Gamma Rays and Internal Pairs from Be^9+H^1

R. J. MACKIN, JR.*
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California
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Gamma radiation following the reaction $Be^9(p,\alpha)Li^{6*}$, resonant at $E_p=2.56$ Mev, has been studied with a magnetic lens spectrometer. The gamma-ray energy, determined from photo- and Compton-electron spectra, is found to be 3.572 ± 0.012 Mev, not corrected for a possible 26-kev Doppler shift. The internal pair (positron) spectrum agrees most closely (to 4.5 percent) with the assignment of the radiation as magnetic dipole. Electric quadrupole is less likely and all other assignments are excluded. The magnetic-dipole character is consistent with the identification of the 3.57-Mev level of Li^6 as the analog of the He^6 ground state with $J=0^+$, $T=1$. Reaction data are analyzed to suggest that the resonant state of the compound nucleus (the 8.89-Mev level of B^{10}) has $J=2^+$, $T=1$.

INTRODUCTION

THE proton bombardment of beryllium exhibits resonance at 2.565 Mev for neutrons,[1,2] 3.58 $\pm$0.04-Mev gamma rays,[1,3] and gamma rays of energy greater than 6 Mev.[2] Day and Walker[3] have shown by observations of $\alpha-\gamma$ coincidences that the intense 3.58-Mev gamma rays follow the reaction $Be^9(p,\alpha)Li^{6*}$. As they point out, such a large gamma-ray yield from a level of Li^6 more than 2 Mev above the energy necessary for dissociation into He^4+H^2 implies the operation of a selection rule which inhibits that mode of disintegration. For instance, if the state is characterized by angular momentum $J=0$, even parity, or by isotopic spin $T=1$, the particle decay is forbidden. This paper presents new measurements on the gamma radiation and evidence from internal conversion pairs which supports the angular momentum assignment for the level.

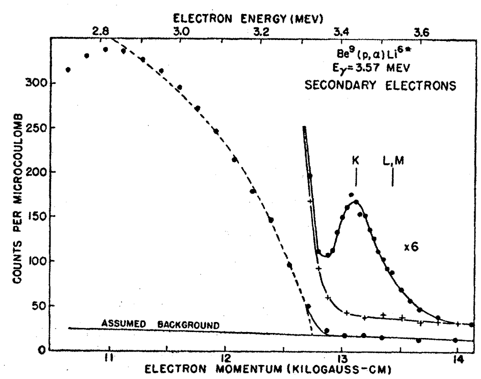

FIG. 1. Secondary Compton and photoelectric spectra from $Be^9(p,\alpha\gamma)Li^6$ at 2.72-Mev bombarding energy. Target thickness was 19 mg/cm². The Compton spectrum (dashed curve) was produced in 350 mg/cm² Al and the photopeak (ordinate multiplied by 6) in additional 23 mg/cm² Th.

EXPERIMENTAL METHOD AND RESULTS

A magnetic lens spectrometer, previously described,[4] was used with 1.9 percent resolution to study secondary electrons from gamma radiation produced by the proton bombardment of beryllium. A beam of magnetically analyzed protons from a 3-Mev electrostatic accelerator entered along the spectrometer axis to bombard a Be disk at the focal point. The beam current was measured with a current integrator accurate to about one percent, and the total gamma-ray yield at 90° was monitored with a shielded Geiger counter. The detector of focused electrons was a scintillation counter employing a *trans*-stilbene crystal. The RCA 5819 photomultiplier was shielded from the magnetic field of the spectrometer by a solenoid.[5] This detector presented the advantage of reducing background by discriminating against low-energy scattered electrons.

Figure 1 shows the Compton electron spectrum produced in a 350-mg/cm² Al converter located immediately behind the target. The dashed curve is the theoretical spectrum from an "infinitely thick" converter [reference 6, Eq. (11)] for a yield of $4.63\times10^{-6}\gamma/p$ ($E_p=2.72$ Mev). Day and Walker[2] reported 4.76 $\times10^{-6}\gamma/p$ at this energy. In the same figure, and on a sixfold greater scale, is the photoelectron spectrum produced in a 23-mg/cm² Th foil. Crosses indicate the background to the photospectrum. To the K-peak energy must be added the thorium K-shell binding energy and a 7-kev correction for electron energy loss in the converter.[4] There results a gamma-ray energy 3.574 $\pm$0.020 Mev.

In Fig. 2 is the spectrum of Compton electrons produced in a 23-mg/cm² Be target converter. Also shown is the Compton spectrum from the 3.097 ± 0.005-Mev gamma ray[6] from $C^{12}(d,p)C^{13*}$ produced in 39-mg/cm² graphite at $E_d=1.5$ Mev. It is normalized to the same peak height. Detailed comparison of the two curves shows the energy difference of the two gamma rays to be 473 kev, resulting in an independent (except for

* Assisted by the joint program of the U. S. Atomic Energy Commission and the U. S. Office of Naval Research.
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calibration constant) measurement of the new line as 3.570±0.015 Mev. The average of the values is 3.572 ±0.012 Mev. It is probably necessary to subtract from this figure a 26-kev Doppler shift arising from the motion of the Li^{6*}.

