponds to $M(Li^5)=5.0140\pm0.0002$ amu or a mass defect of $13.1\pm0.2$ Mev.

It should be mentioned that both the $He^3(d,\gamma)$ and the $He^3(He^3,p)$ reaction should tend to give somewhat too *low* an energy for the $Li^5$ ground state because of the large width of this state. In the case of the $(d,\gamma)$ reaction, the $E_\gamma^3$ dependence of the $E1$ transition probability favors leaving the $Li^5$ system at an energy less than the resonance energy for this state as found from the $p+He^4$ scattering data. A detailed discussion of this effect must await a theoretical treatment of radiative transitions between virtual states with large reduced widths.[25]

It would be interesting, but experimentally more difficult, to look for $\gamma$ rays from the mirror reaction $T(d,\gamma)He^5$. The large yield of energetic neutrons from the $(d,n)$ reaction would complicate the detection procedures, however. Finally, on the basis of the $Li^5$ level parameters found here the $He^4(p,\gamma)Li^5$ reaction should have a cross section of $\sim10^{-30}$ cm$^2$ at $E_p=23$ Mev, the lab energy required to form the 16.7-Mev state of $Li^5$.

The authors wish to acknowledge the assistance of Dr. K. F. Famularo in several phases of the experiment. Professor John H. Williams provided encouragement and many helpful suggestions.

[28] D. H. Wilkinson, Phil. Mag. **44**, 450 (1953).
[29] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[30] Sher, Halpern, and Mann, Phys. Rev. **84**, 387 (1951). See comment on p. 392 on $Li^6(\gamma,n)$ reaction.
[31] R. T. Frost and S. S. Hanna, Phys. Rev. **91**, 462(A) (1953).