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The Reaction $Be^9(p,\alpha\gamma)Li^6$

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The energy of the gamma-radiation produced when Be^9 is bombarded by 2.6-Mev protons has been measured with a scintillation spectrometer and found to be 3.58 ± 0.04 Mev. A suggestion of Hushley that this gamma-ray is produced in the reaction $Be^9(p,\alpha\gamma)Li^6$ was verified by observing coincidences between the gamma-rays and low energy alpha-particles. The excited state of Li^6 which emits the gamma-rays probably has spin zero and even parity and is presumably the analog of the ground state of the isobaric nucleus, He^6. The thick target yield and cross section at resonance were found to be 4.8×10^{-6} gamma-rays per proton and 0.11×10^{-24} cm^2, respectively.

I. INTRODUCTION

In the bombardment of beryllium with protons, a strong resonance for production of both gamma-rays and neutrons was observed at 2.56 Mev by Hushley.[1] From measurements of the absorption of secondary electrons, Hushley found that the energy of the gamma-radiation was about 3.0 Mev, which is less than half the 8.8 Mev available for simple capture radiation. From this fact and from the great intensity of the gamma-radiation, Hushley concluded that the gamma-rays were probably emitted by a residual nucleus left after particle decay of the compound nucleus, B^{10}. After considering various possibilities, he concluded that the reaction was probably $Be^9+p\rightarrow B^{10*}\rightarrow Li^{6*}+\alpha$, $Li^{6*}\rightarrow Li^6+h\nu$.

We have used a scintillation counter to obtain a more accurate value for the energy of the gamma-ray, and have confirmed Hushley's conclusion about the origin of the gamma-radiation by measuring coincidences between the gamma-rays and low energy alpha-particles.

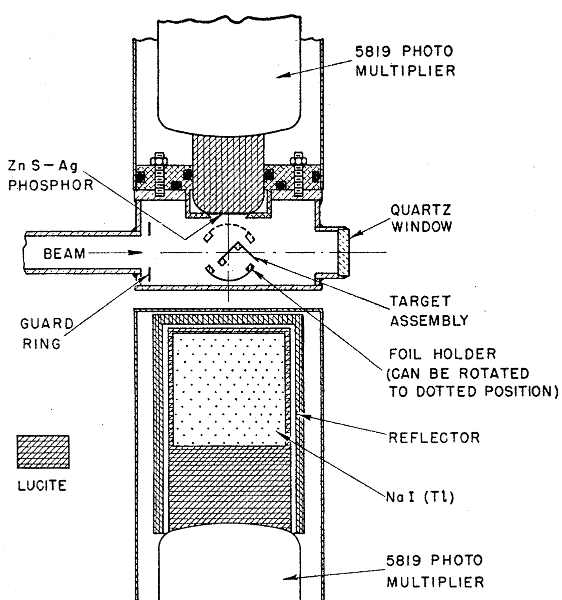

FIG. 1. Arrangement for measuring alpha-gamma coincidences. A 0.00015-inch aluminum foil is mounted on a rotatable holder so that it may be inserted between the target and the particle counter to cut out low energy alpha-particles.

II. THE GAMMA-RAY ENERGY

The energy of the gamma-radiation produced by bombarding a thin beryllium target with 2.6-Mev protons was measured by the scintillation counter technique now in widespread use.[2] The scintillation counter consisted of a cylindrical NaI(Tl) crystal $1\frac{1}{2}$ inches long and $1\frac{1}{2}$ inches in diameter mounted on a selected 5819 photomultiplier tube (the bottom counter of Fig. 1). Pulses from the photomultiplier were amplified and then analyzed by a single-channel differential discriminator designed by M. Sands. The observed pulse-height spectrum is shown in Fig. 2, where the usual three peaks corresponding to a single gamma-ray may be seen. The lowest energy peak, the pair peak, results from pairs produced in the NaI crystal if both the subsequent annihilation quanta escape from the crystal. The highest energy peak corresponds to the full gamma-ray energy, while the central peak results from Compton scattering and from pair production with escape of one of the annihilation quanta. Figure 2 shows also the pulse-height spectrum from the 2.62-Mev gamma-ray of ThC″. This was used for the energy calibration. To minimize the effects of small drifts in the apparatus, the lowest energy Be^9 peak and the highest energy ThC″ peak were measured several times alternately. A value 3.58 ± 0.04 Mev was obtained for the Be^9+proton gamma-ray. The gamma-ray energy was also measured at a proton bombarding energy of 2.3 Mev. The result obtained here was $E_\gamma=3.56\pm0.04$ Mev.

