Lifetime of the 3.56-Mev State in Li^6†

R. J. A. LEVESQUE* AND S. M. SHAFROTH
Northwestern University, Evanston, Illinois

(Received January 12, 1959)

An upper limit for the mean life of the 3.56-Mev state in Li^6 of 5×10^{-14} sec has been established by a Doppler shift method. This supports the 0^+, $T=1$ assignment for this level. It has also been established by a Doppler shift technique that the angular distribution of the recoil alphas arising from the $Be^9(p,\alpha)Li^{6*}(\gamma)Li^6$ reaction is symmetric about 90° in the center-of-mass system at the resonant bombarding energy of 2.56 Mev. At 2.93-Mev bombarding energy the angular distribution of the alphas is peaked forward of 90°.

INTRODUCTION

THE existence of a level at 3.56 Mev in Li^6 was first suggested by Hushley[1] as a possible explanation for a large yield of 3-Mev gamma rays arising from the bombardment of beryllium with 2.56-Mev protons. Day and Walker[2] verified Hushley's prediction by studying the coincidences between the gamma-ray and the alpha particles arising from the reaction. Their measurement of the gamma-ray energy yielded 3.58 Mev. Later measurement by Mackin[3] established the energy of the radiation to be 3.572±0.012 Mev and its multipolarity to be most probably magnetic dipole or with less likelihood electric quadrupole. Since the ground state has spin 1 and even parity, the second excited state must have even parity and spin 0, 1, 2, or possibly 3. The fact that no inelastically scattered deuteron groups[4] were found leading to this state indicates that its isotopic spin is 1 and that it is the analog of the Be^6 and He^6 ground states. The value of the exitation energy and the fact that this level does not decay into a deuteron and an alpha particle, which is energetically possible above 1.53 Mev, supports this assignment. If the state has spin 0, even parity and isotopic spin 1, then the breakup of the level into an alpha and a deuteron is doubly forbidden. The fact that the angular distribution of the 3.56-Mev gamma is isotropic and the alpha-gamma angular correlation is isotropic to within 4% in the plane of the reaction, also supports the 0^+ assignment.[5]

From a study of the alphas arising from the bombardment of beryllium with protons, Browne and Bockelman[6] have concluded that the energy of the second excited state of Li^6 is 3.560±0.006 Mev. Because this measurement is, to within experimental error, the same as the energy of the gamma radiation, they concluded that the Doppler shift must be zero and therefore that the lifetime must be long. This conclusion is not warranted since the error in the two measurements are large enough to allow the full Doppler shift.

It has been shown by Kurath[7] that the energy levels of the p-shell nuclei can be fitted with intermediate coupling wave functions. Using these wave functions,

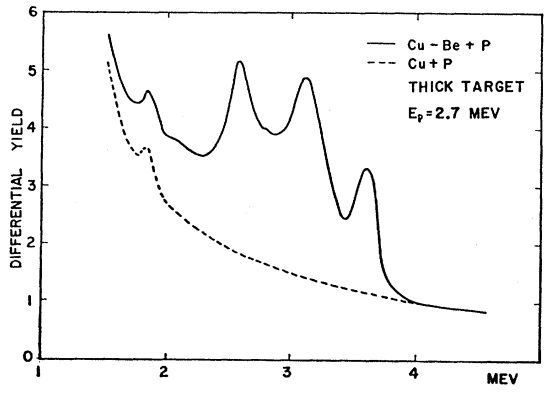

FIG. 1. Spectrum produced by proton bombardment of Cu-Be alloy (2% Be). The three highest peaks are due to the 3.56-Mev Li^6 gamma. The dotted curve shows the spectrum arising from proton bombardment of copper. It has been normalized arbitrarily to fit the high-energy tail of the Cu-Be curve.