The background count rate observed above the end point and with zero field was found to be nearly independent of spectrometer current but strongly dependent upon the bias setting of the scintillation-detector discriminator. To minimize this background for the internal pair measurements, the positron spectrum was covered in overlapping segments, the bias being set for each segment at the highest value consistent with complete counting of all focused particles. A 19-mg/cm² Be foil with no converter was used for this measurement. The resulting spectrum, adjusted to a common background, is shown in Fig. 3. External pairs produced less than two percent of the measured counts. The solid curves represent theoretical spectra corresponding to various multipole orders of the transition,[6] with scale

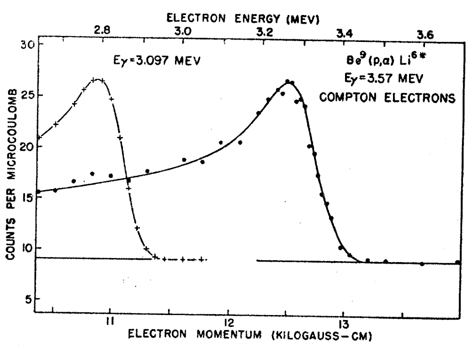

FIG. 2. Thin-converter Compton spectra from (1) $Be^9(p,\alpha)Li^{6*}$, solid circles, target converter 23 mg/cm² Be; (2) $C^{12}(d,p)C^{13*}$, crosses, $E_\gamma=3.097$, $E_d=1.5$ Mev, target-converter 39 mg/cm² graphite; peak height and background are matched to those of the Li^6 line.

determined by the gamma-ray yield. The Born approximation curves,[7] which drop to zero at the end point, have been adjusted to match more accurate end-point values.[8] The Compton electron spectrum was checked before and after the positron measurements to insure that any yield change resulting from carbon deposits was negligible.

Comparison of the areas under the various curves (above 3500 gauss-cm) was used to produce a quantitative measure of the agreement between the data and the respective assignments. This was regarded as a more accurate procedure than evaluation of the total internal pair coefficient, because the latter involves the area under a curve of counts/momentum (the spectrometer window is proportional to its momentum setting) thereby placing undue weight upon the statistically poorer low-momentum points. The area under the experimental curve was determined by connecting adjacent points with straight lines. If this area is taken as unity, the other areas are:

$E1$	1.66,
$E2$	1.13,
$M1$	0.955,
$E3$	0.82.

The curve representing a magnetic dipole transition gives closest agreement with experiment. The $E2$ curve is high by about 1.5 times the estimated probable error (which consists primarily of uncertainty in the yield measurement), and all others differ by more than twice the probable error. The 3.57-Mev level is thus assured of parity the same as that of the ground state (by $M1$ or $E2$) and the data are in agreement with a spin assignment of 0, 1, or 2 (the ground state has $J=1^+$).

DISCUSSION

The He^6 ground state almost certainly has spin zero, even parity. He^6 is an even-even nucleus and the beta decay to the Li^6 ground state is allowed, favored.[9] It thus seems likely that the 3.57-Mev level in Li^6 is the analog state expected on the assumption of charge independence of nuclear forces. The energy correspondence is only roughly in accord with this interpretation, but there is considerable uncertainty, for this particular case, in the Coulomb energy difference between the two isobars.[10]

Several inferences may be drawn from the $T=1$ characterization of the 3.57-Mev level. Nothing more can be said about its very small width for deuteron emission, because the strict angular momentum selection rule based on the $J=0^+$ assignment accounts for this. However, if the isotopic spin selection rules are rigid (that is, if there is little mixing of states with different T) it follows that the compound-nucleus state involved in the reaction (the 8.89-Mev level of B^{10})

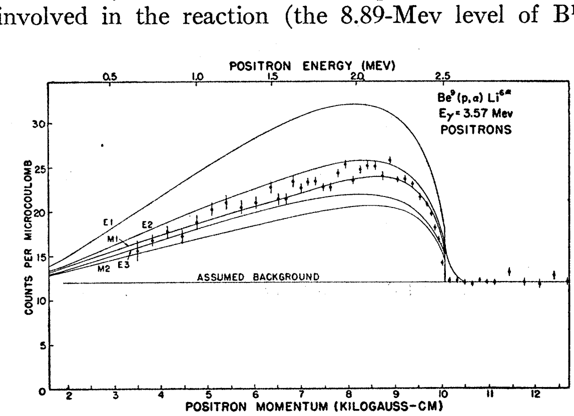

FIG. 3. Positron spectrum. Internal pairs from the 3.57-Mev gamma ray of $Be^9(p,\alpha)Li^{6*}$. $E_p=2.72$ Mev. Magnitude of theoretical spectra is determined by yield $4.63\times10^{-6}\gamma/p$. Curve $E1$ represents electric dipole, $E2$ electric quadrupole, etc.

