Mean Lives of the 2.15- and 1.74-MeV Levels in ^{10}B

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The mean lives of the 2.15- and 1.74-MeV levels of ^{10}B were measured by the Doppler-shift attenuation method. The reaction ^{11}B(^{3}He,^{4}He)^{10}B was used and the direction of the recoiling ^{10}B nuclei was selected by a coincidence technique. The mean lives were found to be $(1.41\pm0.17)\times10^{12}$ sec for the 2.15-MeV level and $(1.52\pm0.24)\times10^{-13}$ sec for the 1.74-MeV level. The results are compared with estimates based on the independent-particle model. The mean lives of allowed $M1$ transitions are found to agree with these estimates. Evidence was found for the inhibition of an $M1$ transition for which $\Delta T=0$ in a self-conjugate nucleus, and for enhancement of an $E2$ transition.

I. INTRODUCTION

THE extent of collective effects in light nuclei has been the subject of some theoretical study.[1] Also of interest have been the effects of isotopic-spin selection rules which inhibit some transitions for which $\Delta T=0$ in self-conjugate nuclei. The 2.15- and 1.74-MeV excited states of ^{10}B offer an opportunity to study both of these effects. In the experiment described here the mean lives of these two states have been measured by the Doppler-shift attenuation method and compared with values calculated from the independent-particle model.

II. THE ATTENUATED DOPPLER-SHIFT METHOD

The method of measuring nuclear mean lives by atteunuated Doppler shifts has been described in detail by several authors,[2–4] so only a brief discussion will be given here. The method can be applied to nuclear states with mean lives between approximately 2×10^{-14} and 2×10^{-12} sec which decay by the emission of γ radiation to lower states. The excited nuclei are produced by a reaction in which velocities of the order of 10^{-2} times the velocity of light are imparted to the nuclei. They are then slowed down by a backing on which the thin target is supported. Thus, for those mean lives lying in the range suited to this method, the nuclei will have a mean velocity at emission somewhat less than the initial velocity they had upon formation of the state. The mean final velocity can be determined from the Doppler shift of the γ-ray energy given by

$$E_L-E_0=\Delta E=E_0(\bar{v}/c)\cos\theta\,, \quad (1)$$

where ΔE is the difference between E_0, the γ-ray energy in the rest frame of the nucleus, and E_L, the energy of the γ ray in the laboratory frame. θ is the angle between the direction of the recoiling nucleus and that of the γ ray, and $\bar{v}/c$ is the ratio of the mean final velocity of the moving ion to the velocity of light. In order to lessen the dependence of the measurement of the mean final velocity on the energy calibration of the apparatus, the γ ray was observed at two angles. To obtain the largest measurable shift these angles were chosen to be 0° and 180° to the direction of the recoiling nucleus.

The initial velocity of the recoiling nucleus is determined from the kinematics of the reaction. In the case studied here the reaction ^{11}B(^{3}He,^{4}He)^{10}B was used to form excited states of ^{10}B. This reaction has a Q value of 9.121 MeV, which is sufficiently large compared to the ^{3}He energy of 1.8 MeV to make the velocity distribution of the recoiling ^{10}B almost isotropic in the laboratory coordinate system. That is, the net mean velocity is too small to give a detectable Doppler shift. Thus it is necessary to select ^{10}B nuclei recoiling in a given direction by counting only those γ rays which are in coincidence with α particles emitted at a fixed angle to the beam. This uniquely determines the direction and magnitude of the initial velocity of the recoiling ^{10}B*.

The difference between the initial velocity and mean final velocity of the excited recoiling nucleus is directly related to its mean life through the stopping power of the slowing-down material. This can be shown by noting that

$$dE/dx=m(dv/dt)\,, \quad (2)$$

where E is the energy of the recoiling nucleus of mass m_1, and x is the distance traveled in the stopping material. Rearranging and integrating one obtains:

$$\text{mean life}=\int_{v_0}^{\bar{v}_f} m\left(\frac{dE}{dx}\right)^{-1} dv\,. \quad (3)$$

III. EXPERIMENTAL PROCEDURE

A beam of 1.8-MeV ^{3}He nuclei was produced by the Van de Graaff accelerator at the University of Arizona. It was directed at thin (20 μg/cm^2) ^{11}B targets evaporated on either copper or magnesium backings. The high stopping power of the copper is preferred for short-lived states and the low stopping power of the magnesium for long-lived states. The energy lost by the ^{10}B in the target is small (less than 3%) so that the

[1] D. Kurath, Phys. Rev. **101**, 216 (1956).
[2] S. Devons, G. Manning, and D. St. P. Bunbury, Proc. Phys. Soc. (London) **A68**, 18 (1955).
[3] E. K. Warburton, D. E. Alburger, and D. H. Wilkinson, Phys. Rev. **129**, 2180 (1963).
[4] A. E. Litherland, M. J. L. Yates, B. M. Hinds, and D. Eccleshall, Nucl. Phys. **44**, 220 (1963).

error incurred by neglecting the difference in the stopping powers of ^{11}B and copper or magnesium is very small.

