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Widths of ^{11}B levels below 9.0 MeV

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The widths of nine energy levels in ^{11}B at 2.125, 4.445, 5.021, 6.743, 6.793, 7.286, 7.978, 8.559, and 8.920 MeV were determined by carrying out self-absorption and photon scattering measurements. The temperature variation of the scattering cross section was measured at $T = 298$ K and $T = 730$ K to study in some detail the effective temperature T_e of ^{11}B in B_4C, BN, and elemental B. The influence of T_e on the deduced values of the radiative widths of ^{11}B is discussed.

[NUCLEAR REACTIONS $^{11}B(\gamma,\gamma')$, $E=10.3$ MeV bremsstrahlung. Deduced Γ_0, effective temperatures. BN, B_4C, B natural targets.]

I. INTRODUCTION

The interest in the ^{11}B nucleus arises from its being a light nucleus with strong $M1$ transitions where one can test some theoretical predictions concerning the level widths. This nucleus is also used for calibration purposes in nuclear resonance fluorescence (NRF) measurements employing bremsstrahlung radiation.

In the past, several measurements of the widths of these levels were carried out using inelastic electron scattering and the NRF technique.[1-5] Because of some inconsistencies in the results of the two methods, it was considered very useful to remeasure the widths of the strong levels trying to avoid possible pitfalls in the process of analyzing the data.

In the present work, we measured the ground state widths of nine levels in ^{11}B using bremsstrahlung radiation. The widths of five levels were determined using self-absorption measurement, while the widths of the other four levels were obtained using calibration levels in ^{23}Na, ^{24}Mg, ^{27}Al, ^{31}P, ^{208}Pb, and the strongly excited ^{11}B levels. One of the main objectives of the present work has been to study, in a critical manner, the influence of the effective temperature[6-9] on the determination of the level widths. For this purpose the temperature variation of the scattered intensity was studied in detail.

This study is of particular importance for the case of boron, because ^{11}B is a light nucleus (mass M) and hence the Doppler width Δ of a nuclear level E_x, given by $\Delta = E_x(2kT_e/Mc^2)^{1/2}$, where T_e is the effective temperature,[6-9] is particularly large exceeding the natural width of all bound levels. In addition, because elemental B and some of its compounds do not obey a Debye behavior, the procedure of calculating T_e from the Lamb formula[6] is not appropriate. We shall also show that by following the Lamb procedure for calculating T_e large errors in the value of Γ_0 in ^{11}B could be obtained.

A preliminary report[10] on the present measurements contained an error in the analysis of the data yielding values of Γ_0's higher by ~20% than those given here. These preliminary results were quoted in Ref. 11.

II. EXPERIMENTAL PROCEDURE

The photon source was a bremsstrahlung beam produced by electrons hitting a 100 mg/cm gold foil. The electron beam, $E_e = 10.3$ MeV, and 18 μA was obtained from the MUSL-2 (Microtron Using a Superconducting Linear Accelerator) having a 100% duty factor.[12] The beam was stopped in a 15 g/cm^2 thick block of carbon placed in a Faraday cup immediately behind the gold converter. The experimental arrangement is essentially the same as that given in Ref. 12. The only difference is a 5 cm borated paraffin shield surrounding the 50 cm^3 Ge(Li) detector which was found to be very effective against a fast neutron background. A photon hardener consisting of copper (6 cm), lead (1.25 cm), and borated plastic (5 cm), placed in front of the detector, was used. The energy resolution of the γ-ray spectrometer was 10 keV full width at half maximum (FWHM) at $E_\gamma = 9$ MeV. The targets were square shaped, 10 cm × 10 cm consisting of B, B_4C, and BN (purity: 99%) of thickness ~3 g/cm^2 placed inside Lucite containers. The absorbers consisted of various chemical compositions and thicknesses as mentioned for each specific case below. A schematic arrangement of the absorber-scatter-detector geometry is shown in Fig. 1.