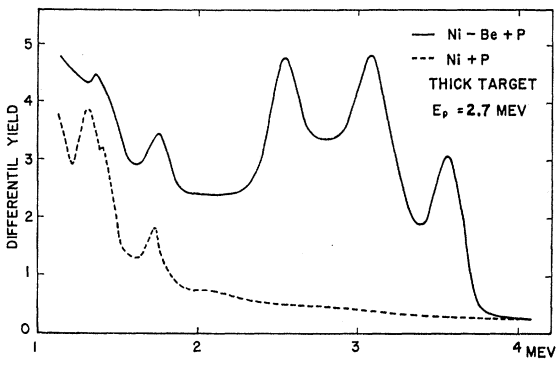

FIG. 2. Spectrum produced by proton bombardment of Ni-Be alloy (2% Ni). The three highest peaks are due to the 3.56-Mev Li^6 gamma. The dotted curve shows the spectrum arising from proton bombardment of nickel. It has been arbitrarily normalized to fit the high-energy tail of the Ni-Be curve.

† Research supported by the National Science Foundation.

* Present address: Physics Department, University of Maryland, College Park, Maryland.

[1] W. J. Hushley, Phys. Rev. **67**, 34 (1945).
[2] R. B. Walker and R. L. Day, Phys. Rev. **85**, 582 (1952).
[3] R. J. Mackin, Phys. Rev. **94**, 648 (1954).
[4] Browne, Bockelman, Buechner, and Sperduto, Phys. Rev. **90**, 390 (A) (1953).
[5] Stoltzfus, Friichtenicht, and Nelson, Bull. Am. Phys. Soc. Ser. II, **1**, 329 (1956).
[6] C. P. Browne and C. K. Bockelman, Phys. Rev. **105**, 1301 (1957).
[7] D. Kurath, Phys. Rev. **101**, 216 (1956).

Kurath[8] has also calculated the mean lifetime of this state to be 8×10^{-17} sec.

A measurement of the mean life of the 3.56-Mev state in Li^6 would decide whether the radiation is electric quadrupole or magnetic dipole, and would help in verifying the assigned spin and parity. A Doppler shift measurement is sufficient to distinguish between the two multipolarities of the radiation, although it cannot verify the exact prediction of Kurath.

Part of the present work has been reported previously.[9] The Doppler shift method has also been used to place a lower limit on the lifetime of this state by Rose and Warburton.[10]

EXPERIMENTAL PROCEDURE

The measurement of lifetimes by the Doppler shift technique has been discussed extensively by Devons.[11] In the present work the state was prepared by means of the $Be^9(p,\alpha)Li^{6*}(\gamma)$ reaction. In order to measure the lifetime as accurately as possible, it is necessary to slow down the recoil nuclei in a heavy material. A target evaporated on a layer of high-density material would not be satisfactory for a very short lifetime measurement, since a large fraction of the recoils would decay in the target material itself. For this reason, an alloy of 2% beryllium in nickel was used for one of the targets, the other one being a pure thick beryllium target. A copper-beryllium alloy was also investigated as a possible target material. Figure 1 shows spectra obtained when Cu-Be and Cu were bombarded with 2.7-Mev protons. The spectrum resulting from 2.7-Mev proton bombardment of Ni-Be and Ni is shown in Fig. 2. It is apparent that the background in the region of the 3.56-Mev gamma is much lower in the case of the Ni-Be target and therefore it was used in the present work.

The target and counter arrangement is shown in Fig. 3. The counter was placed on a rotating arm at a distance of 3 to $4\frac{1}{2}$ inches from the target. The targets were bombarded with 2.57- to 2.93-Mev protons from the Northwestern electrostatic accelerator. The gamma-ray energy was measured at 0° and 145° or 150° to the beam direction with a scintillation counter consisting of a $1\frac{3}{4}$-in. diam×2-in. NaI crystal mounted on a Dumont 6342 photomultiplier tube. The information from the counter was fed into a Radiation Counter Laboratories 256 channel analyzer. For each gamma-energy measurement, approximately 4000 counts were accumulated in the channels corresponding to the 3 pair peaks. This took on the order of 20 minutes. The shift in each peak was used to compute the average shift. Five or six independent measurements of the shift were made for each entry in Table I. This table lists the results of 4 measurements of the shift under various conditions.