The pulse-height spectrum was examined carefully in the region 1.2–2.6 Mev with the aid of the differential discriminator and also by photographing the pulses on an oscilloscope. Neither method disclosed any further peaks. From the fluctuations in the pulse-height curve

[1] W. J. Hushley, Phys. Rev. **67**, 34 (1945).

[2] S. A. E. Johanssen, Arkiv Fysik **2**, 171 (1950); R. Hofstadter and J. A. McIntyre, Phys. Rev. **80**, 631 (1950); W. H. Jordan and P. R. Bell, Nucleonics **5**, 30 (1949).

we estimate that the intensity of any lower energy gamma-ray is less than two percent of the 3.58-Mev gamma-ray. This is of particular interest in view of the fact that a level in Li^6 has recently been found at 2.187 Mev by Browne, *et al.*,[3] by means of the reaction $Be^9(p,\alpha)Li^{6*}$. Above 3.6 Mev we find no gamma-rays with relative intensity greater than one-half percent.

The fact that only one gamma-ray of appreciable intensity is observed and that it does not change energy as the proton energy is varied indicates that the radiation comes from a residual nucleus, thus supporting Hushley's suggestion that the gamma-radiation is produced in the reaction $Be^9(p,\alpha\gamma)Li^6$. To obtain further evidence on this origin we looked for coincidences between the gamma-rays and the low energy alpha-particles expected to precede them.

III. ALPHA-GAMMA COINCIDENCES

Coincidences between the gamma-rays and low energy alpha-particles were observed with the detector and target arrangement shown in Fig. 1. The alpha-particle scintillation counter employed a layer of activated ZnS phosphor sufficiently thin that protons scattered from the Be target lost only part of their energy in traversing it. Thus the pulses from scattered protons and other reaction products, which were about 15 times as numerous as the low energy alpha-particle pulses, were reduced to a size comparable with that of the latter. The target was a thin beryllium foil, nominally 22 micro-inches thick, mounted over a hole in a brass support. Behind it was a piece of tantalum, arranged to collect the protons passing through the target but not to scatter protons into the particle counter.

Figure 3 shows the excitation curve near the resonance for both gamma-rays and alpha-gamma coincidences. The latter curve has been corrected for accidental coincidences and is plotted on such a scale that the two curves would coincide if every gamma-ray followed a low energy alpha-particle and if the efficiency of the alpha-particle counter were 100 percent. Because of the large background of scattered protons it was not possible to measure the efficiency for low energy alpha-particles. However we feel that the value of 60 percent indicated by Fig. 3 is quite reasonable.

In order to see whether the observed coincidences were actually produced by low energy alpha-particles, counts were taken with a thin aluminum foil between the target and the particle counter. For this purpose a 0.00015-inch aluminum foil was mounted on a rotatable holder in the target chamber as shown in Fig. 1. This thickness is sufficient to stop alpha-particles of about 850 kev (those expected from the $Be^9(p,\alpha\gamma)Li^6$ reaction have an energy of about 400 kev at 90°), but will allow more energetic alpha-particles and scattered protons to pass through. Since most of the individual counts in the particle counter were produced by higher energy particles, the aluminum foil did not change appreciably either the "singles" rate of the particle counter or the accidental coincidence rate. It did, however, reduce the coincidence counting rate to about 16 percent of the rate without the aluminum filter. The remaining 16 percent are presumably accidental coincidences since the insertion of a 1.5 μsec delay line in one arm of the coincidence circuit produced no further reduction in coincidence rate. Furthermore, the coincidence counts with aluminum filter dropped to 6 percent when the proton beam intensity was decreased by about a factor of three. During the coincidence measurements the proton beam current was kept at about 2×10^{-9} amp in order to reduce the accidental coincidences to an acceptable rate. The resolving time of the coincidence circuit was approximately 0.1 μsec.