The α particles were detected by a silicon surface-barrier detector with a sensitive area of 200 mm^2 placed at 1.5 cm from the beam. A $\frac{1}{2}$-mil Mylar cover over the detector prevented elastically scattered ^3He nuclei from reaching the counter. For the mean-life measurement of the 1.74-MeV level the α-particle detector was placed at 90° to the beam. Angular distribution measurements indicated that at this angle the population of the 2.15-MeV level relative to the 1.74-MeV level was a minimum. This was necessary in order to minimize the contribution to the population of the 1.74-MeV level by γ-ray transitions from the 2.15-MeV level. Since the higher energy level is long-lived, the nuclei would be moving slowly on the average after such a transition. For the mean-life measurement of the 2.15-MeV level the α-particle detector was set at 110° to the beam. Angular-distribution measurements indicated a maximum in the population of the 2.15-MeV level at this angle. Further, since for α particles going in the backward directions the velocities of the recoiling ^{10}B nuclei and the Doppler shift are larger than for α particles going in the forward directions, this choice improved the accuracy of the experiment.

The γ rays were detected by a 3-×3-in. NaI(Tl) crystal and photomultiplier connected to a multichannel analyzer. The front face of the crystal was 4 in. from the target and in the plane defined by the beam and the α-particle detector. For measurements on the 1.74-MeV level, the ^{10}B nuclei recoiled at 65° to the beam and the γ rays were detected at 65° and −115° to the beam. For measurements on the 2.15-MeV level, the ^{10}B nuclei recoiled at 48° to the beam but it was convenient to detect the γ radiation at 65° and −115°. This lack of optimum conditions resulted

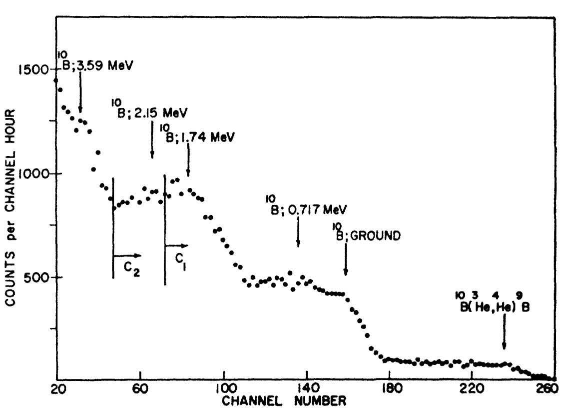

FIG. 1. Pulse-height spectrum of α particles from $^{11}B(^3He,^4He)^{10}B$ at 90° to the ^3He beam. The ^3He nuclei had an energy of 1.8 MeV. The detector was covered by $\frac{1}{2}$-mil of Mylar. C_1 and C_2 are the acceptance criteria for the coincidence pulses in the measurements on the 1.74-MeV level and the 2.15-MeV level, respectively.

in a loss of about 4% of the shift. The finite size of the NaI(Tl) crystal had to be accounted for by averaging $\cos\theta$ over the crystal dimensions.

The pulses from the α-particle detector and amplifiers were discriminated and shaped before being put into the coincidence gate. For measurements on the 1.74-MeV level the discriminator was set approximately so that pulses from that level were passed while those from the 2.15-MeV level were not. However, because of the poor energy resolution resulting from the large spread of angles accepted by the α-particle detector, it was not possible to make this setting precisely. The spectrum of α particles from the detector is shown in Fig. 1, together with the position of the discriminator setting. For measurements on the 2.15-MeV level the discriminator was set to pass all pulses produced by α particles to levels below the 3.59-MeV level in ^{10}B, as indicated in Fig. 1.