In the temperature variation measurement, a 2.03 g/cm^2 thick BN target enclosed in a thin walled graphite container was used. Here, the

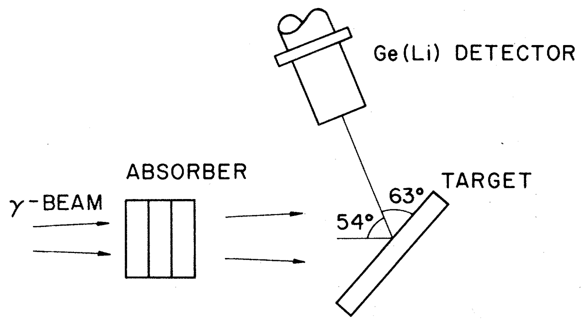

FIG. 1. Schematic arrangement showing the absorber and the geometry of the target and detector.

scattered intensities at $T=298$ K and $T=730$ K were compared using a thick resonant absorber (5.03 g/cm^2) of elemental B (at room temperature). The target was heated using an insulated electric wire wrapped directly on the graphite container and a temperature controller was used to keep the temperature at $T=730\pm10$ K.

III. RESULTS AND DISCUSSION

The scattered spectrum for a B_4C target for an electron beam energy of $E_e=10.3$ MeV is shown in Fig. 2. It shows some elastic and inelastic transitions in ^{11}B together with some "background"

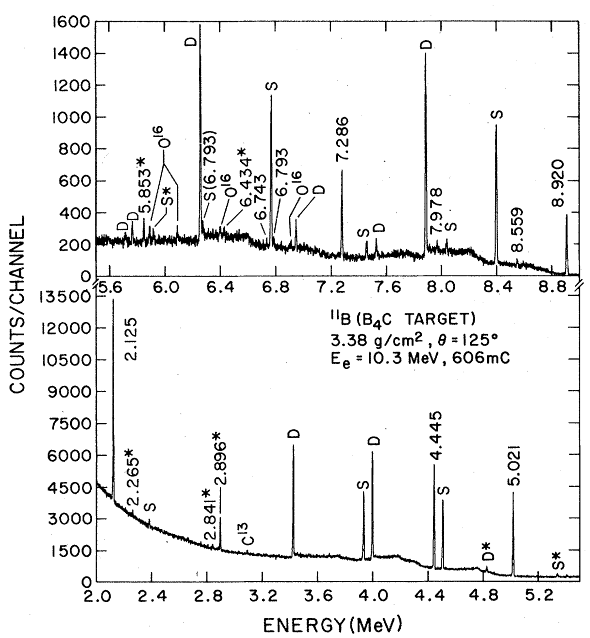

FIG. 2. Scattered spectrum from ^{11}B (in the form of a B_4C target) obtained using bremsstrahlung beam with electrons of $E_e=10.3$ MeV. S and D refer to the single and double escape peaks while other lines refer to the full-energy peaks. Asterisks indicate inelastic transitions between ^{11}B levels. The ^{16}O and ^{13}C lines originate from the Lucite container of the target.

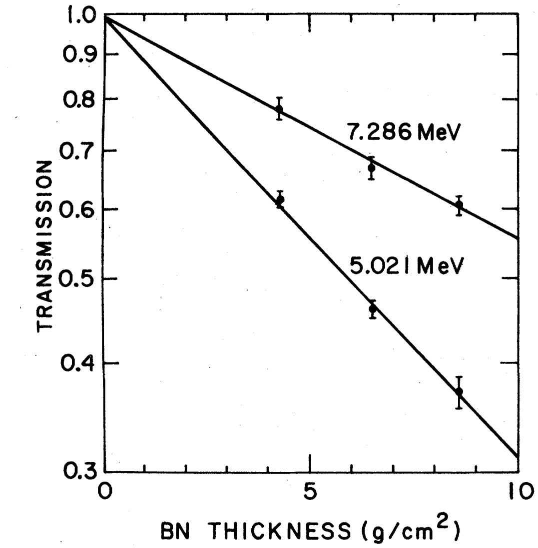

FIG. 3. Relative scattered intensities of the 7.286 and the 5.021 MeV lines from a 3.2 g/cm^2 BN target as a function of BN absorber thickness. The bremsstrahlung beam passes through the absorber before hitting the target. The absorption includes both the atomic and the nuclear effects. The solid lines show the calculated values obtained using the level widths given in Table II (with atomic attenuation coefficients deduced using a comparative nonresonant graphite absorber).

