Lifetime Measurements for the First Excited States of O^{17} and B^{10} from Recoil Studies*

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(Received August 24, 1953)

The following lifetimes have been measured: O^{17} 870-kev level, $(2.5\pm1)\times10^{-10}$ sec; B^{10} 720-kev level, $(7\pm2)\times10^{-10}$ sec. These values are compared with theoretical estimates based on the independent-particle model. Core excitation is required to explain the O^{17} lifetime.

THE measurement of the distance traversed by an excited recoil nucleus before de-excitation can be used for determining lifetimes of the order of 10^{-11} sec or longer.[1] We have applied this method to the γ rays emitted by the first excited states of O^{17} (870 kev) and B^{10} (720 kev).[2] These states were excited by deuteron-induced reactions on O^{16} and Be^9; a schematic view of the experimental setup is shown in Fig. 1. A collimated deuteron beam ($\frac{1}{8}$-in. diam) strikes a thin target mounted on a Ni backing (0.6 mg/cm^2) and the recoils are ejected into vacuum. The γ rays are detected by means of a NaI(Tl) spectrometer[3] (10 channels) of 8 percent resolution for the 870-kev photopeak. The crystal sees the region accessible to the recoils through a tungsten collimator and subtends a solid angle of 5×10^{-4} steradians. Mechanical displacement of the target with respect to this collimator enables one to vary the distance of flight of the recoils seen by the detector.

$O^{16}(d,p)O^{17*}$. The targets consisted of thin uniform SiO layers on Ni backing foils; the SiO was directly evaporated onto these foils. They were bombarded with 0.5 μa of deuterons of 1.32 Mev. Some preliminary runs with thin mica gave reproducible results, but these were discarded as these targets displayed some change in appearance after long bombardments. The thickness of these SiO targets was determined in a magnetic spectrometer[4] by measuring the energy loss, in the SiO layer, of monoenergetic protons scattered by the Ni foil. The result was 18 kev (for protons of 1230 kev); the uniformity of the targets, checked by the same method, was found to be better than 10 percent.

Figure 2 shows a comparison of the results obtained with theoretical curves calculated for various lifetimes. The magnitude of the effect is seen by comparison with the points obtained (curve B) with targets covered by a Ni foil thick enough to stop all recoils. Curve B represents the transmission of the collimator and should ideally be a step function. Its rounded-off edges determine the resolution of the set-up, which is seen to be of the order of 0.1 mm. The curve obtained without the additional Ni backing intersects curve B at a point which corresponds to the fraction of recoils escaping in the forward direction from the target; in the case illustrated in Fig. 2 this fraction is 0.8.

To calculate theoretical curves such as shown in Fig. 2, the range-velocity relation for the recoils as well as their angular distribution have to be known. For simplicity we assumed that R depends linearly on v, an assumption which finds some support in the available data.[5] The critical parameter is clearly the ratio, $f=t/R_M$, of the thickness, t, of the target to the maximum range, R_M, of the (forward) recoils. While the value of t is determined experimentally as indicated above with fair accuracy, R_M is known to only about

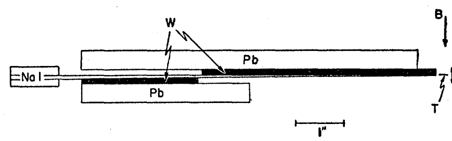

FIG. 1. Experimental set up. T = target, B = beam. Vacuum enclosure of target, mechanical means for moving it in direction of double-headed arrow, and equipment associated with the NaI crystal are not shown.

20 percent. In calculating the probability $W(z,\theta)d\theta$ that a recoil of radiative lifetime τ, emitted with an initial velocity $v_0(\theta)$ at an angle θ with respect to the normal, Z, to the target, radiates after traversing a distance z from the target surface it is convenient to measure the velocity component along Z, $v_0^{(z)}(\theta)$, in units of $v_0(0)$ and z in units of $v_0(0)\tau$, i.e., to introduce the dimensionless variables

$$u=v_0^{(z)}(\theta)/v_0(\theta)=v_0(\theta)\cos\theta/v_0(0), \quad \text{and} \quad x=z/v_0(0)\tau.$$

One finds easily

$$W(x,\theta)=\begin{cases}(u/f)F(x/u)-(1/f)(u-f)F(x/(u-f)) & \text{for } \theta\leqslant\theta_c,\\ (u/f)F(x/u) & \text{for } \theta>\theta_c,\end{cases}$$

* Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

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[1] J. C. Jacobsen, Phil. Mag. 47, 23 (1924); Devons, Hereward, and Lindsay, Nature 164, 586 (1949).