The coincidence circuit was that incorporated in the multichannel analyzer and had a resolving time of about 2 μsec. The ratio of true to chance coincidences was obtained by counting under experimental conditions with the exception that the pulses from the α-particle detector were put out of time coincidence with the γ rays by 2 μsec. The counting rate obtained in this way was compared to the experimental counting rate. The beam current was adjusted so that the ratio of true to chance coincidences was always greater than 3:1. A typical beam current under these circumstances was 0.5 μA. The contribution of chance coincidences to the peak under consideration is Doppler broadened but, due to the small mean velocity of noncoincident recoiling ^{10}B nuclei, it is not measurably shifted. This contribution was found to make no detectable error in the shift measurement.

Since stopping-power data for ^{10}B in copper and magnesium are not available, conversions were made from data for boron in nickel and aluminum displayed in the compilation by Northcliffe.[5] The stopping powers in this compilation have an estimated uncertainty of approximately 10%. The conversions were made using the theoretical formula developed by Lindhard and Scharff[6] for the electronic stopping power per atom, which is

$$-\frac{d\mathcal{E}}{dx}=\xi_e\frac{8\pi e^2}{a_0}\frac{Z_1Z_2}{(Z_1^{2/3}+Z_2^{2/3})^{3/2}}\frac{v}{v_0}, \qquad (4)$$

where ξ_e is not a rapidly varying function of the properties of the stopping material. Z_1 and Z_2 are the charges of the moving ion and the stopping material. a_0 is the Bohr radius of the electron and e is its charge. v/v_0 is the ratio of the velocity of the moving ion to $e^2/\hbar$. The formula agrees to within 15% of experimental values[3] of stopping power for the region $v/c=0.35\times10^{-2}$, where c is the velocity of light in a vacuum. However,

[5] L. C. Northcliffe, Ann. Rev. Nucl. Sci. **13**, 67 (1963).
[6] J. Lindhard and M. Scharff, Phys. Rev. **124**, 128 (1961).

for the purpose of conversions from one stopping material to another where the dependence on velocity cancels, it was assumed that this formula is a good approximation up to $v/c=2.7\times10^{-2}$, corresponding to the initial velocity of the ^{10}B nuclei in this experiment. The conversion was made by means of the multiplicative factor as shown below:

$$\left.\frac{dE}{dx}\right|_a=\left(\frac{A_b}{A_a}\right)\left(\frac{Z_a}{Z_b}\right)\left(\frac{Z_b^{2/3}+Z_1^{2/3}}{Z_a^{1/2}+Z_1^{2/3}}\right)^{3/2}\left.\frac{dE}{dx}\right|_b, \quad (5)$$

where A_i and Z_i are the atomic mass number and charge of the ith stopping material and Z_1 is the charge of the moving ion, boron. The correction applied to the data for nickel and aluminum to obtain stopping power for copper and magnesium was itself small (about 5%), and the error introduced by this correction into the uncertainty in stopping power is negligible compared to experimental error in the stopping-power data. The stopping-power curves were then used to plot $(dE/dx)^{-1}M(^{10}\text{B})/m_p$ versus velocity of the recoiling ^{10}B nuclei shown in Fig. 2. The upper end point v_0 is determined by the kinematics, and the lower end point $\bar{v}$ by the Doppler shift of the γ-ray peak. The mean life of the emitting state is proportional to the area between these end points under the appropriate curve in Fig. 2. The proportionality constant involves the conversion of units only. The error in the mean life is proportional to the errors in area under these curves which depends on the uncertainty of the stopping power and the error in the measurement of the mean final velocity.

IV. RESULTS

1.74-MeV Level

The mean life of the 1.74-MeV level in ^{10}B was determined from the Doppler shift of the 1.02-MeV γ ray from the $1.74\rightarrow0.72$-MeV transition, the only one which occurs. An example of the coincidence

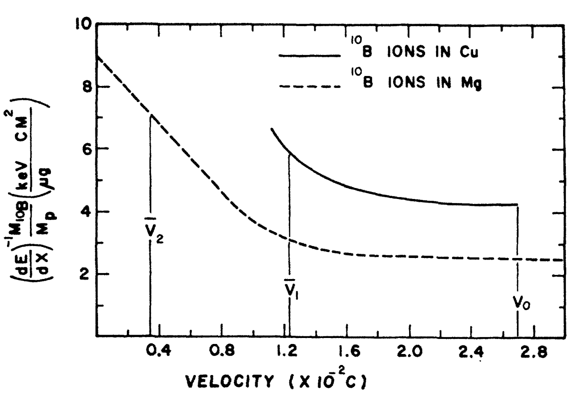

FIG. 2. Inverse stopping power times the ^{10}B mass number versus boron velocity. V_0 is the initial velocity of the excited recoiling ^{10}B nuclei, $\bar{V}_1$ and $\bar{V}_2$ are the mean final velocities for the recoiling ^{10}B nuclei in the 1.74-MeV level and the 2.15-MeV level, respectively.