transitions in ^{13}C, ^{16}O originating from the Lucite container. Other weaker inelastic transitions in ^{11}B were observed and are not indicated due to the large scale reduction of Fig. 2. Note the quality of the data and the high signal to background ratio. Two sets of measurements of nuclear self-absorption for the strongly excited levels at 2.125, 4.445, 5.021, 7.286, and 8.920 MeV were carried out as a function of the B thickness for three different thicknesses using absorbers and scatterers in BN and B_4C forms. Further, another set of measurements was carried out using nonresonant absorbers of graphite having about the same atomic attenuation as that of the B-containing absorbers.

Transmission results obtained using a 3.2 g/cm^2 BN target with BN absorbers are given in Fig. 3. The ground-state level widths were extracted from the transmission data following the same method described by Metzger for a white photon spectrum scattered from a target.[9] The scattered intensities of the 2.125, 4.445, and 5.029 MeV levels were properly corrected for being fed from higher levels. Using the results of the atomic attenuation by the nonresonant absorber, the nuclear absorption was deduced. The results, for the five strongly excited levels, obtained using a 8.61 g/cm^2 BN absorber are given in Table I. The widths of the weakly excited states at 6.743, 6.793,

TABLE I. Measured nuclear attenuation α_N of ^{11}B levels using a 8.61 g/cm^2 BN absorber and a 3.2 g/cm^2 BN target.

E_x (MeV)	α_N
2.125	0.746 ± 0.048
4.445	0.553 ± 0.010
5.021	0.464 ± 0.015
7.286	0.729 ± 0.014
8.920	0.58 ± 0.015

7.978, and 8.559 MeV were determined from their relative scattering cross sections. The latter was obtained by comparing the scattered intensities with those of the strongly excited levels of ^{11}B and some other levels in ^{23}Na, ^{24}Mg, ^{27}Al, ^{31}P, and ^{208}Pb of known Γ_0, Γ which were taken as calibration levels.[13,14] In doing so, the spins of the ^{11}B levels were taken from the literature,[1] while branching ratios Γ_0/Γ for the 7.978 MeV and the strongly excited levels were obtained directly from the areas of the elastic and inelastic ^{11}B lines and were found to agree well with the compiled values.[1] The measured widths are given in Table II and are averages obtained using the B_4C and the BN data. The present results seem to be somewhat lower by about 20% than the compiled values of Ref. 1. The largest deviation occurs for the 8.559 MeV level which is smaller by 45% than that measured by inelastic electron scattering.[2,5] The reason for this large discrepancy is not clear.

It should be noted that in extracting the values of Γ_0 of the strongly excited levels from self-absorption it was necessary to know not only the branching ratios and the spins which were taken from Ref. 1 but also the Doppler width. This is dependent on the effective temperature T_e of ^{11}B at $T=298$ K, in the particular chemical compound; it was deduced as explained below.

A. Effective temperature of ^{11}B

As mentioned in Sec. I, it turned out that the normal procedure for calculating T_e is not applicable to the present case. According to Lamb, T_e is given by[6]

$$\frac{T_e}{T}=3\left(\frac{T}{\theta_D}\right)^3\int_0^{\theta_D/T} x^3\left(\frac{1}{e^x-1}+\frac{1}{2}\right)dx\,. \qquad (1)$$

This formula is obtained from a consideration of the motion of the atoms by viewing them as Planck oscillators having a *continuous* frequency distribution given by the Debye approximation $g(\nu)d\nu \propto \nu^2 d\nu$ with an upper cutoff frequency ν_D related to the characteristic Debye temperature θ_D. This procedure is applicable to *elements* where a single Debye temperature gives a good description of T_e

TABLE II. Widths of levels in ^{11}B.