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[9] Wu, Rustad, Perez-Mendez, and Lidofsky, Phys. Rev. **87**, 1140 (1952).

[10] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).

has $T=1$. It then follows that production by alpha emission from this B^{10} level of the ground state and 2.18-Mev level of Li^6 (both $T=0$) should be inhibited, and it has in fact been observed[11] that these alpha-particle groups do not display the 2.56-Mev resonance. Although a $J=0^+$ assignment for the 8.89-Mev level is also sufficient to explain these observations, it is shown in the appendix that the large resonant cross section for production of the 3.57-Mev level precludes this assignment. Upper limits on the partial widths for the above reactions would be of interest in establishing the purity of the T assignments involved.

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APPENDIX: SPIN OF THE 8.89-MEV LEVEL OF B^{10}

It is possible to infer a spin assignment for the 8.89 Mev level of B^{10}, formed by 2.56-Mev protons on beryllium. It will be noted first that the presence of the alpha group leading to the (presumed) $J=0^+$, $T=1$ state of Li^6 implies $T=1$ and parity $(-)^J$. An argument to set a lower limit on J proceeds from a comparison of the measured maximum resonant cross section for production of the 3.57-Mev gamma rays following the alpha emission with the Breit-Wigner expression for this quantity:

$$\sigma_R=4\pi\lambdabar^2[(2J+1)/(2i+1)(2s+1)]\Gamma_p\Gamma_\alpha/\Gamma^2, \quad (1)$$

where $\lambdabar$ is the wavelength ($\times 1/2\pi$) of the incident proton, J is the angular momentum of the resonant state, i and s are the spins of the incident particle and target nucleus, Γ_p is the partial width for proton emission, Γ_α is the partial width for alpha emission leading to the 3.57-Mev level of Li^6, and Γ is the total width. $\Gamma=\Gamma_\alpha+\Gamma_p+\Gamma_n+\Gamma'$, where Γ_n is the neutron width and Γ' is a sum of several other widths ($\alpha_0,\alpha_1,d,\ n+p$) which is expected to be small in view of the $T=1$ character of the level.

The charge independence of nuclear forces implies equality of the reduced widths for neutron and proton emission (γ_n^2 and γ_p^2) forming mirror levels. Γ_n/Γ_p is thus equal to the ratio of the barrier penetration factors, which may be computed from square well[12] and Coulomb[13] wave functions. Maximizing (1) with respect to Γ_p results in:

$$\sigma_R(\max)=\pi\lambdabar^2[(2J+1)/(2i+1)(2s+1)] \times(1-\Gamma'/\Gamma)^2/(1+\Gamma_n/\Gamma_p). \quad (2)$$

If Γ'/Γ is neglected, the value of this quantity as a function of J is given in Table I. The experimental value[2] of σ_R is 0.11×10^{-24} cm², a figure believed accurate to within ten percent considering the excellent agreement between the thick target yield quoted in reference 2 and that of the present investigation. It follows that $J\geqslant 2$. The same conclusion results if Γ_n is obtained from Hushley's estimate[1] that the neutron yield is roughly equal to the gamma-ray yield.

To set an upper limit on J, the expression (1) may be solved for Γ_α, taking $\Gamma=35$ kev[2] and $\Gamma'=0$. The reduced width γ_α^2 may then be found (necessarily including the level shift correction[14]) and compared with the Wigner sum-rule limit,[15] $3\hbar^2/2Ma$. Here M is the reduced mass and a is the alpha-channel radius, taken as $1.45(4^{\frac{1}{3}}+6^{\frac{1}{3}})\times10^{-13}$ cm. The results are:

J	$\gamma_\alpha^2\cdot 2Ma/3\hbar^2$
2^+	0.19 or 0.33
3^-	2.5 or <0.

The first result found for $J=3$ is highly unlikely (the Wigner limit being only an estimate) while the latter is physically unrealizable, as are those for higher J's. It thus seems probable that the 8.89-Mev level of B^{10} has $J=2^+$. For this spin value, the proton (or neutron) reduced width is 0.0053 or 0.0016 of the Wigner limit.

TABLE I. Maximum possible values of Breit-Wigner cross section for $Be^9(p,\alpha)Li^{6*}$ reaction for various assumed values of compound state spin J.

J	l_p	Γ_n/Γ_p	$\sigma_R(\max)$ (10^{-24} cm²)
0^+	1	0.270	0.031
1^-	0	0.572	0.076
2^+	1	0.270	0.156
3^-	2	0.062	0.262

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