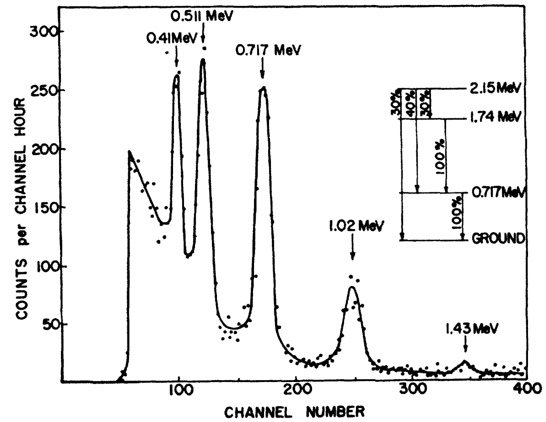

FIG. 3. Pulse-height spectrum of γ rays in coincidence with α particles satisfying the criterion C_1 of Fig. 1. This is typical of the spectra used to determine the mean life of the 1.74-MeV level. The multichannel-analyzer sensitivity was set so as to count only in channels above about 60.

spectrum obtained with the discriminator set at C_1 (see Fig. 1) is shown in Fig. 3. The 0.511-MeV peak in the spectrum results from chance coincidences of annihilation radiation from positrons from ^{13}N produced by $^{11}\text{B}(^3\text{He},n)^{13}\text{N}$ reactions. The 0.41-MeV γ rays came from the $2.15\rightarrow1.74$-MeV transition in ^{10}B and from neutron-induced reactions in the NaI(Tl) crystal. The other γ rays are from the other transitions in ^{10}B indicated in the figure. As mentioned in the last section, when measuring the shift of the 1.02-MeV peak the fact that the 2.15-MeV level decays about one-third of the time through the 1.74-MeV level must be taken into account. The magnitude of this contribution was determined by estimating the population of the 2.15-MeV level relative to the 1.74-MeV level from the ratio of counts in the 1.02-MeV peak to those in the 1.43-MeV peak produced by transitions from the 2.15-MeV state to the 0.72-MeV state. This ratio combined with differences in counting efficiency and the known branching ratios of the 2.15-MeV state[7] showed that less than one-seventh of the 1.02-MeV peak resulted from cascades from the 2.15-MeV level. The effect of the contribution of these cascade γ rays was shown to be too small to be seen in these measurements.

The reason the 0.41-MeV peak was not used to estimate the magnitude of this correction is that much of that peak resulted from chance-coincident γ rays from neutron-induced reactions in the NaI(Tl) crystal. The excitation of levels around 0.4-MeV in NaI(Tl) crystal was the result of inelastic scattering of neutrons produced in the reactions $^{11}\text{B}(^3\text{He},n)^{13}\text{N}$ and $^{10}\text{B}(^3\text{He},n)^{12}\text{N}$. A separate measurement using a Pu-Be neutron source was made to determine the magnitude of the γ rays from this process. Alpha particles from an ^{241}Am source were used to provide random pulses to the coincidence gate at a known rate, and the chance-coincident γ rays

[7] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 11, 1 (1959).

produced by (n,n') reactions in the crystal were then counted. By this procedure it was found that the γ rays from the neutrons inelastically scattered were sufficient to account for about 50% of the 0.41-MeV peak.

After subtracting the background and making the correction for the unshifted 1.02-MeV γ rays in the cascade from the 2.15-MeV level, the shift from five runs in the forward and backward directions was determined to be 7.25 ± 0.5 channels in 246 channels. The error is the square root of the sum of squared deviations from the sample mean. This shift corresponds to a mean final velocity of $(1.54\pm0.11)\times10^{-2}$ times the velocity of light. The mean life of the 1.74-MeV level is then determined to be $(1.52\pm0.24)\times10^{-13}$ sec. The error in the determination of the mean final velocity and the 10% uncertainty in stopping power of the copper backing contribute approximately equally to the error in the mean life.

