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Simple Capture of Alpha-Particles

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Gamma-rays have been observed from the simple capture of alpha-particles in lithium. The gamma-ray energies were too large for simple capture in Li^6, but not inconsistent with the reaction $Li^7(\alpha,\gamma)B^{11}$. Three resonances were observed at bombarding energies of 0.401, 0.819, and 0.958 Mev. The corresponding excited states in B^{11} are at 8.90, 9.16, and 9.25 Mev. The yields were too small to use thin targets, but the resonances appeared as steps in the thick target yield curve. The slope of the steps was largely of instrumental origin for the first two resonances and suggested a width of about six kev for the upper resonance. Among the other light elements, only Be and B yielded gamma-rays when bombarded by 1.4-Mev alpha-particles; but in these cases, the sharp resonances characteristic of simple capture were absent.

I. INTRODUCTION

SIMPLE capture of particles with emission of gamma-radiation has been observed frequently. Many elements throughout the periodic table show simple capture of neutrons, and proton capture has been reported in many of the lighter elements. Theory does not suggest any reason why simple capture should not be observed for alpha-particles in light nuclei. The Q values are positive except for atomic number below three, while the competing reactions involving heavy particle emission have negative Q values in most cases. The only problem is to find whether or not the nuclei produced in the reaction have excited states of appropriate energy in which the alpha-particles can be captured. The yield of gamma-rays from simple capture should be independent of the penetrability of the potential barrier as long as the width of the level remains much larger than a few electron volts.[1]

Natural sources of alpha-particles are unsuitable for a study of simple capture because the yield of gamma-radiation is always small and because the yield curves usually show sharp resonances.

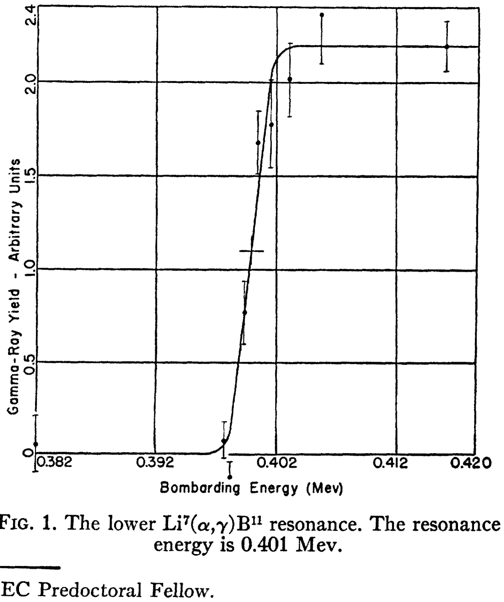

Fig. 1. The lower $Li^7(\alpha,\gamma)B^{11}$ resonance. The resonance energy is 0.401 Mev.

II. EXPERIMENTAL ARRANGEMENT

The alpha-particles were produced by accelerating singly charged helium atoms in the Illinois Institute of Technology electrostatic generator. The beam to be used was bent magnetically and was passed through a narrow slit. The part of the beam which struck the edges of the slit was used as the signal for a controlled corona system of the type described by McKibben, *et al.*[2] Using this regulating system kept the energy of the beam constant to about ±1.2 kev.

Thick targets were used containing the elements Li, Be, B, C, N, and O. For the first three the metals were used, and for the last three, graphite, urea, and quartz. The lithium metal probably formed a carbonate which decomposed under bombardment. A black spot formed on each target under bombardment, but this was minimized by using a dry-ice cold trap between the pump and the target chamber and by changing to new spots

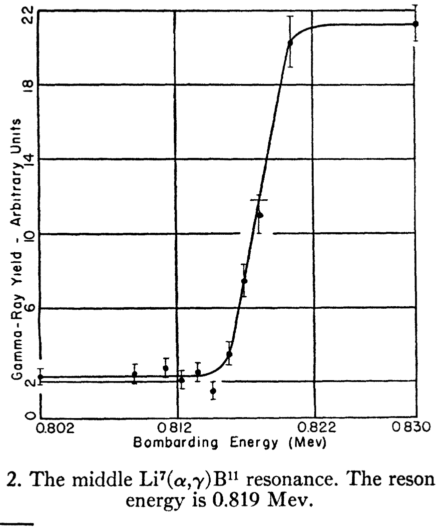

Fig. 2. The middle $Li^7(\alpha,\gamma)B^{11}$ resonance. The resonance energy is 0.819 Mev.

