Partial Widths of the 16.11-Mev State in C^{12}

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The alpha-particle spectrum, gamma-ray spectrum, and the ratio of gamma-ray to alpha-particle yield have been measured for the 163-kev $B^{11}+p$ resonance which forms the 16.11-Mev state in C^{12}. The results are combined with the previously known total width and gamma-ray yield to give new values for the gamma-ray widths, the partial alpha width for decay to the Be^8 ground state, and the proton width. The new values for the partial widths, which differ from those previously listed by as much as an order of magnitude, are shown to be in agreement with the independent-particle model predictions.

INTRODUCTION

THE 16.11-Mev state in C^{12} has been investigated by several workers[1] and many of its properties are well established. However, a previous investigation[2] indicated that some of the partial widths heretofore accepted might be in error and therefore the present investigation was undertaken in order to re-examine the relative rates for the various decay modes. The motivation for this investigation increased when a literature search revealed that some of the values listed[1] for the partial widths were based upon old data,[3] which were really only rough estimates.

An energy level diagram showing the various decay modes of the 16.11-Mev state is given in Fig. 1. The 16.11-Mev state has a well-established[1] spin of 2 and positive parity, and a total width of about 6 kev (c.m.). The narrowness of the state implies that it is a $T=1$ state and it is taken to be the analog of the first excited state in B^{12}.

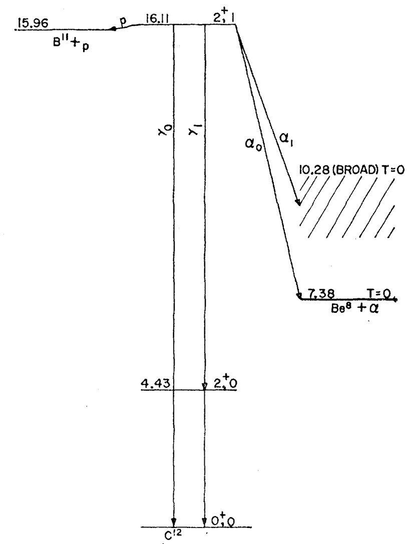

FIG. 1. Principal modes of decay of the 16.11-Mev state in C^{12}. The partial widths for these decays are given in Table I.

Designating the alpha-particle transition to the ground state of Be^8 as α_0 and that to the Be^8 first excited state as α_1, and, similarly, the gamma-ray transitions to the ground and first excited states of C^{12} as γ_0 and γ_1, respectively, the present work was undertaken in order to re-evaluate $\Gamma_{\alpha 0}$, $\Gamma_{\gamma 0}$, and $\Gamma_{\gamma 1}$. Furthermore, accepting a gamma-ray yield measurement of other workers,[4] a new value of Γ_p was determined.

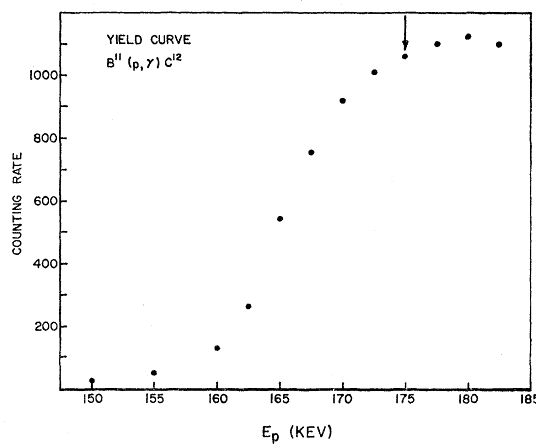

FIG. 2. Yield of gamma rays of energy $\gtrsim 3$ Mev when a thick metallic natural boron target is bombarded with protons. The intensity units are arbitrary and the proton energy scale is nominal. The arrow indicates the bombarding energy at which most of the data were taken.

