Lifetime of the First Excited State of B^{11}†

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Using the reaction $B^{11}(p,p')B^{11*}$ as the source of Doppler-broadened 2.14-Mev gamma radiation, resonance fluorescence from the first excited state of B^{11} has been observed. For a bombarding energy of 3.0 Mev and a thick target of B_4C, the shape of the cone containing gamma rays capable of exciting the 2.14-Mev level was determined. It agrees with the expectation based on the known excitation curve and the kinematics of the $B^{11}(p,p')$ reaction assuming an isotropic distribution of the B^{11*} recoils. From the experimental resonance scattering cross section a mean life of 4.8×10^{-15} second was calculated for the first excited state of B^{11}, assuming the spin of this level to be $\frac{1}{2}$. A self-absorption experiment yielded $\tau_\gamma=4.3\times10^{-15}$ second when a value of 1250° was used for the Debye temperature of B_4C. A final value of $(4.7\pm0.6)\times10^{-15}$ second was adopted for the mean life of the 2.14-Mev first excited state of B^{11}. This value of the lifetime further strengthens the argument for spin $\frac{1}{2}$, but it does not allow any conclusion about the $M1$ or $E1$ character of the gamma-ray transition and thus about the parity of the 2.14-Mev level.

INTRODUCTION

EXPERIMENTAL evidence on the spin and parity of the first excited state of B^{11} has been somewhat contradictory. The arguments for and against a spin value of $\frac{1}{2}$ have been reviewed by Wilkinson.[1] He strengthened the evidence for spin $\frac{1}{2}$ by establishing an upper limit of 4×10^{-14} second for the lifetime of the 2.14-Mev level and by pointing out that such a short lifetime, in view of the observed isotropy of the gamma radiation, is consistent only with spin $\frac{1}{2}$. The adverse evidence from investigations of $B^{10}+d$ reactions at deuteron energies of 6–9 Mev was weakened by the suggestion that a modified stripping process, in which the spin of the outgoing nucleon is flipped, may be involved.

At a deuteron energy of 15.1 Mev, Lee, and Wall[2] recently found agreement between the measured proton angular distribution and the stripping theory for $l_n=2$. They reported that the height and width of the first maximum in this distribution changed more rapidly with small changes in the deuteron energy than expected. However, the angular position of the maximum remained at a value appropriate to an orbital angular momentum transfer of two units. Since Wilkinson's arguments for spin $\frac{1}{2}$ are also valid if the level has even parity, Lee and Wall's results lead to $\frac{1}{2}+$, making the transition electric dipole instead of magnetic dipole.

The present work was undertaken in the hope that a determination of the lifetime of the 2.14-Mev transition might allow a decision between the possibilities of $M1$ and $E1$, i.e., a decision between $\frac{1}{2}-$ and $\frac{1}{2}+$. The short upper limit of 4×10^{-14} second practically assured the possibility of observing resonance fluorescence from this level provided a strong source of 2.14-Mev gamma radiation was available. The reaction $B^{11}(p,p')B^{11*}$ turned out to be a suitable source and it was used for all the experiments described in this paper.

Aside from minor differences arising from the use of inelastic scattering as the source of the exciting radiation, the resonance scattering and the self-absorption experiments were carried out in very much the same way as the previously described experiments using the (p,α) reactions of N^{15} and F^{19}.[3,4] For details, reference is made to these earlier papers, and it will only be pointed out here that in the simple scattering experiment the resonance effect is proportional to $N(E_r)\Gamma$, where $N(E_r)$ is the number of incident gamma rays per unit energy interval at the resonance energy, and Γ is the natural width of the level, which is assumed to decay only by a direct gamma-ray transition to the ground state. The self-absorption experiment does not require a knowledge of $N(E_r)$, the attenuation being proportional to Γ/Δ, where $\Delta=(E_\gamma/c)(2kT/M)^{\frac{1}{2}}$ is the thermal Doppler width of the absorption line.