[3] Browne, Williamson, Craig, and Donahue, Phys. Rev. **83**, 179 (1951).

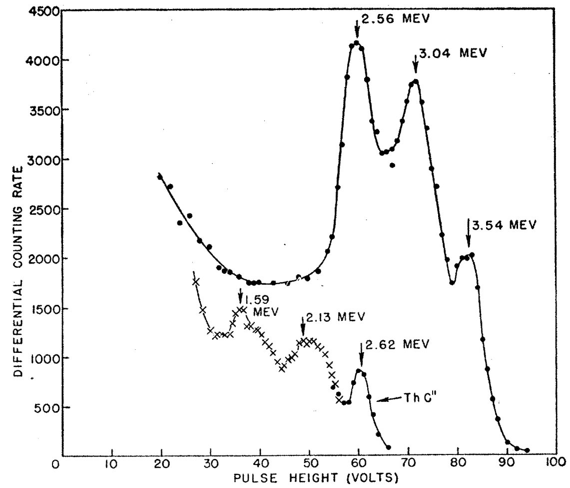

FIG. 2. Differential pulse-height distributions for gamma-rays from $Be^9(p,\alpha\gamma)Li^6$, and for the 2.62-Mev gamma-rays from ThC″ used as an energy calibration. The channel width of the differential discriminator was 1 volt.

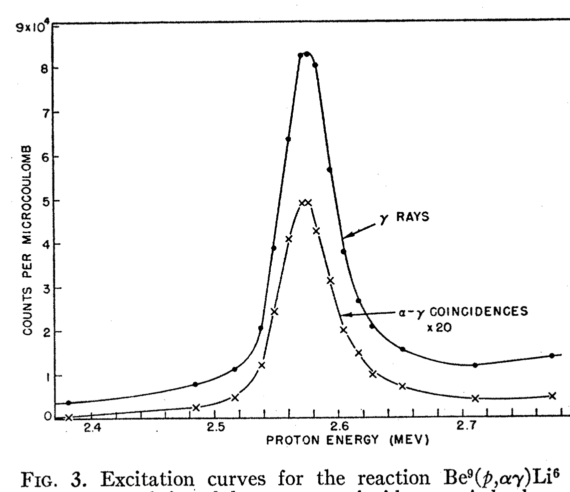

FIG. 3. Excitation curves for the reaction $Be^9(p,\alpha\gamma)Li^6$ for gamma-rays and for alpha-gamma coincidences. A background of accidental coincidences (about 16 percent) has been subtracted from the coincidence curve.

As a further check to show that the 3.58-Mev gamma-ray was the one in coincidence with the alpha-particles, the pulses from the gamma-ray scintillation counter were photographed on an oscilloscope whose sweep was triggered by the output pulses from the coincidence circuit. Although it seemed unlikely that any other gamma-ray could be sufficiently intense to produce the large number of observed coincidences, this method would have increased its intensity relative to the 3.58-Mev gamma-ray by a factor of five (the ratio of true to accidental coincidences). The picture thus obtained showed no pulses due to gamma-rays other than the one at 3.58 Mev, which appeared with the intensity to be expected if it were in coincidence with the alpha-particles. Thus, the evidence is in strong support of the hypothesis that the reaction produces a low energy alpha-particle, leaving Li^6 in an excited state at 3.58 Mev which decays by emitting a gamma-ray.

IV. THE CROSS SECTION

Several gamma-ray excitation curves were run in order to determine the cross section, energy, and width of this resonance. The protons from the electrostatic generator were analyzed in energy by a 90° electrostatic analyzer, operated with a resolution of about 0.1 percent. The proton charge striking the target was measured with a current integrator having an accuracy of better than one percent, while the detector was the NaI scintillation counter used previously. The curves thus obtained showed an asymmetry which was at first thought to be due to the superposition of the resonance on a rising background. However, when the data were corrected for the energy dependence of Γ_α, the width for alpha-particle emission, the excitation curves exhibited the characteristic symmetrical shape of the Breit-Wigner formula.