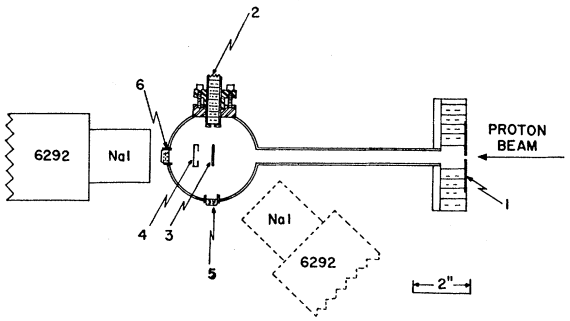

FIG. 3. Target chamber. (1) Mollybdenum aperture. (2) Charged particle counter (not used in present work). (3) Target. (4) Mollybdenum beam stop. (5) and (6) Vycor windows.

Since drifts in the counter would have disastrous effects on the results of the experiment, a calibration run using the 2.165-Mev gamma ray from ThC″ (Fig. 4) was made before and after each energy measurement. The distance of the thorium source was adjusted to produce approximately the same counting rate as the reaction gamma rays. The latter was monitored throughout the experiment and variation in the counting rate was minimized by adjusting the beam

TABLE I. Doppler shifts.

Target	E_p	Observed % shift[a,b] $\Delta E/E_0$	% shift calculated for recoil into vacuum[c,d]
Thick Be	2.66	1.20±0.07[e]	1.33
Thick Ni-Be	2.66	1.18±0.07[e]	1.33
25-kev Be	2.93	1.02±0.06[f]	1.47
25-kev Be	2.57	1.38±0.06[f]	1.38

[a] Probable errors.
[b] Corrected for neutron induced background.
[c] Angular distribution of recoil Li^{6*} nuclei assumed symmetric about 90° (center of mass).
[d] Corrected for solid angles.
[e] 0–145°.
[f] 0–150°.

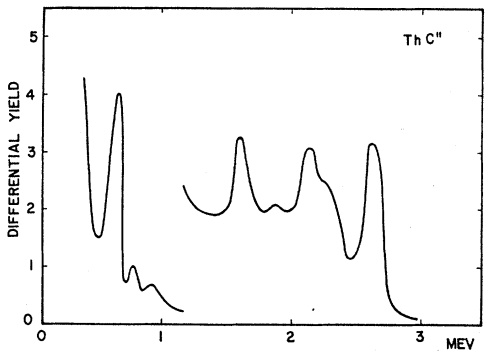

FIG. 4. Spectrum produced by the 2.615-Mev ThC″ gamma used for calibration of the counter before and after each change in angle.

[8] D. Kurath (private communication).
[9] R. J. A. Levesque and S. M. Shafroth, Bull. Am. Phys. Soc. Ser. II, **2**, 303 (1957).
[10] H. J. Rose and E. K. Warburton, Phil. Mag. **2**, 1468 (1957).
[11] Devons, Manning, Bunbury, Proc. Phys. Soc. (London) **A68**, 18 (1955); Devons, Manning, and Towle, Proc. Phys. Soc. (London) **A69**, 173 (1956); Devons, Manning, Towle and, Bunbury, Proc. Phys. Soc. (London) **A69**, 165 (1956).