E_x (MeV)	Transition	Present work[a] Γ_0 (eV)	Present work[a] Γ (eV)	Reference 1 Γ_0 (eV)	Reference 1 Γ_0/Γ	Assumed J^π	Γ_0/Γ_W	Theory[d] Γ_0 (eV)
2.125	$M1$	0.118 ± 0.013	0.118 ± 0.013	0.136 ± 0.010	1	$\frac{1}{2}^-$	0.59	0.1
4.445	$M1$	0.55 ± 0.02[b]	0.55 ± 0.2	0.61 ± 0.03	1	$\frac{5}{2}^-$	0.29	0.8
	$E2$			0.017 ± 0.002			7.1[c]	
5.021	$M1$	1.64 ± 0.07	1.97 ± 0.07	2.24 ± 0.3	0.85	$\frac{3}{2}^-$	0.62	2.0
6.743	$E2$	0.021 ± 0.005	0.030 ± 0.007[e]	>0.06	0.70	$\frac{7}{2}^-$	1.3	
6.793	$E1$	0.26 ± 0.03	0.39 ± 0.05[e]	>0.02	0.66	$\frac{1}{2}^+$	0.0025	1.0
7.286	$E1$	0.99 ± 0.07	1.14 ± 0.08	0.96 ± 0.52	0.87	$\frac{5}{2}^+$	0.0076	0.73
7.978	$E1$	0.53 ± 0.07	1.15 ± 0.15	>0.02	0.46	$\frac{3}{2}^+$	0.0031	0.51
8.559	$M1$	0.53 ± 0.05[b]	0.66 ± 0.09[e]	0.73 ± 0.10	0.53	$\frac{3}{2}^-$	0.04	0.15
	$E2$			0.23 ± 0.03			3.0[c]	
8.920	$M1$	4.16 ± 0.23	4.31 ± 0.24	5.0 ± 0.6	0.95	$\frac{5}{2}^-$	0.28	3.8

[a] The calculated errors arise mainly from uncertainties in statistics, T_e and Γ_0/Γ.
[b] This refers to the $M1+E2$ widths.
[c] This was obtained using the present value of Γ_0 and the $E2/M1$ ratio of Ref. 1.
[d] References 19 and 20. The $E1$ predicted values correspond to the second set of the single-particle energies (Ref. 20). The $M1$ predicted values may change by ~30% depending on the choice of the two-body matrix elements.
[e] This Γ is obtained using the Γ_0/Γ of Ref. 1.

TABLE III. Calculated and measured ratios R_T of scattered intensities from ^{11}B levels (in the form of BN) at T= 730 K and T= 298 K.

E_x (keV)	R_T Experiment	Calc.[a]	Calc.[b]
2125	1.06 ± 0.03	1.07	1.14
4445	1.10 ± 0.03	1.12	1.22
5021	1.11 ± 0.02	1.12	1.23
7286	1.04 ± 0.03	1.04	1.08
8920	1.11 ± 0.03	1.10	1.14

[a] This calculation was carried out for a 5.03 g/cm^2 B absorber and a 2.03 g/cm^2 BN scatterer with a geometry indicated in Fig. 1. The ^{11}B effective temperatures were taken to be T_e= 990 K and T_e= 700 K at T= 730 K and T= 298 K, respectively, in both B and BN.

[b] This calculation assumed the same scatterer and absorber thickness and the same geometry as in footnote a. The effective temperatures used were T_e = 806 K and T_e= 475 K for both B and BN at T= 298 K and T= 730 K, respectively, where the values of T_e were deduced using the Lamb formula [Eq. (1)] with θ_D= 1100 K.