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

[3] H. H. Woodbury, thesis, California Institute of Technology, 1953 (unpublished).

[4] We are indebted for these measurements to Prof. W. A. Fowler and his group.

[5] P. M. S. Blackett and D. Lees, Proc. Roy. Soc. (London) A134, 658 (1932), and other papers discussed in reference 2.

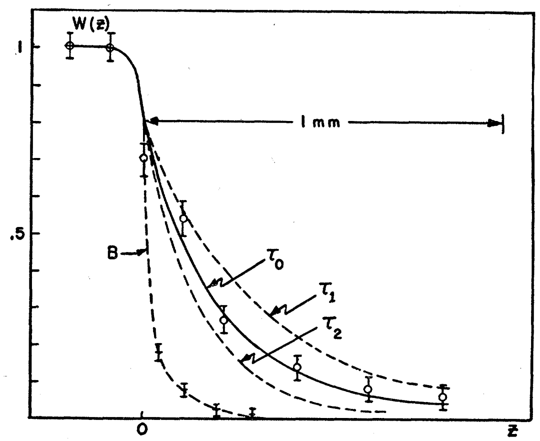

FIG. 2. Normalized intensity $W(z)$ *vs* target position z for 870-kev γ ray from $O^{16}(d,p)O^{17*}$ at 1.32-Mev deuteron energy. SiO target, 0.77-mm air equivalent (f=0.51); B=experimental curve obtained with target covered with Ni foil. The theoretical curves were calculated for the following lifetimes in units of 10^{-10} sec: $\tau_0=2.5$, $\tau_1=3.75$, $\tau_2=1.67$.

where θ_c is that "critical" angle for which the projected range, $t/\cos\theta_c$, is just equal to the range of the recoils, $t/\cos\theta_c\equiv R(v_0(\theta_c))$, while $F(y)\equiv\exp[-y]-y\int_y^\infty \exp[-\eta]d\eta/\eta$. $W(x,\theta)$ has to be weighted with the angular distribution of the recoils and integrated over θ. This was done numerically, using a distribution interpolated from published data;[6] effects of scattering in the target, which are estimated to be small, were not considered at this point. Figure 3 shows the distributions $W(x)$ obtained for various values of f. For the purposes of this experiment, it is practical to use thicknesses such that $0<f<1$; thus 18 kev correspond to $f=0.51$. One sees that in this range f influences mainly the fraction of recoils stopped in the target, $1-W(0)$. This quantity, which is difficult to determine accurately, becomes thus the principal source of uncertainty in the fitting of theoretical curves to the experimental data and therefore in the determination of the lifetime.

The curves in Fig. 2 represent theoretical distributions corrected for scattering[7] and for the deviation of the transmission of the collimator from an ideal step function. The solid curves through the experimental points were calculated for a lifetime of 2.5×10^{-10} sec, and the dashed ones for lifetimes of 3.75×10^{-10} and 1.7×10^{-10} sec, respectively.

We conclude that the lifetime of the 870-kev state of O^{17} is $(2.5\pm1)\times10^{-10}$ sec. This transition to the ground state is $E2$, $1/2^+\rightarrow5/2^+$, assigned to the extra neutron as $s_{\frac{1}{2}}\rightarrow d_{\frac{5}{2}}$ in the $j-j$ independent particle model (IPM). This description predicts[8] for a *proton* making the same transition a lifetime of 8×10^{-11} sec (using a "radius" of $1.5A^{\frac{1}{3}}\times10^{-13}$ cm), whereas a neutron outside the O^{16} core should yield a lifetime $Z^{-2}A^4$ times longer, i.e., 10^{-7} sec, due entirely to the motion of the core. To fit the observed lifetime on this picture, one has to assume a 2.9 times larger "radius," which does not appear reasonable. The observed lifetime can, however, be explained in terms of small departures from the extreme IPM, as the following somewhat rough argument shows: Write the wave function of O^{17} in its ground state as

