Lifetimes of the 4.43-Mev Excited State of C^{12} and the 4.46-Mev Excited State of B^{11}†*

V. K. RASMUSSEN, F. R. METZGER, AND C. P. SWANN
Bartol Research Foundation of the Franklin Institute, Swarthmore, Pennsylvania
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Doppler-broadened 4.43-Mev γ radiation from the reaction $N^{15}(p,\alpha)C^{12*}$ has been used to measure the lifetimes of the 4.43-Mev level of C^{12} and the 4.46-Mev level of B^{11} by the nuclear resonance fluorescence technique.

For C^{12}, the 90° and 126° scattering give mean lives of $(6.7_{-0.4}{}^{+1.5})\times10^{-14}$ sec and $(5.5_{-0.4}{}^{+1.2})\times10^{-14}$ sec, respectively. The self-absorption of the resonance radiation gives $(6.6\pm1.3)\times10^{-14}$ sec. The adopted mean value is $(6.5\pm1.2)\times10^{-14}$ sec.

For B^{11}, the angular distribution of the resonance-scattered radiation is $1+(0.1\pm0.1)P_2(\cos\theta)$, and the cross section corresponds to $\tau=(1.02_{-0.07}{}^{+0.23})\times10^{-15}$ sec if the spin of the excited states is $\frac{5}{2}$. Interpretation of the self-absorption of the resonance radiation is uncertain because of lack of information as to the Debye temperature of B_4C. Values of 1250°K and 1860°K give $\tau=1.33\times10^{-15}$ sec and $\tau=1.14\times10^{-15}$ sec. The adopted mean value is $\tau=(1.17\pm0.17)\times10^{-15}$ sec.

I. INTRODUCTION

SEVERAL previous investigations of the lifetime of the first excited state of C^{12} have been made. Thomas and Lauritsen,[1] and Mills and Mackin[2] infer from the existence of Doppler broadening of the γ rays that the mean life is $<3\times10^{-13}$ sec. Devons, Manning, and Towle,[3] by using the diminution in the Doppler broadening to measure the extent to which excited C^{12} nuclei are slowed down before they radiate, find a mean life of $(2.6\pm0.9)\times10^{-14}$ sec. From the cross section for inelastic scattering of 187-Mev electrons Helm[4] calculates a mean life of 5.3×10^{-14} sec with a probable error of around 20%. Theoretical calculations of this lifetime have been made by Ferrell and Vischer[5] and by Kurath.[6] They both find that with reasonable values of the parameters involved they can match the electron-scattering results.

The various experimental values for the mean life are short enough to suggest its measurement by the nuclear resonance fluorescence technique described by Swann and Metzger.[7] In fact, with Devons' lifetime the effect would be quite large.

A suitable reaction for producing this 4.43-Mev γ radiation is $N^{15}(p,\alpha)C^{12*}$. At a proton energy of 3.2 Mev, the observed γ rays show a Doppler broadening of 110 kev, suggesting that levels near 4.43 Mev in other nuclei could also be investigated with this same source. One example is the second excited state of B^{11} at 4.46 Mev. According to the summary of Ajzenberg and Lauritsen,[8] the decay of this state is predominantly to the ground state and the most probable value for the spin is $\frac{5}{2}$. From this spin, which would allow dipole radiation, and from the observation by Jones and Wilkinson[9] of the full Doppler shift from the reaction $Li^7(\alpha,\gamma)B^{11*}$, the lifetime of the level is expected to be short enough to make the resonance fluorescence easily observable.

II. METHOD AND EXPERIMENTAL PROCEDURES

The use of resonance fluorescence for measuring γ-ray transition probabilities is discussed by Swann and Metzger[7] (SM) and in the additional references given there. It may be repeated here that we are concerned with excited levels that decay only by emission of a single photon of almost the same energy as that incident—i.e., with resonant elastic scattering. For convenience, we repeat the relations between the number of scattered photons and Γ, the width of the level. We note that these were developed using the approximations that Γ is small compared to the Doppler broadening due to thermal motion of the scattering nuclei, and that the source strength, $N(E)dE$, and the ordinary electronic absorption, $\eta_e(E,x)=\exp[-\sum n_i\times\sigma_i(E)x]$ vary negligibly over the Doppler width. Then the number of photons scattered into a solid angle of 4π from the lamina x to $x+dx$ of the scatterer is

$$S(x)dx=N(E_r)\eta_e(E_r,x)n\sigma_0\tfrac{1}{2}\pi\Gamma\times\left[1+\sum_{m=1}^{\infty}\frac{(-1)^m(nKx)^m}{m!(m+1)^{\frac{1}{2}}}\right]dx. \quad (1)$$

Here E_r is the energy of the γ rays at exact resonance,

† A preliminary report of this work was given by Swann, Metzger, and Rasmussen, Bull. Am. Phys. Soc. Ser. II, 2, 29 (1957).