2.15-MeV Level

The mean life of the 2.15-MeV level was determined from the Doppler shift of two of its three possible decay modes, the 0.41-MeV γ ray from the $2.14\rightarrow1.74$-MeV transition, and the 1.43-MeV γ ray from the $2.15\rightarrow0.72$-MeV transition. For measurements on this level, a magnesium-backed target was used. An example of the coincidence spectrum obtained with the discriminator set at C_2 (see Fig. 1) is shown in Fig. 4. For this curve the discriminator was set to pass all the pulses produced by α particles to the 2.15-MeV level. As a result the number of 0.41-MeV γ rays in true coincidence with α particles was much larger than the number of 0.41-MeV γ rays from chance coincidences. This is in contrast to the situation depicted in Fig. 3. The 0.41-MeV γ-ray peak had good statistics and the proximity of the 0.511-MeV annihilation peak offered a good reference from which to measure the shift. However, since the Doppler shift is proportional to the γ-ray energy, in this case it was small and difficult to measure accurately. Four independent hour-long runs in each direction were made giving a Doppler shift of 0.55 ± 0.13 channels in 85 channels. The error is again the square root of the sum of squared deviations from the sample mean. This shift corresponds to a mean final velocity of $(10.5\pm2.4)\times10^{7}$ cm/sec.

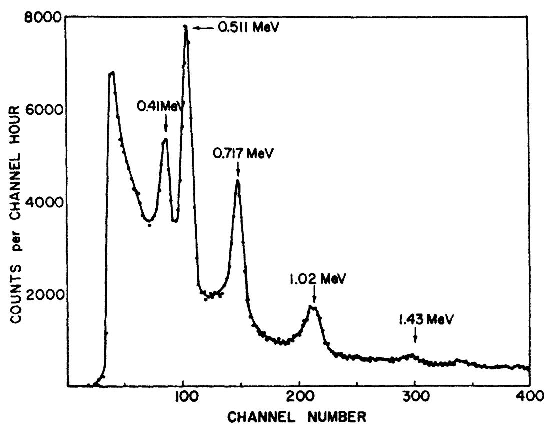

FIG. 4. Pulse-height spectrum of γ rays in coincidence with α particles satisfying the criterion C_2 of Fig. 1. This is typical of the spectra used to determine the mean life of the 2.15-MeV level. The multichannel-analyzer sensitivity was set so as to count only in channels above about 60.

Although the shift of the 1.43-MeV γ-ray peak was three times that of the 0.41-MeV γ-ray peak, the 1.43-MeV peak had poor statistics. The shift was measured from the same four runs described above and was 1.6 ± 0.8 channels in 300 channels, which gives a mean final velocity of $(9.0\pm4.5)\times10^{7}$ cm/sec. The value adopted for the mean final velocity was $(10.2\pm2.4)\times10^{7}$ cm/sec. This velocity together with the stopping-power data gave $(1.43\pm0.17)\times10^{-12}$ sec for the mean life of the 2.15-MeV level. The mean life is not sensitive to the error in the measurement of the mean final velocity because the mean life depends on the difference between the initial velocity and the mean final velocity which is very large compared to the error in mean final velocity. Thus most of the error in the mean life results from the 10% uncertainty in the stopping-power data.

V. CONCLUSIONS

The mean life of the 1.74-MeV level in ^{10}B is $(1.52\pm0.24)\times10^{-13}$ sec, which is 7.5 times the Weisskopf limit.[8] This is in good agreement with the estimate of Wilkinson[8] that $M1$ mean lives in this portion of the periodic table are about 7 times the Weisskopf limit.

The mean life of the 2.15-MeV level is $(1.41\pm0.17)\times10^{-12}$ sec. If we assume the branching ratios[7] 3:4:3 are correct, the $M1$ transition to the 1.74-MeV level, for which $\Delta T=1$, is a factor of 12 slower than the Weisskopf limit, also in reasonably good agreement with Wilkinson's estimate. The $M1$ transition to the 0.72-MeV level, for which $\Delta T=0$, is 500 times slower than the Weisskopf limit and about 70 times slower than Wilkinson's revisions to the Weisskopf estimate. This is evidence of the isotopic spin selection rule which inhibits $M1$ transitions in self-conjugate nuclei for which $\Delta T\neq\pm1$.[9] The $E2$ transition to the ground state is 5 times faster than the Weisskopf limit. This supports other evidence[10] that even for nuclei with A as low as 10 some collective motion must be considered in order to adequately describe quadrupole transitions.

ACKNOWLEDGMENT

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[8] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, pp. 852–889.
[9] G. Morpurgo, Phys. Rev. **110**, 721 (1958).
[10] E. K. Warburton, D. E. Alburger, and D. H. Wilkinson, Phys. Rev. **129**, 2191 (1963).