EXPERIMENTAL RESULTS

A thin, metallic, powdered boron target was bombarded with protons accelerated by a Cockcroft-Walton generator. The target was viewed by a silicon *p-n* junction detector and a 5-in.-diam 5-in.-thick NaI(Tl) crystal. The silicon (α) spectrometer was movable about the target while the NaI(Tl) (γ) spectrometer was fixed at 90° to the incident beam. A gamma-ray yield curve is shown in Fig. 2 with the arrow indicating the bombarding energy at which most of the data were taken. No contribution ($\lesssim 1\%$) was seen for α_0 or γ_1 below

[1] F. Ajzenberg-Selove and T. Lauritsen, Nyclear Phys. **11**, 1 (1959).
[2] S. S. Hanna and R. E. Segel, Proc. Roy. Soc. (London) **A259**, 267 (1960). G. L. Miller, R. E. Pixley, and R. E. Segel, *ibid.* **A259**, 275 (1960).
[3] J. D. Cockroft and W. B. Lewis, Proc. Roy. Soc. (London) **A154**, 261 (1936). J. H. Williams, W. H. Wells, J. T. Tate, and E. L. Hill, Phys. Rev. **51**, 434 (1937); R. B. Bowersox, *ibid.* **55**, 323 (1939).
[4] T. Huus and R. B. Day, Phys. Rev. **91**, 599 (1953).

resonance while α_1 showed a contribution below resonance equal to $\sim 5\%$ of the intensity just above the resonance. This nonresonant contribution to α_1 was subtracted off in determining the relative partial widths for the state.

A typical alpha-particle spectrum is shown in Fig. 3. The silicon detector was covered with a thin nickel foil and also had a dead layer; hence the nonlinear energy scale in Fig. 3. The spectrum in Fig. 3 shows a clearly resolved sharp group, α_0, as well as a continuum.

The alpha spectrum is complicated by the fact that Be^8 itself is unstable to alpha emission and therefore each alpha decay of a state of C^{12} ultimately yields three alpha particles. A disintegration proceeding through a sharp state in Be^8 (α_0) yields a monoenergetic group plus a continuum, with the spectrum of the continuum depending on the decay energies of the two steps and the angular correlation between successive radiations. A decay proceeding through a broad state in Be^8 (α_1) results in two continua, which in the present case overlap. We have estimated that for each α_1 decay an average of about 1.8 alpha particles would have been recorded in our spectra.

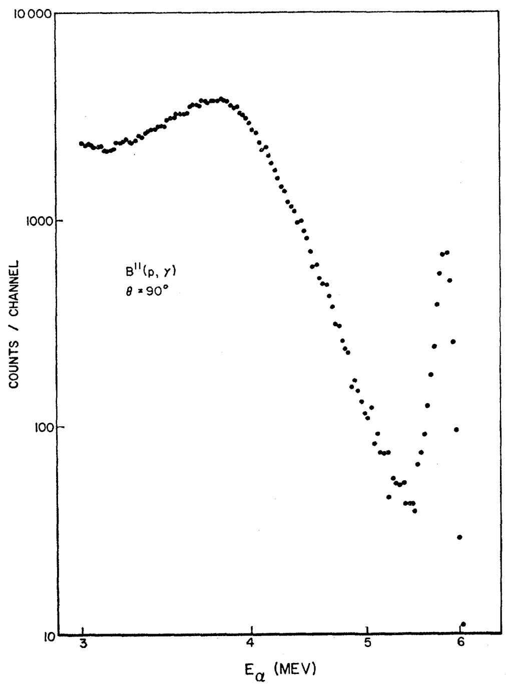

FIG. 3. Alpha-particle spectrum from the disintegration of the 16.11-Mev state in C^{12} viewed at 90° (lab) to the incident proton beam. The energy scale is nonlinear as the alpha particles had to traverse some absorbing material before reaching the depletion region of the silicon detector.

Alpha spectra were taken at various angles between 60° and 165° with respect to the incident proton beam. Summing the spectra over a sphere and correcting for the alpha (α_1) particles which failed to reach the silicon spectrometer depletion region, we find for the relative intensity of the two modes of alpha decay $\Gamma_{\alpha 1}/\Gamma_{\alpha 0} = 22 \pm 3$.