SOURCE OF THE EXCITING RADIATION: $B^{11}(p,p')B^{11*}$

The yield of the 2.14-Mev gamma radiation from $B^{11}+p$ has been measured[5] for bombarding energies up to 5.3 Mev. Below 2.4 Mev, the yield is very small. A resonance is observed at $E_p=2.66$ Mev, the next peak in the yield curve falling at a proton energy of 3.15 Mev. The yield at proton energies greater than 3 Mev is of no interest for the resonance fluorescence studies because of the occurrence of the (p,n) threshold of B^{11} at $E_p=3.015\pm0.003$ Mev.[6]

Pure (>99%) boron carbide, pressed into a recess in a graphite disk, was used as the target, the graphite disk being contained in an air-cooled copper housing. The average bombarding current was 5 microamperes of 3-Mev protons. When the detector, a sodium iodide crystal of $1\frac{3}{4}$ in. diameter and 2 in. length, surrounded

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[1] D. H. Wilkinson, Phys. Rev. **105**, 666 (1957).

[2] K. S. Lee and N. S. Wall, Bull. Am. Phys. Soc. Ser. II, **2**, 208 (1957) and N. S. Wall (private communication).

[3] C. P. Swann and F. R. Metzger, Phys. Rev. **108**, 982 (1957).

[4] Rasmussen, Metzger, and Swann, Phys. Rev. **110**, 154 (1958).

[5] Bair, Kington, and Willard, Phys. Rev. **100**, 21 (1955).

[6] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).

by $\frac{1}{8}$ in. of lead, $\frac{1}{8}$ in. of aluminum, and $\frac{1}{4}$ in. of boron carbide, was exposed to the direct radiation of this source at a distance of 40 inches, the counting rate in the full energy (2.14-Mev) peak was approximately 700 counts per second. This was about six times smaller than the counting rate observed with the $N^{15}(p,\alpha)$ reaction and forty-five times smaller than the counting rate observed with the $F^{19}(p,\alpha)$ reaction when pulse heights suitable for resonance scattering experiments[3,4] were accepted. However, the λ^2-dependence of the resonance cross section works in favor of the low-energy transition. In addition, the 2.14-Mev line from $B^{11}(p,p')$ is only about 11 kev wide while the 4.4- and 7-Mev gamma lines from the (p,α) reactions were 110 and 135 kev wide. Thus, as far as the counting rate for a given lifetime is concerned, one is approximately as well off with the 2.14-Mev radiation produced by $B^{11}+p$ as with the more powerful (p,α) sources. If one considers the background counting rates, however, the situation is less favorable for the 2.14-Mev transition. For the high-energy transitions studied previously, the main source of background was capture radiation due to neutrons from the machine, the contributions from cosmic radiation and radioactive materials in the room being negligible. As one decreases the energy below 2.6 Mev (ThC″), the background from radioactive substances in the concrete of the walls and the floor of the laboratory increases sharply and becomes an important portion of the counting rate at 2.14 Mev. Neutrons from parts of the vacuum system hit by the proton beam are also more efficient in affecting the counting rate in the 2.14-Mev region, especially if any hydrogenous material, which would give rise to 2.2-Mev capture radiation, is exposed.

All the elemental boron targets and the boron carbide targets which were studied gave rise to considerably more neutrons than did the $N^{15}H_3$ targets used as the sources of 4.4-Mev radiation.[4] The neutron yields from the different samples varied by factors of two or three, but even for the best sample (>99% B_4C) the counting rate with a "long counter"[7] was well above the background rate measured with the beam on a tantalum disk. Under these circumstances it was essential that the matching of the scatterers could be tested. This was possible because the incoming proton provides the major portion of the recoil momentum in the reaction $B^{11}(p,p')$. The recoils are, therefore, moving in the direction of the proton beam forming a cone of, at most, 27.5 degrees half-angle with the beam direction. If one is studying resonance fluorescence in B^{11}, the velocity component necessary to compensate for the gamma-recoil energy losses is small, i.e., the gamma rays with resonance energies are emitted almost at 90 degrees (88 degrees) with respect to the B^{11*} recoils. With the B^{11*} recoils forming a forward cone, the resonant gamma rays will form a cone of emission angles near 88 degrees with the beam direction.