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[1] R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952).

[2] W. R. Mills, Jr., and R. J. Mackin, Jr., Phys. Rev. **95**, 1206 (1954).

[3] Devons, Manning, and Towle, Proc. Phys. Soc. (London) **A69**, 173 (1956).

[4] Richard H. Helm, Phys. Rev. **104**, 1466 (1956).

[5] R. A. Ferrell and W. M. Visscher, Phys. Rev. **104**, 475 (1956).

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

[7] C. P. Swann and F. R. Metzger, Phys. Rev. **108**, 982 (1957), subsequently referred to as SM.

[8] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[9] G. A. Jones and D. H. Wilkinson, Phil. Mag. **43**, 958 (1952).

n is the number of nuclei of the resonant variety per cm^3 of the scatterer, $\sigma_0=4\pi\lambda^2(2J_2+1)/2(2J_1+1)$, and $K=\sigma_0\Gamma\pi^{\frac{1}{2}}/(2\Delta)$, where $\Delta=(E/c)(2kT/M)^{\frac{1}{2}}$ is the thermal width of the absorption line. The sum in the square brackets represents the selective absorption of the incident spectrum by the resonance scattering. By placing an appropriate absorber between the source and the scatterer this selective absorption may be used to give a value of the lifetime independent of the source strength, $N(E_r)$, but dependent on the thermal width, Δ.

In general, the experimental procedure was the same as that in the O^{16} measurements, and for details reference is made to that paper (SM). Bashkin and Carlson[10] and Lidofsky *et al.*[11] have found several prolific resonances for 4.43-Mev γ rays from the reaction $N^{15}(p,\alpha)C^{12*}$. Of these, we have used those at 3.00 and 3.30 Mev, and part of the underlying broad 3.35-Mev resonance, as shown in the excitation function of Fig. 1. The target was one atmosphere of NH_3, enriched to 60% N^{15}, contained in the gas cell shown in Fig. 2. The target thickness for 3.2-Mev protons was 0.5 Mev. The energy of the protons incident on the $\frac{1}{4}$-mil tantalum window, about 3.75 Mev, was adjusted slightly as required to give maximum γ-ray yield. Monitoring was by means of a NaI(Tl) γ counter ten

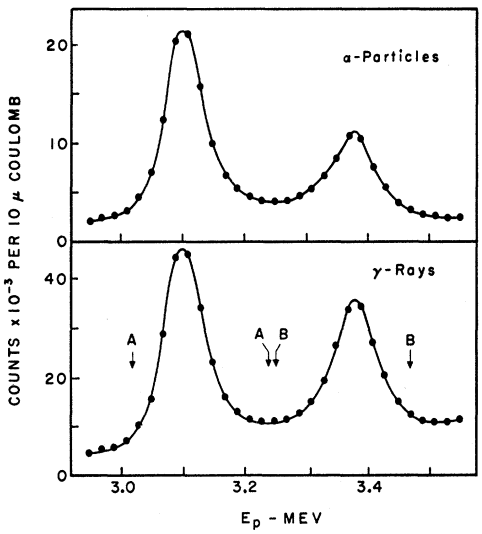

FIG. 1. Excitation function for α particles and 4.43-Mev γ radiation from $N^{15}(p,\alpha)C^{12*}$. The *proton energy given is not that at the* N_2^{15} *target* but that of the protons incident on the ~1.4-mg/cm^2 Al window of the gas cell. For these curves, the counters of the variable-angle target chamber of Part III were both at 90° to the beam. The target seen by the γ-ray counter was a few (~10) kev thick and twice as thick as that seen by the α-particle counter. The α-particle curve may be distorted somewhat (~10%) by uncertainties in the counting efficiency and background. The arrows labeled *A* and *B* mark the limits of the scans over the resonances in Part III.

[10] S. Bashkin and R. R. Carlson, Phys. Rev. **106**, 261 (1957).
[11] Lidofsky, Jones, Bent, Weil, Kruse, Bardon, and Havens, Bull. Am. Phys. Soc. Ser. II, **1**, 212 (1956).