versus T. For chemical compounds and some other elements such as B, the Lamb treatment is no longer true because one should account for the contribution of *discrete* frequencies arising from the vibrational normal modes of the molecules or the lattice. The proper way of extracting the effective temperature of an atom in a solid is to consider the frequency distribution function of the atoms or the phonon spectrum of the atoms in the solid.[9,15] This is usually obtained by employing methods of lattice dynamics using data taken from infrared spectra and inelastic scattering of cold neutrons. For boron no calculation of $g(\nu)$ was reported because no n-scattering data are available (this is due to the high n-absorption cross section of ^{10}B in the thermal region). Thus we used the compound BN for which the value of T_e at 298 K is known from nuclear resonance scattering studies[8] on ^{15}N. Such a study has shown that the measured value of T_e versus T of nitrogen in BN did not conform to a Lamb type behavior [Eq. (1)]. In addition, it yielded $T_e = 540 \pm 30$ K for the effective temperature of N in BN. Relying on this result and assuming that the kinetic energies of B and N in the various normal modes of BN are distributed inversely as their mass ratio,[9,16] the effective temperature of ^{11}B in BN at T= 298 K can be seen to be $T_e = 700 \mp 30$ K. The results of Ref. 8 were also employed, with some extrapolation, to deduce the values of T_e at T= 730 K (used in the temperature variation measurements). It was found to be $T_e = 990 \pm 30$ K.

It should be emphasized again that the present approach for calculating T_e is different from that of Lamb in two respects: (1) We no longer assume the Debye frequency distribution (see above). (2) We obtain two effective temperatures, one for each element of the diatomic compound such as BN, so that $T_e(\mathrm{B}) \neq T_e(\mathrm{N})$. It is of interest to note that the present value of T_e for ^{11}B in B_4C and B (see Sec. III C) is higher by ~40% than that used in some earlier studies.[4,17] This increases the deduced values of Γ_0 as explained later.

Since the radiative widths deduced from self-absorption measurements are strongly dependent on the Doppler width and hence on T_e, an experimental test of the consistency of the above calculated value of T_e for ^{11}B in BN was made by measuring the temperature variation of the scattered cross section as discussed below.

B. Temperature variation of scattered intensities

As mentioned in Sec. II, the scattered intensities from the ^{11}B levels (using a BN target) were measured at T= 298 K and T= 730 K after passing the beam through a 5.3 g/cm^2 thick resonant absorber of elemental B (at room temperature). The use of a self-absorber in such a measurement served to enhance the dependence of the scattered intensities on the Doppler widths of the ^{11}B levels and hence on T_e of the BN scatterer.[16] As mentioned above, the present procedure for calculating T_e of ^{11}B in BN and B (see Sec. III A) yields T_e = 700 K and T_e = 990 K at T= 298 K and T= 730 K, respectively. However, at these two temperatures, the use of the Lamb formula [Eq. (1)] together with a Debye temperature θ_D = 1100 K for boron (as was done by Kumagai *et al.*[17]), yields T_e = 475 K and T_e = 806 K. Table III compares the ratio of the predicted scattered intensities obtained using the above two sets of values of T_e with experiment. The results indicate a much better agreement with predictions made using the first set of values of T_e and hence strongly supports the use of the present procedure for calculating T_e.

It may be noted that in deducing the experimental ratio of scattered intensities for the 4.445 MeV level, the small overlapping contribution of the 4.440 MeV level of ^{12}C (present in the graphite container) was accounted for.

C. Effective temperature of ^{11}B in other scatterers

After finding the effective temperature T_e of B in BN, it was of interest to estimate the T_e of ^{11}B in elemental B and also in B_4C. This was done by measuring the transmission with 8.61 g/cm^2 BN absorber while B and B_4C were used as scatterers. The nuclear absorptions obtained were almost identical for all the 5 levels of ^{11}B to those given in Table I for a BN scatterer. By considering the statistical accuracy of the measurements together with the calculations, it was found that the T_e of ^{11}B in elemental B and in B_4C is the same to within 30 K as that of BN. It should be added that a difference in T_e of ∓ 50 K could have been easily observed in the above measurement.