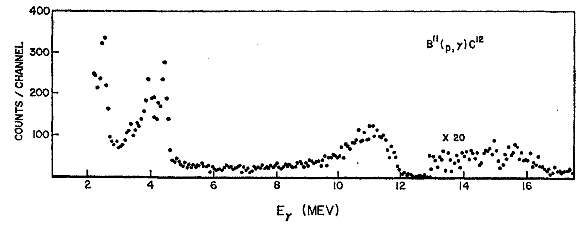

FIG. 4. Pulse-height spectrum from 5-in.-diam. 5-in.-thick NaI(Tl) crystal placed at 90° to a proton beam bombarding a thick boron target. The face of the crystal was 6 in. from the target.

A gamma-ray spectrum is shown in Fig. 4. The two gamma rays from the 11.68–4.43-Mev cascade are clearly discernible. The spectrum also includes a 2.50-Mev calibration line (sum peak from Co^{60}) as well as a weak peak ascribable to γ_0. After allowing for summing of the γ_1 cascade we find that $\Gamma_{\gamma 1}/\Gamma_{\gamma 0} \sim 25$.

The intensity of the γ_1 cascade was determined by measuring the area under the 4.43-Mev peak and dividing by the computed[5] NaI(Tl) crystal peak efficiency, making a small correction (4%) for the absorption in the target chamber walls. Allowing for the gamma-ray angular distribution,[6] it was found that

$$\Gamma_{\gamma 1}/\Gamma_\alpha = (1.02 \pm 0.15)10^{-3}.$$

DISCUSSION

The total width (c.m.) of the 16.11–Mev state in C^{12} is known[7] to be 6.7 ± 0.5 kev. The single-particle proton width[8] is about 100 ev and therefore the total width must be due mainly to the alpha width, i.e., $\Gamma_\alpha = \Gamma_{\alpha 0} + \Gamma_{\alpha 1} = 6.7 \times 10^3$ ev. Combining $\Gamma_{\alpha 0} + \Gamma_{\alpha 1}$, $\Gamma_{\alpha 0}/\Gamma_{\alpha 1}$, $\Gamma_{\gamma 1}/\Gamma_\alpha$, and $\Gamma_{\gamma 0}/\Gamma_{\gamma 1}$ we can solve for these partial widths individually and the results, together with the previously[1] listed values, are given in Table I. We have used other workers'[9] determination of $\Gamma_{\gamma 0}/\Gamma_{\gamma 1} = (3.3 \pm 1)\%$ which appears to be more accurate than, though consistent with, our estimate of 4% for this ratio. The value of Γ_p listed in Table I was determined by combining the gamma-ray yield measurement of Huus and Day[4] with the $\Gamma_{\gamma 1}$ measured here.

[5] W. F. Miller, J. Reynolds, and W. J. Snow, Argonne Natl. Lab. Rept. No. 5902 (unpublished).

[6] P. J. Grant, F. C. Flack, J. G. Rutherglen, and W. M. Deuchars, Proc. Phys. Soc. (London) **A67**, 751 (1954).

[7] S. E. Hunt and W. M. Jones, Phys. Rev. **89**, 1283 (1953). We note that the result of this determination of the width of the state, while the most recent and apparently the most accurate, is higher than previous measurements—see reference 1. We use the total width given by Hunt and Jones throughout, but point out that using the lower values of Γ of other workers would not materially change any of the conclusions of this paper.

[8] We define the single particle width as $\frac{3}{2}(k/A_1^2)\hbar/\mu a$, where k = wave number of the proton (alpha) in the center-of-mass system, A_1^2 = 1-wave barrier penetrability, μ = proton (alpha) reduced mass, a = nuclear radius, here taken as $1.45 \times 10^{-13} A^{\frac{1}{3}}$ cm.

[9] D. A. Craig, W. G. Cross, and R. G. Jarvis, Phys. Rev. **103**, 1414 (1956).

TABLE I. Parameters of the 16.11-Mev state in C^{12}. All widths are in ev.