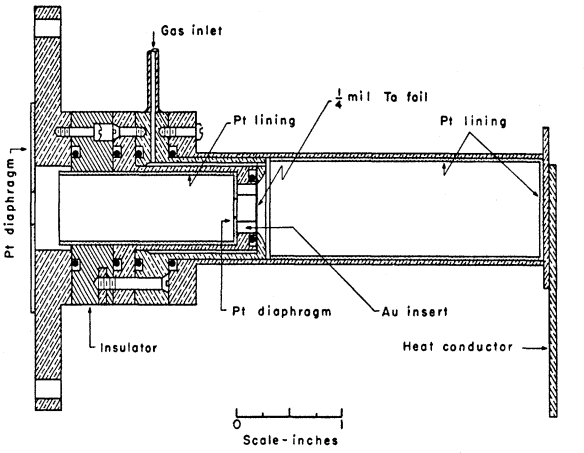

FIG. 2. Gas cell used in the resonance fluoroescence measurements. The part labeled "heat conductor" was a copper strip soft-soldered to the end of the cell. This strip was immersed in liquid nitrogen to freeze out $N^{15}H_3$ when it was desired to fill the cell to higher pressure than that prevailing in the storage reservoir.

feet from the target. To measure the intensity distribution along the cell, required for solid-angle calculations in parts IV and V, a γ counter behind a $\frac{1}{16}$-inch wide lead slit was scanned along the beam direction. The 3.00- and 3.30-Mev resonances were displayed nicely, although not with maximum resolution, and it was established that the yield of 4.43-Mev γ rays from the entrance window and from the end of the cell where the beam was stopped was negligible. A conventional ring geometry, similar to that described by SM, was used for the scattering and self-absorption measurements.

The extent to which neutrons can interfere with resonance scattering experiments is discussed by SM. From preliminary measurements of the scattering by carbon, it was clear that neutrons would be much more troublesome in this experiment than in the O^{16} measurements, mainly because a given neutron flux produces more extraneous pulses in the region corresponding to 4.4-Mev γ rays. By various expedients this neutron background was reduced to satisfactory proportions. The neutron flux was minimized by cleaning carbon deposits from the tantalum lining of the beam tube, using platinum or gold linings in and near the gas cell, and by being quite careful about the purity of the NH_3 in the target. Neutron-producing contaminents, except water, were removed by freezing the NH_3 with liquid nitrogen and pumping with a mechanical pump. This was done after every few hours of running. Water vapor, which could be introduced at times by small leaks into the gas-handling system, was removed by passing the gas over solid NaOH. A $\frac{1}{4}$-inch thick boron carbide shield around the counter was effective in reducing the counting rate from the remaining neutrons. Finally, since hydrogen was found to be especially suitable for scattering neutrons into the counter, nominally nonhydrogenous materials such as graphite and anhydrous $LiNO_3$ were used as scatterers.

The neutron effect remaining was corrected for, within limits of uncertainty as to the neutron spectra involved, by measuring the counting rates with various scatterers when a carbon target on a tantalum disk was substituted for the gas cell. This target gave about ten times more neutrons (as measured with a modified long counter[12]), and much less γ radiation, than the NH_3 target. The neutrons from the γ-ray target were monitored continuously by the long counter, placed some distance away to avoid extraneous scattering of γ radiation.

III. MEASUREMENT OF THE γ-RAY SOURCE STRENGTH

In resonance scattering experiments one is concerned with $N(E_r)$, the γ-ray source strength at energies in the immediate neighborhood of the resonance line, rather than the average source strength obtained by dividing the number of photons by the Doppler width of the line. This may be obtained either from a general knowledge of the $\alpha-\gamma$ angular correlations at the proton resonances involved or, as discussed in Appendix I, from a measurement of the $\alpha-\gamma$ coincidence rate at certain specific angles. Since the complete correlation function would be of interest in itself, preliminary measurements of it were made. These indicated that the correlations were quite complicated, so that fitting them by theoretical expressions and then deriving the intensity ratios needed would, at best, be laborious. Measurements of the $\alpha-\gamma$ coincidence rate with the counters at such angles that the photons were of the resonant energy were then made.

A variable-angle target chamber, using thin NaI(Tl) for counting protons or α particles, was available. This counter rotated in a plane inclined at 6° to the proton beam, and was so positioned that angles of observation from 0° to 168° on either side of the beam could be reached. A γ-ray counter, mounted on the same base, could be moved over a whole hemisphere except for certain areas blocked by the particle counter and the beam tube.

The target for this part of the experiment was nitrogen gas, enriched to 95% N^{15}, contained in a gas cell that rotated with the particle counter. The beam entered and left the cell through 1.4-mg/cm^2 Al windows; reaction particles left through an approximately 0.1-mg/cm^2 Formvar window which was supported, for some of the measurements, by three 8-mil diameter wires. The α-particle counter was so collimated that charged particles from the aluminum windows could not reach it directly. This meant that the counter and the γ-ray counter observed different target thicknesses. From the cell and collimator dimensions the ratio of these target thicknesses was found to be 0.505 ± 0.03, independent of the angle of observation. It was found that nitrogen absorption in the aluminum windows was negligible.