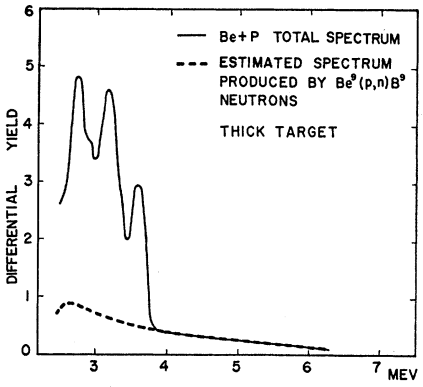

FIG. 5. The spectrum produced by proton bombardment of beryllium. The three peaks are due to the 3.56-Mev Li^6 gamma and the high-energy tail is due mostly to neutrons. The dotted curve shows what the pulse-height distribution would be if there were no 3.56-Mev gamma.

intensity. The effect of spectrum distortion due to neutrons produced in the $Be^9(p,n)B^9$ reaction was investigated.[12] The pulse-height distribution in the range from 3–7 Mev arising from Be^9+p is exhibited in Fig. 5. The three peaks are the 3.56-Mev gamma and the high-energy tail is mostly due to the neutron response of the NaI crystal. The dotted curve shows what the pulse-height distribution would be if there were no 3.56-Mev gamma, i.e., it is the neutron induced spectrum. The gamma spectrum distortion due to the neutrons was corrected by using this information. The maximum value of this correction was 0.03%. This was applied to the 2.93-Mev run.

DISCUSSION

The value for the Doppler shift in the two thick materials gives a measure of the lifetime. The change in energy of a gamma ray due to the Doppler effect can be written

$$\Delta E=E_0 c\lambda\alpha/(\lambda\alpha+1),$$

where α is the slope of the range-velocity curve and C is a constant dependent on the particular reaction and the angle of observation. If one calls S the ratio of the shift in nickel to the shift in Be, then the mean life is given by

$$\tau=\alpha_1(1-S)/(S-\alpha_1/\alpha_2),$$

where α_1 and α_2 are proportional to the slowing down times for the lithium ions in nickel and in beryllium, respectively. A value for alpha can be estimated from the range velocity relationship of Li^7 ions in air as measured by Teplova *et al.*[13] After correction for the difference in density between air and nickel or beryllium and the difference in mass between Li^6 and Li^7 one obtains

$$\alpha_1=1.2\times10^{-13}\text{ sec},\quad \alpha_2=5.8\times10^{-13}\text{ sec}.$$

The method used here to estimate alpha can be used at higher velocity in order to compare with the slowing down time obtained from the range-velocity relationship measured by Devons and Towle.[14] Such a comparison shows that at these higher velocities the alpha obtained from the measurements of Teplova is lower than that obtained from the measurement of Devons, the ratio of the two being 1.36. Therefore α_1(Ni) and α_2(Be) will be raised by this factor. Thus we take:

$$\alpha_1=1.63\times10^{-13}\text{ sec},\quad \alpha_2=7.83\times10^{-13}\text{ sec}.$$

To put a limit on the lifetime we will use the shift in nickel as being 0.97%, i.e., three probable errors from the measured value. This gives a mean life

$$\tau_{\text{mean}}=5.2\times10^{-14}\text{ sec}.$$

If the angular distribution of the Li^6 ions is symmetric about ninety degrees in the center-of-mass system, one can calculate an expected shift for the case where there is no stopping material; i.e., $\alpha=\infty$. Under these conditions, the shift is independent of the exact form of the angular distribution and is only dependent on the velocity of the center of mass. In the case of the thick target measurements, the velocity of the center of mass must be averaged over the yield curve[15] from 2.67 Mev to 2.0 Mev. The shift under these conditions is expected to be 1.33%. The difference between the expected shift and the experimentally determined one could be explained by either a lifetime of the order 10^{-14} sec or an angular distribution of the Li ions peaked in the backward direction. Since at resonance one would expect an angular distribution symmetric around 90°, the backward peaking of the Li^6 nuclei would be due to the yield off resonance.

In order to understand why the measured shift was less than the vacuum shift two Doppler shift measurements were made on a 25-kev unbacked beryllium target. One was at a proton energy slightly above the resonant energy of 2.56 Mev so as to maximize the gamma yield and the other was at 2.93 Mev. The results are shown in the bottom two entries of Table I. The measurement at resonance shows good agreement with the calculated vacuum shift. Therefore we conclude that the lifetime is fast compared to the slowing down time in beryllium and the angular distribution of the recoils is symmetric about 90° (center of mass) at the resonant proton energy. However the measurement at 2.93 Mev exhibits a much smaller shift than would be expected if the angular distribution of the recoil Li nuclei were symmetric about 90° (center of mass). Therefore we conclude that in this case the Li^{6*} nuclei go more often backward than forward.