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[1] Broström, Huus, and Tangen, Phys. Rev. 71, 661 (1947).

[2] McKibben, Frisch, and Hush, U. S. Atomic Energy Commission Declassified Document No. MDDC-222 (1946) (unpublished).

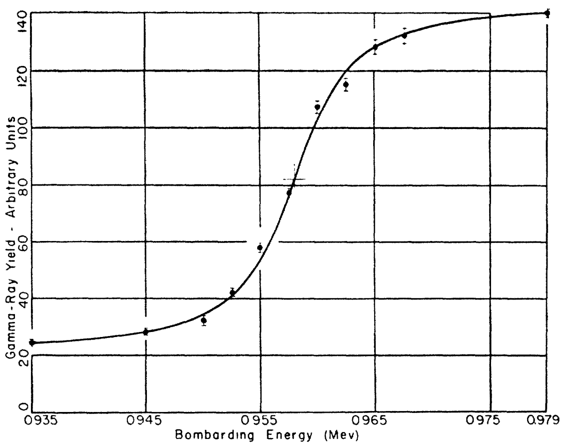

FIG. 3. The upper $Li^7(\alpha,\gamma)B^{11}$ resonance. The resonance energy is 0.958 Mev. The curve was calcaulated for $\Gamma=6$ kev.

on the target frequently. The yield of gamma-radiation from lithium was found to increase with time when the targets were new. This was caused by decomposition rather than by contamination, since the common contaminants gave no gamma-rays at all. Lithium fluoride targets were also used to facilitate calibration of the generating voltmeter. The beams falling upon the targets were measured by a current integrator of the type described by Watt.[3]

The gamma-rays were detected by a pair of coincidence beta-counters placed immediately outside the target holder in line with the analyzed beam. The absorption between the two counters owing to the walls was equivalent to 0.3 mm of aluminum. The counters were 4 cm apart and between them was placed an aluminum absorber 1.6 mm thick to reduce the background caused by x-rays from the electrostatic generator.

III. PROCEDURE AND RESULTS

When the lithium target was used, three resonances were observed for bombarding energies below 1.4 Mev. These resonances are shown in Figs. 1–3, and will be referred to as the lower, middle, and upper resonances, respectively. In all three figures, the abscissa interval is 10 kev. Although the yields of gamma-rays are in arbitrary units, the same arbitrary scale has been used in all three diagrams, so that each figure is a continuation of the preceding one. The vertical lines on the experimental points represent the probable error due to statistics of counting. The data have been corrected for background counts.

The voltage was measured by a generating voltmeter[4] which was calibrated from observations on the $F^{19}(p\alpha',\gamma)O^{16}$ resonance[5] at 0.8735 Mev. The calibration changed gradually during the day in a way which suggested that it was caused by the heating-up of the electrostatic generator during operation. The effect was eliminated by recalibration of the generating voltmeter immediately before and after each determination of the position of the resonance in question. Only a few minutes were required to change from hydrogen to helium in the ion source. To avoid changing of the target, a LiF target was used. Consistent results were obtained and the final values for the positions of the resonances were 0.401, 0.819, and 0.958 Mev. The errors are ±0.001 Mev except for the lower resonance in which there may be an additional error caused by nonlinearity of the generating voltmeter.