Normally, the accessible angle of observation with this cell ranged from 35° to 145°, but with the $N^{15}(p,\alpha)C^{12*}$ reaction at $E_p=3$ Mev where the α particles gave four to eight times smaller scintillation pulses than 3-Mev protons it was somewhat more restricted. At forward angles, the number of protons elastically scattered into the counter became uncomfortably large at around 40°, and at back angles, as the α-particle pulses decreased in size, the background set a practical working limit of $\sim$140°. This background, consisting mostly of low-energy protons of uncertain origin, was also troublesome at intermediate angles because it obscured the possible low-energy tail of the desired α group, thus introducing an uncertainty in the efficiency with which the group was counted.

The pulse-height spectrum from either the α counter or the γ counter could be displayed on a 20-channel analyzer. The analyzer could be "gated" by conventional slow discriminators in the α-counter circuit, by a fast ($\sim$0.01 μsec) coincidence circuit, or by coincidences between the "slow" and "fast" circuits. The yield of γ rays was monitored by a second γ counter fixed at 90° to the beam, the excitation function shown in Fig. 1 then being used in reducing the data to counts per unit incident proton beam.

The angle between the proton beam and the γ counter was kept at 24°. When the rather large angle (half-angle $\sim$7°) subtended by the γ counter is considered, this covers the angles of emission of the γ rays most frequently used in the resonance scattering experiments. The γ counter was rotated around the beam in increments of azimuthal angle of 30° or 60°, and the α-particle counter was moved correspondingly to keep the center-of-mass angle between the counters at that (constant) value that would give coincident γ rays of just the resonant energy. For C^{12}, where the emitting and absorbing levels are the same, this angle can be calculated with considerable accuracy as 110° for a mean proton energy of 3.15 Mev. For B^{11}, the 28 ± 11 kev difference in energy between the emitting and absorbing levels results in an uncertainty of $\pm13°$ in the calculated 78.5° angle.

In this measurement, the interest lies in the average value of the $\alpha-\gamma$ angular correlation for a 500-kev target, as used in the resonance experiment. Since both the gas cell construction and the energy loss of the reaction α particles in escaping from the target limited the target thickness to a few kev, it seemed that the simplest way to get the desired average was to change the beam energy during runs. A stepping relay was used to add or remove resistors in the control circuit for the beam analyzer magnet thus swinging the field in this magnet over a limited range. The accelerator voltage followed this change through the action of the corona-control circuitry. It was found possible to scan the beam energy with a period of $\sim$65 seconds and

[12] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

over a range of 220 kev in 22 steps of approximately equal size and duration. From the excitation curve (Fig. 1) it is clear that two such scans will cover the significant part of a 500-kev target.

From these measurements and Eq. (3) of Appendix I, the desired ratio of the γ-ray source strength in the neighborhood of the resonance energy to the average value for the line may be calculated. This is found, for observation at 24° to the proton beam, to be $0.88_{-0.06}^{+0.2}$ for the B^{11} resonance radiation and $0.86_{-0.06}^{+0.2}$ for the C^{12} resonance radiation. The estimated lower limit is based on both uncertainties in the geometry and on the reproducibility of the data while the upper limit reflects primarily the uncertainty as to whether or not all the α particles were being counted, as mentioned previously.

IV. RESULTS AND DISCUSSION: C^{12}

The spins of the ground state and first excited state of C^{12} are well established as 0 and 2. The angular distribution of the resonance radiation must then have the form $1.25-3.75\cos^2\theta+5\cos^4\theta$. The total cross section and the mean life can thus be obtained from a scattering measurement at a single angle. As a check on the subtraction of neutron effects, the resonance scattering was measured at two angles, 90° and 126°, which gave the maximum change in the differential cross section for those angles that were easily available.

The carbon scatterer was in the form of a graphite ring of purity >99%. Anhydrous $LiNO_3$ in a thin-walled aluminum container was used for the comparison scatterer. Scattering in of neutrons was measured using a carbon target, as described previously. The results are shown in Table I. Typical pulse-height distributions are given in Fig. 3.

The mean life of the first excited state of C^{12} may be calculated from the data of Table I in the manner described in SM. For convenience in this calculation, the long, cylindrical source of γ rays given by the gas cell was replaced by two point sources located approximately at the peaks of the 3.00- and 3.30-Mev resonances. For the 90° data this gives $\tau=(6.7_{-0.4}^{+1.5})\times10^{-14}$ sec and for 126°, $\tau=(5.5_{-0.4}^{+1.2})\times10^{-14}$ sec, where the errors reflect primarily the uncertainty in the source strength measurement, the statistical error in the data being somewhat smaller than this and geometric uncertainties and the effect of approximations in the calculation being still smaller.