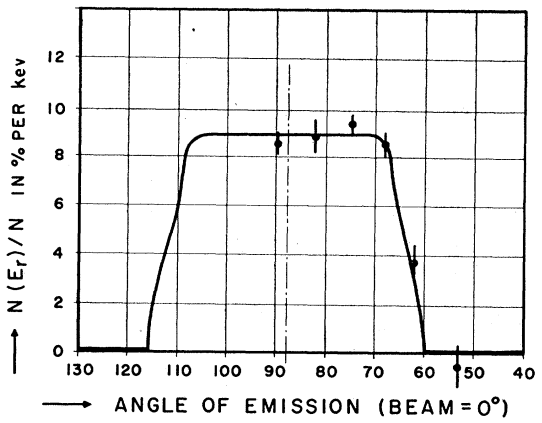

FIG. 1. Comparison of the calculated and the measured shapes of the effective cone of emission for a thick B_4C target bombarded with protons of 3.0 Mev energy. The average of the experimental points at 90, 82.2, and 74.6 degrees was normalized to the value of the "plateau" of the calculated curve.

Using the known yield curve[5,8] for the $B^{11}(p,p')$ reaction, and assuming isotropic recoil and gamma-ray distributions, the fraction of gamma rays per unit energy interval at the resonance energy was calculated for different emission angles and is represented in Fig. 1. It can be seen that for emission angles smaller than 60 degrees and larger than 115 degrees none of the gamma rays fall into the resonance region. If the main scatterer (B_4C) and the comparison scatterer ($LiNO_3$) are placed in this "nonresonant" region, they should give rise to identical counting rates. One thus has the possibility of matching the scatterers under counting rate and scattering angle conditions which are very similar to those met in the actual resonance scattering experiment.

The restriction to a finite range of emission angles is typical of inelastic scattering reactions. It is an awkward feature when the angular distribution of the resonance radiation is to be measured. On the other hand, it is an advantage in many cases because it results in a smaller Doppler width of the emission line, i.e., a larger intensity per unit energy interval.

Another peculiarity of the (p,p') reaction is the possibility of self-absorption in the source, one of the main complications in atomic resonance fluorescence which was avoided with the (p,α) reactions where the target element differs from the element of the residual nuclei. For most nuclear resonance fluorescence experiments, the self-absorption is rather small and the restrictions imposed on the source not severe. In the case of the 2.14-Mev level, the only precaution taken was to limit the diameter of the B_4C target to $\frac{1}{4}$ in., avoiding in this manner appreciable self-absorption

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

[8] T. Huus and R. B. Day. Phys. Rev. **91**, 599 (1953). These authors also showed that the yield of 2.15-Mev quanta from $B^{10}(p,p')$ is negligible at energies up to 2.9 Mev.

even when the scatterer was located at 90 degrees with respect to the proton beam.

EXPERIMENTAL PROCEDURE, RESULTS

Cylindrical ring scatterers of 16.5 in. outside diameter, 13.1 in. inside diameter and 1.06 in. length were used for the simple scattering experiments. Longer scatterers of 15.7 in. outside diameter, 13.3 in. inside diameter, and 3 in. length were used for the self-absorption studies.

An absorber of 210 g/cm^2 of heavy metal (W+Cu) and 70 g/cm^2 of gold shielded the $1\frac{3}{4}$ in.-diameter, 2 in.-long sodium iodide crystal from the direct radiation. A detectable fraction of the primary beam reached the crystal through this absorber. However, it was decided that the gain in solid angle offset the disadvantage of a slightly increased background counting rate. The distance from the source to the center of the crystal was 10.5 in. For a first set of experiments, B_4C of 93% purity served as target, absorber, and scattering material. A resonance fluorescence effect was observed both in a simple scattering experiment and in a self-absorption study. However, the level widths deduced from the two experiments differed considerably. Although the discrepancy could have been of statistical nature, it was decided to continue the measurements with purer (>99%) material.