	Reference 1	Present work
Γ_{lab}	7000	7300 ± 500[a]
Γ_p	5	69 ± 15[b]
$\Gamma_{\alpha0}$	100	290 ± 45
$\Gamma_{\alpha1}$	5000	6300 ± 500
$\Gamma_{\gamma0}$	2[c]	0.22 ± 0.09[c]
$\Gamma_{\gamma1}$	70	6.8 ± 1.1

[a] Reference 7.
[b] Using the gamma-ray yield given in reference 4.
[c] Taking $\Gamma_{\gamma0}/\Gamma_{\gamma1}=(3.3\pm1)\%$ from reference 9.

Keszthelyi and Fodor[10] report observing the resonance absorption of the 16.11-Mev line (γ_0) and find $\Gamma_{\gamma0}=7.6\pm1.9$ ev which is a factor of some 30 greater than our result. No direct evidence appears to be present in the literature that would resolve this discrepancy. However, accepting the gamma-ray yield measurement of Huus and Day, the large Γ_γ of Keszthelyi and Fodor (there is general agreement as to the value of $\Gamma_{\gamma0}/\Gamma_{\gamma1}$) would imply $\Gamma_p\cong2$ ev ($\theta_p^2\cong0.02$). The alpha-particle yield is directly proportional to Γ_p (if $\Gamma_p\ll\Gamma_\alpha$) and therefore the result of Keszthelyi and Fodor would imply that the previous[3] estimates of the alpha-particle yield were too high. However, Beckman, Huus, and Zupančič[11] quote communications which state that the older estimates of the alpha-particle yield were too low, which would agree with the results of the present experiment but not with the gamma-ray absorption data. Though we cannot explain the results of Keszthelyi and Fodor, we consider the gamma widths found in the present work to be correct.[12,12a]

The partial widths expressed in single-particle units[8] for the various modes of decay are given in Table II. For gamma-ray emission, the single-particle widths are calculated using the formulas given by Wilkinson.[13] No statistical factors have been included in calculating the dimensionless reduced widths given in Table II.

The 16.11-Mev state in C^{12} can be taken to be the analog of the first excited states in B^{12} and N^{12}. Using the language of pure j-j coupling, the ground and first excited state of the mass-12 $T=1$ triad are due to the coupling of the odd $p_{\frac{1}{2}}$ nucleon to a $(p_{\frac{3}{2}})^{-1}$ core. These states should be good single-particle states and should therefore be expected to have large nucleon reduced widths, hence the large proton reduced width for the 16.11-Mev state.

TABLE II. Reduced widths in single-particle units for various radiations from the 16.11-Mev state in C^{12}. The basis for the single-particle units is given in the text.

Radiation	θ^2
p	0.8
α_0	10^{-4}
α_1	2.5×10^{-3}
γ_0	0.15
γ_1	0.20

The alpha decay is, of course, isotopic-spin forbidden and therefore the small reduced widths for the alpha-particle emission are expected. From our data we can extract estimates for the Coulomb matrix element[13] for which we find $H_{TT'}{}^c=0.02$, 0.33 Mev for the α_0, α_1 transitions, respectively. The Coulomb matrix element strength obtained from $\Gamma_{\alpha1}$ appears reasonable in view of the large nucleon reduced width,[13] while the value derived from $\Gamma_{\alpha0}$ appears to be somewhat small. Stated more realistically, $\Gamma_{\alpha1}$ is about what is to be expected for the 16.11-Mev state while $\Gamma_{\alpha0}$ is smaller than expected.

Other things being equal, one would expect $\Gamma_{\alpha1}/\Gamma_{\alpha0}=(2J_{f1}+1)/(2J_{f0}+1)=5$, to be compared with the experimental results $\Gamma_{\alpha1}/\Gamma_{\alpha0}=22$. This discrepancy is not really great enough to support the conjecture[14] that the first excited state in Be^8 contains a large $T=1$ admixture.

The gamma ray transition to the 4.43-Mev state, γ_1, is an isotopic-spin allowed magnetic dipole and its reduced[15] width falls right into the range expected for such a transition.[13]

The ground state gamma-ray transition, γ_0, is a pure $E2$ transition and its strength again fits well with the prediction of the single-particle model.[13] However, most $E2$ transitions in the light nuclei are of greater than single-particle speed with the enhancement generally ascribed to collective motion. Collective motion should not involve a change in isotopic spin and therefore a $\Delta T=1$ $E2$ should not show this enhancement,[16] thus accounting for the 16.11-Mev transition being of single-particle speed.