TABLE I. Counting rates observed when various scatterers are exposed to 4.43-Mev γ radiation or to a neutron source. The neutron source gave ~10 times more neutrons than the γ-ray source (as measured with a modified long counter) and practically no γ radiation. Pulse heights corresponding to 3 to 4.7 Mev were accepted. The numbers given are on a scale of 16 and are average values for ~10-minute runs with a 5 microampere proton beam. No background has been subtracted.

	90°-scattering		126°-scattering	
Scatterer	γ rays	Neutrons	γ rays	Neutrons
Graphite	34.46±0.52	24.53±0.55	23.42±0.30	21.41±0.58
$LiNO_3$	19.68±0.39	22.56±0.53	17.62±0.26	19.24±0.55
No Scatterer	16.56±0.37	···	15.41±0.25	17.22±0.52

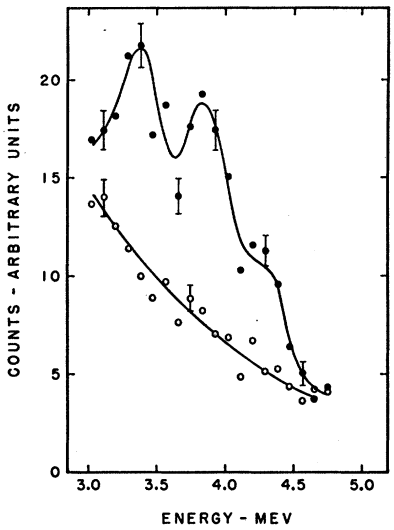

FIG. 3. Resonant scattering of γ rays by the 4.43-Mev level of C^{12}. The points on the upper curve were obtained with a graphite scatterer; those for the lower curve with a $LiNO_3$ scatterer. The shape of the upper curve is taken from the pulse height distribution observed when the NaI(Tl) γ counter was exposed to direct radiation from the target. The ring scatterers were 23 cm i.d., 33 cm o.d., and 10.16 cm thick. The scattering angle was 90°.

A value for this mean life independent of the source strength measurement was obtained by measuring the self-absorption of the resonance radiation. A graphite absorber and a comparison $LiNO_3$ absorber were used. It was found that neither absorber had any appreciable effect on the counting rate attributed to neutrons.

For an effective absorber thickness of 9.35 g/cm², the resonance attenuation was 0.115±0.020. The ratio of the level width to the thermal width of the absorption line may then be obtained from Eq. (1), integrated over the scattering volume. When one uses a Debye temperature for graphite of 1860°K,[13] Lamb's curves[14] give $T_{\text{eff}}=720°$ from which $\Delta=14.8$ ev. The resulting mean life for the 4.43-Mev level of C^{12} is $(6.6\pm1.3)\times10^{-14}$ sec.

The three values of the mean life are seen to agree within the given errors. However, there is an indication of a discrepancy between the two scattering measurements since the principal error here is a common one involving the source strength measurement of Part III. It is possible that the difference may be significant, and two explanations may be mentioned. We have noted that the correction used for the "neutron effect" is of limited validity since the two neutron spectra involved are not known. To indicate the magnitude of

[13] Jules deLaunay, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 2, p. 233.

[14] W. E. Lamb, Phys. Rev. **55**, 190 (1939).

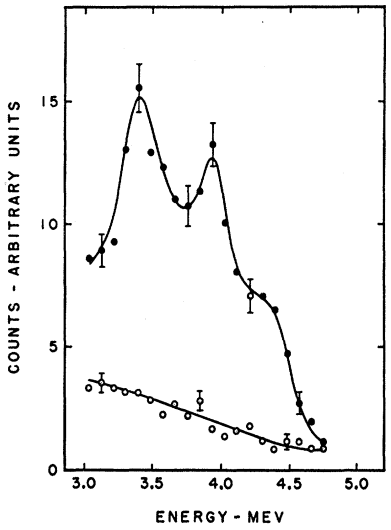

FIG. 4. Resonant scattering of γ rays by the 4.46-Mev level of B^{11}. The points on the upper curve were obtained with a B_4C scatterer, those on the lower curve with a $LiNO_3$ scatterer. The shape of the upper curve is taken from the pulse-height distribution observed when the NaI γ counter was exposed to the direct radiation from the target. The scattering angle was 90°, and the ring scatterers were 24.1 cm i.d., 40.3 cm o.d., and 3.17 cm thick.

the error involved, it may be pointed out that if the correct "neutron effect" were seven times as large as that used, the scattering measurements would both give 7.4×10^{-14} sec for the mean life. Alternatively, since the mean angles between the scatterers and the proton beam differ by $\sim4°$ for the 90° and 126° scattering geometries, it may be that a rapid variation of the $\alpha-\gamma$ correlation is making itself evident.