Using the pure B_4C, the matching of the B_4C and $LiNO_3$ scatterers was checked by a run in which the scatterers were located in the "nonresonant" region. The pulse-height distributions of the scattered radiation between 1.6 and 2.5 Mev energy were registered with a twenty-channel pulse-height analyzer. The counting rates for the $LiNO_3$ scatterer were the same as those without scatterer, both counting rates differing from the background counting rate with the beam off the target by the counting rate due to leakage through the attenuator. The difference in the counting rates for the B_4C and $LiNO_3$ scatterers are plotted in Fig. 2 as full circles. It was concluded that these differences averaged out to zero as well as could be expected. Using the same scattering angle, the scatterers were then placed in the "resonant" region. The counting rate differences for this arrangement are plotted in Fig. 2 as triangles. The scattered radiation from B_4C showed clearly a full energy peak at the pulse height expected for a 2.14-Mev gamma ray. The shape of the pulse-height distribution agreed closely with that obtained when the crystal was exposed to the direct radiation from the target. There could, therefore, be no doubt that resonance scattering from the first excited state of B^{11} had been observed. For the later experiments, the sum of the counting rates in the seven channels corresponding to pulse heights ranging from 44 to 51 volts was taken as being representative of the resonance effect.

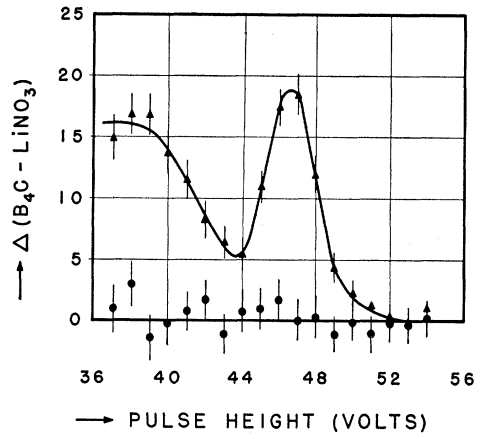

FIG. 2. Resonance fluorescence from the 2.14-Mev excited state of B^{11}. Triangles represent the pulse-height distribution of the resonance radiation. The full energy peak at 46.5 volts corresponds to a gamma energy of 2.14 Mev. Circles were obtained with the scatterers placed in the "nonresonant" position; they give an account of the matching of the B_4C and $LiNO_3$ scatterers as far as nonresonant scattering is concerned.

The next step consisted in determining experimentally the shape of the effective cone of emission and comparing it with the calculated shape depicted in Fig. 1. Data were taken for six different scatterer positions. After correcting for changes in solid angle and in counter sensitivity, the resonance effects observed at the different positions are proportional to the respective values of $N(E_r)$, the number of gamma rays per unit energy interval at the resonance energy. After normalization of the average of the three points at the 90, 82.2, and 74.6 degree positions to the plateau value of the curve in Fig. 1, the experimental points were plotted in this figure with their standard deviations. The agreement with the calculated shape is good. Within the experimental uncertainty the three points closest to 90 degrees fall on a horizontal line. This means that the angular distribution of the recoils in the center-of-mass system must not depart too far from isotropy. A strong "fore and aft" distribution of the recoils in the center-of-mass system would increase the intensity near 90 degrees, while a preferential emission perpendicular to the beam direction would lead to a depression of the curve of Fig. 1 near 90 degrees and elevations near the 70 and 105 degree points.