In order to determine the true resonance width and energy it was necessary to measure the target thickness. This was done by measuring the shift in the 1754 kev resonance[4] of $C^{13}(p,\gamma)N^{14}$, which has a width of less than 2 kev, when the beryllium foil was interposed in the proton beam. A shift of 16.6 kev was found, corresponding to a target thickness of 12.7 kev at 2.58 Mev. Since in the beryllium reaction the foil was placed at an angle of 45° to the beam, the value used for the target thickness was 18 kev. Applying this value to the excitation curves corrected for the energy variation of Γ_α we find the resonance energy to be 2.565 ± 0.005 Mev and the width Γ to be 39 ± 2 kev. The energy calibration was made by means of the 873.5 kev resonance in $F^{19}(p,\alpha\gamma)O^{16}$ using the mass-three beam.

The absolute yield of the gamma-rays was determined by extrapolating the integral pulse-height curve to zero pulse height and dividing by the calculated absorption of the NaI crystal. This method has been checked by measuring in the same way the gamma-ray yield in the reaction $F^{19}(p,\alpha\gamma)O^{16}$ produced by bombarding a CaF_2 crystal with 1.00-Mev protons. A value 7.14×10^{-7} gamma-ray per proton was obtained for the fluorine reaction, to be compared with the best value 6.68×10^{-7}.[5] The agreement is better than the estimated accuracy of our method, which is 10–15 percent.

The thick target yield of the 3.58-Mev gamma-ray was measured with a thick beryllium target and checked by integrating the thin target curve, the two methods giving very good agreement. In this reaction the thick target curve does not have the usual shape, but continues to rise at high energies because of the rapid decrease in the barrier factor for the low energy alpha-particles. Above 2.68 Mev the rise is approximately linear and at 2.72 Mev the thick target yield is 4.76×10^{-6} gamma-ray per proton. From the maximum yield in the thin target curve we have calculated the cross section at resonance, obtaining $\sigma_r=0.11\times10^{-24}$ cm^2. Both the cross section and yield values were calculated under the assumption that the gamma-rays are emitted isotropically. It will be shown in the next section that this assumption is quite reasonable.

V. DISCUSSION

For some time there was a question as to whether the gamma-ray observed by Hushley could actually occur in the decay of an excited state of Li^6. The difficulty is that disintegration into an alpha-particle and a deuteron is possible for energies above 1.53 Mev and in general this mode of disintegration would proceed so quickly that gamma-decay could not compete with it. A possible explanation was suggested by W. A. Fowler and others at this laboratory, who pointed out that if an excited state in Li^6 has spin zero and even parity then the particle disintegration is forbidden by the conservation of angular momentum and parity. Thus it is reasonably certain that any strong gamma-ray of energy greater than 1.53 Mev that occurs in the de-excitation of a Li^6 state must be from a state with spin zero and even parity.

On the basis of both the alpha-particle and independent particle models the ground state of He^6 would be expected to have spin zero and even parity. The ft value of 590 for its β-decay to the ground state of Li^6 is consistent with this, providing Gamow-Teller selection rules apply. Using the estimated Coulomb energy and the $n-H^1$ difference, Lauritsen[6] has calculated that the analogous state in Li^6 should lie at about 3.7 Mev. Thus it seems quite reasonable that the level at 3.58 Mev is indeed this level. From the spin zero property one would expect both the gamma-ray angular distribution and the α-γ angular correlation to be isotropic. We intend to measure the first of these to test this hypothesis. In addition, an experiment to measure the

[4] Seagrave, Day, and Perry, Phys. Rev. **81**, 661 (1951).

[5] This is actually $4\pi Y(90°)$. The value was obtained by Perry and Day (unpublished) by comparison with a calibrated Co^{60} source and is also in excellent agreement with the alpha-particle yield.