A transition from the 16.11-Mev state to the 9.63-Mev state has recently been observed[17] with a branching ratio equal to 1% of γ_1. The 9.63-Mev state is assigned odd parity[1] and spin of 1 or 3 (the latter is currently[17] favored) and therefore the 6.48-Mev transition to this

[10] L. Keszthelyi and J. Fodor, Nuclear Phys. **10**, 564 (1959).
[11] O. Beckman, T. Huus, and X. Zupančič, Phys. Rev. **91**, 606 (1953).
[12] In the present experiment the absolute gamma-ray yield could only be roughly estimated, but it did agree within a factor of two with the yield quoted by Beckman *et al.*
[12a] *Note added in proof.* The present authors have repeated the experiment of Keszthelyi and Fodor but do not observe any resonance absorption which is in agreement with the present work but in contradiction to reference 10 (R. E. Segel and M. J. Bina, Conference on Electromagnetic Lifetimes and Properties of Nuclear States, Gatlinburg, Tennessee, 1961).
[13] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press, Inc., New York, 1960), Chap. VF.
[14] R. F. Holland, D. R. Inglis, R. E. Malm, and F. P. Mooring, Phys. Rev. **99**, 92 (1955).
[15] We define "reduced width" for gamma radiation as the ratio of the actual width to that predicted by the Weisskopf estimate as calculated in reference 13; i.e., reduced width $=|M|^2$ in the usual notation.
[16] E. K. Warburton, Phys. Rev. Letters **1**, 68 (1958).
[17] R. R. Carlson and E. B. Nelson, Bull. Am. Phys. Soc. **6**, 341 (1961).

state would be $E1$. Combining the branching ratio with the present determination of Γ_γ we find for the 6.48-Mev transition, γ_2, $\Gamma_{\alpha 2}=0.06$ ev and reduced width $|M|^2=6\times 10^{-4}$. This reduced width represents an unusually low value for an isotopic-spin allowed $E1$.

It is interesting to compare the reduced widths for the decays of the 16.11-Mev level with the analogous decays from its "partner" level, the first $T=1$ state at 15.11-Mev. Two analogous transitions exist, γ_1 and α_1. Recent work,[2] which also summarizes work to date, lists for the 15.11-Mev state

$$\Gamma_{\alpha 1}\leq 15 \text{ ev}, \quad \text{hence} \quad \theta_\alpha^2\leq 6\times 10^{-6};$$
$$\Gamma_{\gamma 1}=1.56 \text{ ev}, \quad \text{hence} \quad |M|^2=0.061.$$

Thus, the gamma-ray widths for the analogous transitions from the lowest $T=1$ states are fairly similar, agreeing to within about a factor of 3, while the alpha width of the 15.11-Mev state is the smaller by a factor of at least several hundred. The gamma-ray transition is allowed and of single-particle speed and therefore appears to be due to a large portion of the wave function and thus we expect similar $M1$ transition rates from the two states. In contrast the alpha transition is forbidden and only takes place through a small impurity in the wave function which need not be similar for the two states.

A more quantitative comparison of the gamma-ray transition from the lowest two $T=1$ states in C^{12} is predicted by the intermediate-coupling model of Kurath.[18] Using Kurath's theoretical curves (Fig. 3 of reference 18) but the more recent[2] experimental values, we find that for the 15.11-Mev state, $\Gamma_{\gamma 0}$ is fitted by $a/K=5.7\pm 0.5$ and $\Gamma_{\alpha 1}$ by $a/K=5.3\pm 0.5$. Combining these to say that the 15.11-Mev state requires $a/K=5.5\pm 0.4$, the model then predicts that for the 16.11-Mev state, $\Gamma_{\gamma 1}=9.6\pm 0.8$ ev, to be compared with our experimental value of 6.8 ± 1.1 ev. The agreement is satisfactory, and thus an experimental discrepancy with the intermediate-coupling model has been removed.

ACKNOWLEDGMENTS

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[18] D. Kurath, Phys. Rev. **106**, 975 (1957).