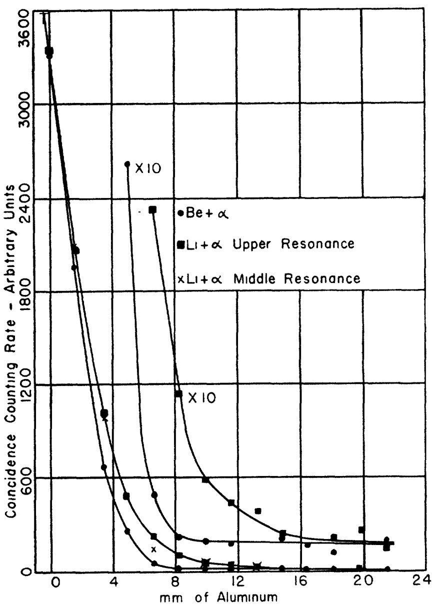

FIG. 4. Absorption curve in aluminum of the secondary electrons produced by gamma-radiation. The lower curve is for 4.45-Mev gamma-rays.

The slope of the step in a thick target yield curve can be used to get the width of the resonance if correction is made for the slope owing to instrumental fluctuations. From the slope of the lower and middle resonances, upper limits of 1 kev can be set to the true width of these resonances. The upper resonance is much broader, and the corresponding width can be determined. The best value in the room coordinate system is 6 kev. The line drawn in Fig. 3 is of theoretical shape for a thick target, obtained by integrating a Breit-Wigner dispersion function with $\Gamma=6$ kev and including the effect of instrumental fluctuations. The shape fits the experimental points quite closely.

Targets of the common contaminants (carbon, nitrogen, and oxygen) yielded no gamma-rays when bombarded by 1.4-Mev alpha-particles. Either Li^6 or Li^7 was the nucleus responsible for the observed effects. It was possible to identify the reaction as $Li^7+He^4 \rightarrow \gamma+B^{11}+8.64$ Mev rather than $Li^6+He^4\rightarrow\gamma+Be^{10}+4.36$ Mev by measuring the energies of the gamma-

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[3] B. E. Watt, Rev. Sci. Instr. **17**, 334 (1946).

[4] Trump, Safford, and Van de Graaff, Rev. Sci. Instr. **11**, 54 (1940).

[5] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).

rays. This was done by inserting aluminum absorbers between the coincidence counters. The absorption curve is shown in Fig. 4. An absorption curve for the 4.45-Mev radiation[6] from $Be^9(\alpha,n)C^{12}$ was taken for comparison and is plotted in the same figure. The method outlined by Fowler, *et al.*,[7] was used to find the energy of the capture gamma-rays. Values from 5 to 7 Mev were obtained, depending upon the degree of absorption. The method gives too low a maximum value when the spectrum is complex. A consistent interpretation is that 15 percent of the radiation is emitted in transitions directly to the ground state of B^{11} and the rest is due to cascade transitions. The excited states in B^{11} corresponding to the three resonances are at 8.90, 9.16, and 9.25 Mev above the ground state. However, the identification of the reaction was less certain for the lower resonance because an accurate absorption curve could not be obtained for radiation of such feeble intensity.

The yield of gamma-rays from simple capture of alpha-particles in lithium was compared to the yield from the 440-kev resonance in the reaction $Li^7(p,\gamma)Be^8$ using the same target and detector. The counting rates above the three resonances were 0.9, 9, and 60×10^{-4} of the counting rates for 0.54-Mev protons. With these low counting rates it was not feasible to use thin targets to study the resonances.

The beryllium and boron targets yielded gamma-rays when bombarded with 1.4-Mev alpha-particles, but in these cases the sharp resonances characteristic of simple capture were absent. From the beryllium target there were no observable gamma-rays of energy greater than the 4.45-Mev energy expected from the $Be^9(\alpha,n)C^{12}$ reaction. The measured energy of the boron gamma-rays was about 3.8 Mev. They were probably produced in the $B^{10}(\alpha,p)C^{13}$ reaction, since excited states in C^{13} at 3.95 and 3.18 Mev are known.