[12] Shafroth, Strait, and Carpenter, Nuclear Instr. **3**, 298 (1958).
[13] Teplova, Dmitriev, Nikolaev, and Fateeva, J. Exptl. Theoret. Phys. U.S.S.R. **32**, 974 (1957) [translation: Soviet Phys. JETP **5**, 797 (1957)].
[14] S. Devons and J. H. Towle, Proc. Phys. Soc. (London) **A69**, 345 (1956).
[15] J. B. Marion, Phys. Rev. **103**, 713 (1956).

It is of interest to estimate the amount of asymmetry necessary to produce this effect. Since no definite information exists concerning the angular distribution of the recoil Li^6 nuclei for proton energies off resonance we express it in the center-of-mass system as

$$f(\theta)=\sum_n A_n \cos^n\theta,$$

where θ is the angle with respect to the incident proton beam. Then at $E_p=2.93$ Mev one obtains in the case of point counters for the magnitude of the asymmetry necessary to produce a shift ΔE the following:

$$\frac{\Delta E}{E_0}=\frac{V_{\text{c.m.}}+V_{\text{Li}}\langle f(\theta)\cos\theta\rangle_{\text{Av}}}{c}(\cos\phi_1-\cos\phi_2),$$

where $V_{\text{c.m.}}$ is the velocity of the center of mass and V_{Li} is the velocity of the recoil Li^{6*} in the center-of-mass system. ϕ_1 and ϕ_2 are the angles made by the counter with the beam direction.

$$\langle f(\theta)\cos\theta\rangle_{\text{Av}}=\sum_{\text{odd}} A_n/(n+2)/\sum_{\text{even}} A_n/(n+1),$$

therefore

$$\sum_{\text{odd}} A_n/(n+2)/\sum_{\text{even}} A_n(n+1)=0.18.$$

The results of the 2.93-Mev run make it plausible that the low value of the measured shift in thick beryllium and thick nickel is due to the nonresonant Li^{6*} recoils.

CONCLUSION

Our measurement shows that the mean lifetime of the second excited state of Li^6 is shorter than 5.3×10^{-14} sec. This is in good agreement with Rose and Warburton[10] who find $\tau_{\max}=4.3\times10^{-14}$ sec. However at $E_p=2.67$ Mev they find the experimental shift from 0° to 160° in thick beryllium is 1.43 ± 0.034 compared to 1.44 calculated. We find 1.20 ± 0.07 compared to a calculated value 1.33 for the 0°–145° shift. A similar situation obtains for their value of the shift in Cu-Be alloy and our value is the Ni-Be alloy. There is less than one chance in 200 that this is accidental. Therefore there is probably an unexplained discrepancy between the two measurements. Nevertheless it is true that no significant difference in the shift between pure thick beryllium and beryllium alloyed with a heavy metal was detected in either experiment. Therefore the conclusions about the short lifetime of the state are not in doubt. The only disagreement lies in the contribution to the shift due to off resonance reactions. Since our limit is 20 times shorter than the lifetime for $E2$ transitions calculated from the Weisskopf formula[16] and since transition enhancement due to collective effects is not expected to shorten the lifetime by more than a factor of 10, we can conclude that the transition almost certainly is $M1$ in character which is consistent with the assignment of 0^+ for this state. Our results also show that the angular distribution of the alpha particles is forward peaked above resonance and is symmetric at resonance. They imply that the alpha angular distribution is forward peaked below resonance.

ACKNOWLEDGMENTS

We are grateful to E. N. Strait for valuable aid in all phases of the experiments and to Murray Peshkin for helpful discussions.

[16] V. F. Weisskopf, Phys. Rev. 83, 1073 (1951).