In calculating a mean value from the three measured mean lives, it was decided to give equal positive and negative errors rather than the unequal errors resulting from the source strength measurement, partly for simplicity and partly because of the indications in the B^{11} experiment, discussed in Part V, that the experimental value for the source strength may have been somewhat low. We thus find for the mean life of the first excited state of C^{12} the value $\tau=(6.5\pm1.2)\times10^{-14}$ sec, which is in agreement with the electron-scattering results and the theoretical calculation[5,6] but appreciably longer than the value of Devons *et al.*[3]

V. RESULTS: B^{11}

Preliminary measurements of the resonant scattering of Doppler-broadened γ rays from the first excited state of C^{12} by a B_2O_3 scatterer showed that the scattering from the 4.46-Mev second excited state of B^{11} is much larger than that from the C^{12} level, i.e., the lifetime is much shorter. For further measurements, B_4C scatterers and absorbers were used to get the maximum ratio of B^{11} nuclei to nonresonant nuclei. The contribution of the carbon to the resonance effect was only 1–2% depending on scattering angle. $LiNO_3$ was used for comparison purposes, and the scatterers were made thinner than those used in the carbon experiment to reduce the correction for self-absorption of the resonance radiation.

From Eq. (1) it is seen that to calculate a lifetime from a resonant scattering measurement one must know the spins of the initial and final levels and must either know or be able to calculate the angular distribution of the resonance radiation. The spin of the ground state of B^{11} is $\frac{3}{2}$, and the most probable value of the spin of the second excited state is $\frac{5}{2}$, both parities presumably being odd. Lifetimes are calculated in what follows on the assumption that the spin is $\frac{5}{2}$. These spins and parities allow mixed dipole-quadrupole radiation, so that the angular distribution of the resonance radiation cannot be calculated, but must be measured.

Since this is the second excited state, any decay to the first excited state would have to be corrected for in calculating the lifetime from the resonance scattering measurements. However, recent measurements by Ferguson *et al.* at Chalk River[15] indicate that the branching ratio is less than 1% and thus negligible.

The resonant-scattering cross section was measured for 90°, 133°, and 148° mean scattering angles. To minimize the effect of any variation in the intensity of the incident γ radiation the same scatterer and scatterer position were used for the 90° and 133° scattering angles, the angle being changed by moving the detector only. For the 148° scattering it was necessary to use a different scatterer, but it was still possible to keep the angle between the proton beam and the γ radiation incident on the scatterer the same (within a degree) as in the other two measurements. Typical results for 90° are shown in Fig. 4.

The three points obtained on the angular distribution are shown in Fig. 5. A least-squares fit to these points

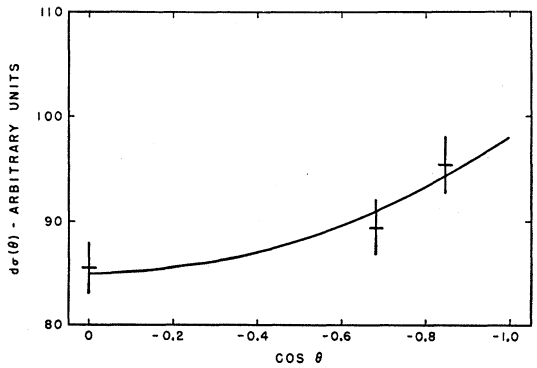

FIG. 5. Angular distribution of the resonance radiation from the 4.46-Mev level of B^{11}. The curve drawn is the distribution $89+8.7P_2(\cos\theta)$.

[15] Ferguson, Gove, Litherland, Almquist, and Bromley, Bull. Am. Phys. Soc. Ser. II, 2, 51 (1957), and H. E. Gove (private communication).

gives $1+(0.1\pm0.1)P_2(\cos\theta)$.[16] Using this, the mean life of the second excited state of B^{11} is found to be $(1.02_{-0.07}{}^{+0.23})\times10^{-15}$ sec, where the error reflects principally the uncertainty in the source strength, $N(E_r)$.

The resonance scattering cross section can also be measured by a self-absorption experiment, as for the C^{12} and O^{16} levels. One point of interest here is that the scattering is enough larger than in previous cases that one might hope to see the expected departure from simple exponential attenuation. This, of course, reflects the fact that we observe the removal of a line of finite width from a continuous spectrum (our detector is sensitive only to the resonance radiation) rather than the attenuation of truly monoenergetic radiation.