D. Influence of T_e on Γ_0

The fact that the values of T_e deduced from specific heat data are much lower than the value obtained in the present work may probably be explained by noting that the specific heat is sensitive mainly to the low-energy acoustical modes of vibrations of B. The high-energy optical modes of vibration, which are the main contributors to T_e, cannot be excited at $T \leq 300$ K which is the temperature at which specific heats are usually measured. It may be added that the value $T_e = 700$ K used in the present work for deducing Γ_0 is higher by ~40% than $T_e' = 475$ K used by Kumagai *et al.*[17] One would therefore expect the present Γ_0's to be higher by a factor of $\sim (T_e/T_e')^{1/2} = 1.21$. However, our results are, on the average, higher by only 4%. This large discrepancy is due to the fact that our measured nuclear absorption is smaller on the average by about 10% than that of Ref. 17. No apparent reason was found to account for such a large difference. In view of this we repeated our nuclear absorption measurements with various absorbers and scatterers with essentially the same results. Perhaps, it may be noted in this connection that the value of Γ_0 obtained by Rasmussen *et al.*[18] for the 4.445 MeV level (using a B_4C absorber and scatterer) is in excellent agreement with the present value only when a value $T_e = 700$ K is assumed.

In order to further check the above values of T_e, another method was used for extracting the Γ_0 of the *strongly* excited levels of ^{11}B by comparing their scattering intensities with those of calibration levels in ^{23}Na, ^{27}Al, ^{31}P, and ^{208}Pb of known width. This procedure, being almost independent of T_e for thin scatterers, yielded values of Γ_0 that were very close to those of the self-absorption measurements thus confirming the present values of T_e.

E. Comparison with theory

In the framework of the shell model, the odd-parity ^{11}B levels studied in the present work arise mainly from excitations within $p_{3/2}$ and $p_{1/2}$ shells. The even-parity levels involve configurations of the form p^6d and p^6s (with a $0s^4$ core).

The shell model configurations of the ^{11}B levels were studied[1] using the single stripping $^{10}B(d,p)$ reaction, the double stripping $^9Be(^3He,p)$ reaction, and the pickup $^{12}C(t,\alpha)$ reaction. In this manner, some of the main shell-model configuration components of the levels listed in Table II were identified.

Theoretically, some of the properties of the negative parity ^{11}B levels were treated by Cohen and Kurath[18] assuming a weak coupling model with excitations occurring in the p shell only. The predicted $M1$ ground state radiative widths (Table II) for the strongly excited states at 2.125, 4.445, 5.021, 8.920 MeV seem to be in fair agreement with the present data. However, the ground state $M1$ transition from the second excited $\frac{3}{2}^-$ 8.559 MeV level is predicted to be weaker by a factor of 4 compared to experiment. In another calculation by Teeters and Kurath,[20] the positive parity states were considered and only the 1 particle-1 hole excitations were taken into account in a weak coupling representation.

The most remarkable feature of the results of those calculations is the relatively large contribution of the $0s \rightarrow 0p$ core excitation to the $E1$ transitions. This fact reveals the importance of the $(0s)^3(0p)^8$ configuration in the ^{15}N levels.

In the calculations of Ref. 20, two sets of single-particle energies were used. In Table II, we quote only the predicted results using the second set because it yielded a better agreement with experiment. It may be seen that the $E1$ ground state radiative widths for the 7.286 and 7.978 MeV levels are in very good agreement with the present data. However, the predicted value for the 6.793 MeV level is a factor of ~4 larger than the measured value. It is of interest to note that the predicted branching ratios for the various $E1$ transitions (not given in Table II) are in fair agreement with the measured value. Further, the $E1$ and $M1$ transitions are expressed in Weisskopf units (Γ_0/Γ_W) and are of about the average $E1$ intensities expected in this region of the periodic table.[21] It should be remarked that the 6.743 MeV level proceeds to the ground state via a pure $E2$ transition and that the intensity of this transition together with the $E2$ transitions from the 4.445 and the 8.559 MeV levels [deduced from measured $E2/M1$) mixing ratios] are again of about the same magnitude as those reported by Endt[21] for this region of nuclear masses.

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