[6] T. Lauritsen, *Energy Levels of Light Nuclei—1950*, Annual Review of Nuclear Science for 1950, to be published.

coefficient for internal pair conversion is being carried out at this laboratory by Mr. R. J. Mackin and Mr. C. Wong. This should provide information on the character of the gamma-ray and hence on the change of spin and parity occurring in the transition. Preliminary results indicate that the gamma-ray is magnetic dipole as is to be expected from the above considerations.

We should like to express our thanks to Professors T. Lauritsen and R. F. Christy for suggesting this problem and for several enlightening discussions on it. We are also indebted to Mr. Torben Huus for assistance in operating the electrostatic generator.

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The (p, n) Reaction on Separated Isotopes of Chromium*

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Several hundred resonances have been observed in the neutron yield from proton bombardment of the enriched isotopes Cr^{53} and Cr^{54}. No characteristic groups of resonances are observed. Upper limits to the level spacing in the compound nuclei Mn^{54} and Mn^{55} are 4 and 5 kev, respectively. The thresholds are found to be 1406±8 kev for $Cr^{53}(p,n)$ and 2202±5 kev for $Cr^{54}(p,n)$.

A. INTRODUCTION

Resonances in the neutron yield of the reaction $Mn^{55}(p,n)Fe^{55}$ have been studied by McCue and Preston.[1] In continuation of a program at this laboratory of investigating a number of light-intermediate weight elements with the best energy resolution practical with our equipment, we have measured the relative yield as a function of energy from the reactions $Cr^{53}+p\rightarrow Mn^{54}\rightarrow Mn^{53}+n$ and $Cr^{54}+p\rightarrow Mn^{55}\rightarrow Mn^{54}+n$. Chromium was chosen because its two heaviest stable isotopes, Cr^{53} and Cr^{54}, could be obtained from Oak Ridge enriched to a high degree and had (p,n) thresholds estimated to be conveniently low. Neutron yield resonances in these reactions correspond to excited states in the compound nuclei Mn^{54} and Mn^{55}. We wished to measure the reaction threshold energies, to search for possible regularities in the level spectra, and to compare the level spacing in two neighboring nuclei with the same number of protons, but containing, respectively, an odd and an even number of neutrons.

B. EXPERIMENTAL METHODS

The proton source was the Rockefeller electrostatic generator[2] at M.I.T. The absolute energy calibration of the machine is based on the $Li^7(p,n)Be^7$ threshold, taken as 1882.2 kev, ±0.1 percent.[3] Relative to this standard, we believe our energy measurements of sharp resonances in the present work should be accurate to ±0.1 percent, allowance being made for long-term drifts in the calibration constant, target contamination, and other sources of error. Resetting accuracy and short-term stability, as in measuring the profiles or separation of neighboring resonances, is close to 0.01 percent. Tests indicate that the effective beam energy resolution width is not over 0.08 percent when the defining slits of the magnetic analyzer are opened to 1 mm, and half as great with 0.5-mm slit openings.

Neutrons were detected by a counter consisting of a 1-inch diameter tube, filled with enriched BF_3 at a pressure of 55 cm of mercury, and embedded in an 8-inch diameter, cadmium-covered cylinder of paraffin. The counter was operated in the proportional region and the pulse-height discriminator, which followed the linear amplifier, was set at a sufficiently high level so that gamma-rays were not counted. The counter assembly was mounted with its axis perpendicular to the proton beam and its side a few centimeters from the target, at which it therefore subtended a rather large angle in the forward direction. The counter was operated in this position in order to get satisfactory counting rates despite the low reaction yields; we cannot assume that the neutron detection efficiency was inde-

Table I. Isotopic analysis of target materials.

Isotope	Natural abundance	Enriched Cr^{53}	Enriched Cr^{54}
Cr^{50}	4.4%	0.193%	0.2%
Cr^{52}	83.5	9.28	7.0
Cr^{53}	9.5	90.06	3.9
Cr^{54}	2.6	0.465	89.0

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[1] J. J. G. McCue and W. M. Preston, Phys. Rev. 84, 1150 (1951).

[2] W. M. Preston and C. Goodman, Phys. Rev. 82, 316 (A) (1951). See reference 1 for additional details.

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