Absorbers of mean effective thickness 1.2, 3.6, and 6.0 g cm^{-2} of B_4C, and carbon absorbers of approximately the same electronic attenuation for comparison, were used, with the scatterer and γ counter at the 133° scattering position. The relative amount of resonance radiation transmitted is shown in Fig. 6. The curve drawn is calculated from Eq. (1) (integrated numerically over the scatterer). It is not quite a straight line, although even with the present lifetime it would be difficult to establish the shape clearly—a straight line, for example, can be drawn through the present data so that it just comes within the statistical error of the three experimental points.

Fitting the experimental absorption requires $\Gamma/\Delta=(3.71\pm0.23)\times10^{-2}$. Calculation of the thermal width, Δ, depends on the Debye temperature of B_4C and on Lamb's curves. After failing to find enough published data to determine this temperature we decided initially, in view of the hardness of boron carbide, to use a value

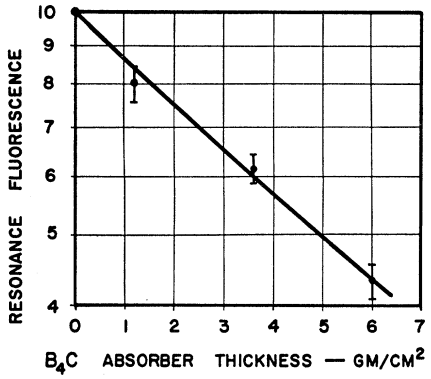

FIG. 6. Attenuation of the resonance radiation from the 4.46-Mev level of B^{11} by B_4C absorbers.

[16] From the least-squares fit itself, the error in the coefficient of $P_2(\cos\theta)$ is ±0.06. The larger error quoted takes account of other experimental uncertainties. For example, the scatterer used for the 90° and 133° scattering subtends an appreciable angle (~8°), so that variations in the incident intensity over the scatterer may be present. Since moving the detector from the 90° to the 133° position changes the relative contributions of the inner and outer parts of the scatterer, some distortion of the angular distributions is possible.

of 1250°K, which happens to be the Debye temperature of elemental boron.[13] The corresponding effective temperature is 530°K, Δ is 13.3 ev, and the mean life resulting is $(1.33\pm0.08)\times10^{-15}$ sec, where the error given reflects only the statistical uncertainty in the data.

It is seen that this agrees with the scattering measurement only if the maximum stated errors are taken in both cases, so that our initial value for the Debye temperature of B_4C might be considered to be an approximate lower limit. As an upper limit, one might take 1860°K which is the Debye temperature of diamond and thus, from an unsophisticated point of view at least, about as high as one might expect to find. The corresponding effective temperature is 720°K and the resulting mean life is $(1.14\pm0.07)\times10^{-15}$ sec. Comparison of this lower limit with the scattering measurement would indicate with reasonable probability that the value used for the source strength, $N(E_r)$, is ~10% low.

As a mean of the scattering and self-absorption values for the mean life of the second excited state of B^{11} we take $\tau=(1.17\pm0.17)\times10^{-15}$ sec. This is calculated by assuming spin $\frac{5}{2}$ for the excited state. If some other spin should be established, the mean life given would have to be multiplied by $6/(2J+1)$ to give the correct statistical weight factor.

VI. DISCUSSION: B^{11}

Ajzenberg and Lauritsen[8] review the experimental evidence that leads to a tentative assignment of spin $\frac{5}{2}^-$ to the second excited state of B^{11} but also allows $\frac{3}{2}$ or $\frac{7}{2}$. Kurath,[6] on the basis of experimental branching ratios of the higher excited states and the predictions of a nuclear model, assigns spin $\frac{5}{2}$ to this state. He then calculates a mean life of $\sim1.5\times10^{-15}$ sec, essentially equal to the experimental mean life.

As is frequently the case, the angular distribution of the resonance radiation does not assist in determining these spin assignments. It does give some information on the quadrupole-dipole mixing ratio and relative phase. For an intermediate state spin of $\frac{5}{2}$, it requires $0\leq\delta\leq0.45$, where δ is the ratio of the quadrupole to the dipole amplitudes.[17] The corresponding intensity ratio is then ≤0.2. For intermediate state spin $\frac{3}{2}$, the phase would be opposite and the intensity ratio ≤0.45, i.e., $-0.66\leq\delta\leq0$.

APPENDIX I: CALCULATION OF SOURCE STRENGTH FROM THE $\alpha-\gamma$ CORRELATION

Although this calculation is straightforward, it is somewhat unusual and the equations used are given here for the sake of completeness.