By comparison of the average number of resonance scattered gamma rays for the 90, 82.2, and 74.6 degree measurements with the total number emitted by the source, and with the value $N(E_r)/N=0.089$ per kev from Fig. 1, the natural width of the 2.14-Mev level was calculated to be (0.138 ± 0.008) ev. This corresponds to a mean life τ_γ of $(4.8\pm0.3)\times10^{-15}$ second if the spin of the first excited state is assumed to be $\frac{1}{2}$.

For the self-absorption experiment, the longer scatterers covered emission angles from 72 to 91 degrees. Absorbers of B_4C and of carbon, which had been matched as far as the electronic attenuation was concerned, were inserted between the source and the scatterer. 3.0 g/cm^2 of B_4C reduced the resonance

scattering effect to $(66.9\pm3.6)\%$ of the effect with the carbon absorber in place. Under the assumption of a pure Doppler form for the effective cross section [Eq. (2) of reference 3], an analysis of the self-absorption experiment led to a value $\Gamma/\Delta=(2.4\pm0.4)\times10^{-2}$, taking spin $\frac{1}{2}$. With an assumed Debye temperature of 1250° for B_4C, the effective temperature to be used in the expression for Δ is, according to Lamb,[9] $T_{\text{eff}}=530°$. With this value the Doppler width of the 2.14-Mev absorption line becomes $\Delta=6.38$ ev, leading finally to a natural width Γ of (0.153 ± 0.023) ev or $(2.45\pm0.4)\times10^{-13}$ erg and a mean life of $(4.3\pm0.6)\times10^{-15}$ second.

The result of this self-absorption experiment could be made to agree even more closely with the simple scattering result if a smaller Debye temperature were chosen for B_4C. The experiments carried out with the 4.46-Mev level of B^{11} indicated,[4] on the other hand, better agreement of scattering and self-absorption experiments when higher values of the Debye temperature of B_4C were used. Thus it appears that 1250° is a choice which satisfies both sets of experiments.

It was felt for this measurement, as for those previously reported, that the uncertainty in the lifetime based on the self-absorption was larger than the quoted statistical error because of the vagueness concerning the effective temperature of B_4C and the uncertainty as to the validity of the Lamb-correction. The lifetime from the scattering experiment was also estimated to be uncertain by appreciably more than the statistical standard deviation because of errors in the angular sensitivity, the self-absorption, electronic attenuation, and similar corrections. For these reasons the uncertainty in the final value of τ_γ was increased by a factor of two over the purely statistical error. Our final value for the mean life of the 2.14-Mev state in B^{11} is then $\tau_\gamma=(4.7\pm0.6)\times10^{-15}$ second.

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

DISCUSSION

Since the experimental value for the lifetime of the first excited state of B^{11} is ten times shorter than the previous upper limit, Wilkinson's[1] arguments for the spin value $\frac{1}{2}$ are strengthened. However, the question of the parity of the level does not seem to be resolved. From Weisskopf's single-particle lifetime formulas[10] the expected mean lives are $\tau_\gamma(M1)\sim3\times10^{-15}$ second and $\tau_\gamma(E1)\sim10^{-16}$ second. Kurath's intermediate-coupling shell-model calculation,[11] considering the transition to be predominantly $M1$, gives a mean life in the range $(2.5\text{–}5)\times10^{-15}$ second. The experimental lifetime is thus consistent with an $M1$ transition and odd parity for the level.

On the other hand, the experimental lifetime is almost equally consistent with an $E1$ transition and even parity. Wilkinson's recent compilation of experimental lifetimes[12] shows that the average $E1$ transition in light nuclei is slower than the "Weisskopf unit" by a factor of 30 and that the spread around this average is large enough to cover our observed factor of 45 easily. Also, one explanation of the apparent anomalies of the stripping experiments, that this level in B^{11} may not be properly described as a single-particle level,[2] would of course imply that the decay cannot be described as a single-particle transition.

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[10] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[11] D. Kurath, Phys. Rev. **106**, 975 (1957).
[12] D. H. Wilkinson, Phil. Mag. **1**, 127 (1956).