IV. DISCUSSION OF RESULTS

The yield of photons from each resonance can be obtained from the counting rates quoted above. Since the counting rate for the $Li^7(p,\gamma)Be^8$ reaction was obtained considerably above the resonance, a correction is necessary so that only the step yield due to the resonance is involved. Since all the data was obtained for 1.60 mm of aluminum absorber between the counters, the values must be corrected to zero absorber thickness. Finally, the efficiency of counting is different for the two reactions, since the gamma-ray energy is different. This final correction was made by taking 5.3 Mev for the average energy of the gamma-rays from the $Li^7(\alpha,\gamma)B^{11}$ resonances and 17.5 Mev for the gamma-rays from the $Li^7(p,\gamma)Be^8$ resonance and using the counting efficiencies given by Fowler, *et al.*[7] Denoting the gamma yield from the $Li^7(\alpha,\gamma)B^{11}$ resonances by $Y_\gamma{}^\alpha$ and the yield from the $Li^7(p,\gamma)Be^8$ resonance by $Y_\gamma{}^p$, we find that $Y_\gamma{}^\alpha/Y_\gamma{}^p$ for the lower, middle, and upper resonances are, respectively, 0.65, 5.6, and 36×10^{-3}.

From theoretical considerations, it can be shown that these ratios are quite reasonable. The familiar Breit-Wigner formula for an (α,γ) reaction assuming that alpha—re-emission is the only competing process, is

$$\sigma_\gamma(E)=\pi\lambda\!\!\!^{-2}(2J+1)\Gamma_\gamma\Gamma_\alpha/(2s+1)(2i+1)[(E_\alpha-E_r)^2+\tfrac{1}{4}\Gamma^2]. \quad (1)$$

The symbols in Eq. (1) are those used by Bethe.[8] Now, if N is the number of target nuclei per cc in the target and $R=dE/dx$ is the rate of loss of energy per cm of target with dE in the relative coordinate system, then,

$$Y_\gamma{}^\alpha=(Nh^2/R4M_\alpha E_\alpha)(\omega\gamma)_\alpha,$$

where we have taken R and $\lambda\!\!\!^{-}$ to be constant over a narrow resonance, and have set

$$\omega=(2J+1)/(2s+1)(2i+1), \quad \gamma=\Gamma_\gamma\Gamma_\alpha/\Gamma_\alpha+\Gamma_\gamma.$$

Writing a similar expression for $Y_\gamma{}^p$ and assuming the target to be the same gives

$$Y_\gamma{}^\alpha/Y_\gamma{}^p=R_pM_pE_p(\omega\gamma)_\alpha/R_\alpha M_\alpha E_\alpha(\omega\gamma)_p,$$

where E is the energy at resonance in the relative coordinate system and M is the reduced mass. Using the measured yield ratios and obtaining the ratios of the R's from the range-energy relation of Bethe,[9] and using the value 8.9 ev for $(\omega\gamma)_p$ as given by Fowler, *et al.*,[7] we find the $(\omega\gamma)_\alpha$ for the lower, middle, and upper resonances to be, respectively; 0.04, 0.6, and 4.7 ev. These figures lie within the range of values quoted by Broström, *et al.*, for the corresponding quantity for the $Al^{27}(p,\gamma)Si^{28}$ reaction. One concludes, therefore, that there is no intrinsic difference between simple capture of protons and simple capture of alpha-particles. The yield of gamma-rays from an alpha-capture reaction will always be expected to be smaller than from the corresponding proton capture reaction because of the higher rate of energy loss per cm and the smaller wavelength associated with alpha-particles as compared with protons. The only compensating factor is the fact that, since the spins of the alpha-particle and proton are, respectively, 0 and $\frac{1}{2}$, it might be expected that on the average $(\omega\gamma)_\alpha$ would be double $(\omega\gamma)_p$. This last point would require much more experimental evidence than is available at this writing.

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[6] C. E. Bradford and W. E. Bennett, Phys. Rev. **78**, 302 (1950).

[7] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).

[8] H. A. Bethe, Revs. Modern Phys. **9**, 69 (1937).

[9] H. A. Bethe, Revs. Modern Phys. **22**, 213 (1950).