If φ is the angle between the γ counter and the proton beam and θ' the center-of-mass angle between

[17] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. 25, 729 (1953).

the γ counter and the α-particle counter, the Doppler shift of the photons[18] is

$$\frac{\Delta E_\gamma}{E_\gamma}=-\frac{v'}{c}\cos\theta'+\frac{v_{\text{c.m.}}}{c}\cos\varphi, \tag{2}$$

where v' is the velocity of the C^{12} nucleus in the center-of-mass system and $v_{\text{c.m.}}$ is the center-of-mass velocity. For convenience, we regard the γ counter as a point counter. Then the photons of nominal energy E in coincidence with α particles will have a range of energy

$$d(\Delta E)=E(v'/c)\sin\theta' d\theta'.$$

Here $d\theta'$ is the mean angular aperture of the α counter in the plane defined by the α-particle and photon directions, and is related to the center-of-mass angular aperture, δ', of our (circular) α counter by $d\theta'=2a\delta'$, where the coefficient a depends on φ and the center-of-mass transformation. We then note that an α particle emitted anywhere in the cone of half-angle θ' can be associated with a photon of the correct energy incident on the γ counter. The coincidence counting rate, N_c, must thus be corrected by the factor $2\pi\sin\theta'(2\delta'/\Omega_\alpha')$, where Ω_α' is the solid angle of the α counter. The number of photons per unit energy interval is thus

$$N(E)=\frac{N_c}{E(v'/c)\sin\theta' d\theta'}\left(\frac{(2\pi\sin\theta')2\delta'}{\Omega_\gamma'}\right)=\frac{1}{a}\left(\frac{2\pi N_c}{(v'/c)E\Omega_\alpha'}\right).$$

For the scattering experiment, we wish to know how this compares with the average value of $N(E)$ over the whole line, i.e., with $\langle N(E)\rangle_{\text{Av}}=N_\gamma c/(2Ev')$, N_γ being the singles γ rate in the coincidence experiment. Dividing by the average value, we find

$$\frac{N(E)}{\langle N(E)\rangle_{\text{Av}}}=\frac{4\pi}{a}\left(\frac{N_c}{\Omega_\alpha' N_\gamma}\right). \tag{3}$$

[18] Effects proportional to v^2/c^2 are negligible.

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Back-Angle Elastic Scattering of 14.6-Mev Neutrons*

J. D. ANDERSON, C. C. GARDNER, M. P. NAKADA, AND C. WONG
University of California Radiation Laboratory, Livermore Site, Livermore, California

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Differential elastic scattering cross sections have been obtained for 14.6-Mev neutrons on Fe, Ag, Cd, Sn, and Pb in 5° steps from 90° to 167°. Time-of-flight techniques and one-meter radius rings were used to reduce background, obtain reasonable counting rates, and preserve angular resolution. Optical model calculations by Bjorklund and Fernbach indicate that a spin-orbit coupling term is needed to fit the data.

I. INTRODUCTION

PREVIOUSLY published measurements of elastic scattering angular distributions for 14-Mev neutrons have not extended beyond 90°.[1] Excellent fits to these data have been obtained through optical model calculations in spite of the different potentials and parameters used.[2–4] In the region beyond 90°, however, the predictions of the various models are quite different. By making measurements beyond 90°, it was hoped that the choice of potentials and parameters could be narrowed; in addition, the prediction[2] of deep minima at back angles could be checked.

Large-angle measurements with 14-Mev neutrons have been difficult because of low signal and high background levels. To overcome these difficulties, a pulsed-beam time-of-flight[5] method with large ring geometry was adopted. The elastically scattered neutrons were then effectively time-separated from a large part of the background neutrons and gamma rays. Since gamma rays produced by the neutrons in the scatterer were also time-separated from elastically scattered neutrons, a large and efficient detector could be used.

II. EXPERIMENTAL DETAILS

Geometry

The experimental geometry is shown in Fig. 1. The 500-kev deuteron beam from the Cockcroft-Walton accelerator is swept and bunched[6] before striking a tritium-loaded titanium target. Two-milli-

* Work was performed under the auspices of the U. S. Atomic Energy Commission.

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[2] Bjorklund, Fernbach, and Sherman, Phys. Rev. **101**, 1832 (1956).

[3] Beyster, Walt, and Salmi, Phys. Rev. **104**, 1319 (1956).

[4] W. S. Emmerich, Westinghouse Research Laboratories, Research Report 60-94511-6-R 17, 1957 (unpublished).

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[6] Ashby, Harris, Klein, and Nakada, University of California Radiation Laboratory Report UCRL-4641, 1955 (unpublished).