$$\Psi(O^{17})=a_0\varphi_{d\frac{5}{2}}(n)\psi_0(O^{16})+a_2\varphi_{s\frac{1}{2}}(n)\psi_{2+}(O^{16})+\cdots,$$

where $\psi_{2+}(O^{16})$ describes a "collectively" excited state of the core and $|a_2|^2/|a_0|^2<1$, and for the excited state as

$$\Psi(O^{17*})=b_0\varphi_{s\frac{1}{2}}(n)\psi_0(O^{16})+b_2\varphi_{d\frac{5}{2}}(n)\psi_{2+}(O^{16})+\cdots.$$

Now, if the transition probability,

$$|\varphi_{s\frac{1}{2}}(n)\psi_{2+}(O^{16})H(E2)\varphi_{s\frac{1}{2}}(n)\psi_0(O^{16})|^2,$$

is assumed to be 20 times larger than the one previously considered for single proton transition, one sees that $|a_2|^2/|a_0|^2$ needs only to be 2/100 to fit the experimental result. This deviation does not necessarily conflict with the small quadrupole moment[9] of O^{17}.

$Be^9(d,n)B^{10*}$. Thin Be foils[10] where bombarded with deuterons at different energies. Best results were obtained at 1.32 Mev with targets of 40 $\mu g/cm^2$. The experimental points are shown in Fig. 4. Their interpretation is not quite straightforward, because the

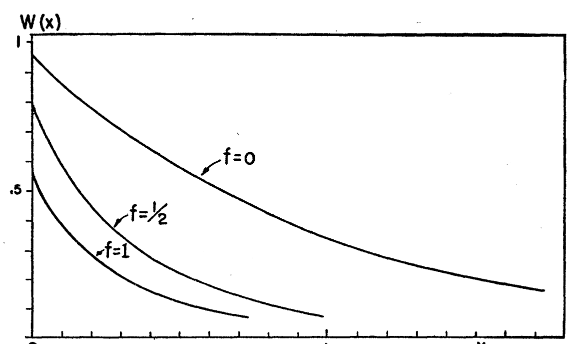

FIG. 3. Theoretical curves $W(x)$ *vs* $x=z/v_0(0)\tau$ for different ratios f of the target thickness t to the maximum range R_M of the recoils.

[6] N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948).

[7] $\langle\theta^2\rangle$, the mean square angle of multiple scattering, is 0.04 for an O^{17} ion traversing an SiO layer of the thickness of our targets with a *constant* average velocity 10^8 cm/sec and an effective charge $z^*=1$, which is slightly larger than the value predicted by J. K. Knipp and E. Teller, Phys. Rev. **59**, 659 (1941). The value of $\cos\theta$ being reduced by a factor $\exp[-\theta^2/4]$, the effect of multiple scattering appears to be small for such velocities. On the other hand, for slower recoils, say for those leaving the target with velocities of $\sim5\times10^7$ cm/sec, it will be appreciable, leading to quasi-isotropy. In modifying the theoretical curves we assumed complete isotropy for the "slow" recoils as defined above. This procedure, which incidentally tends to overemphasize the effect of scattering, seems justified by the smallness of the correction.

[8] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951); S. A. Moszkowski, Phys. Rev. **83**, 1071 (1951).

[9] Geschwind, Gunther-Mohr, and Townes, Phys. Rev. **83**, 209 (1951).

[10] Courtesy of Dr. Hugh Bradner, Radiation Laboratory, University of California, Berkeley, California.

lowest (720-kev) level of B^{10} can be produced both directly and by γ decay from higher states (1.76, 2.15, and 3.6 Mev). To calculate the curve for a given lifetime, one has to know the relative intensities and angular distributions of the neutrons leading to all the states involved. Lacking this information, we made the assumptions contained in Table I, based on available data.[11] Taking the lack of information just mentioned into account, we conclude that the lifetime is $(7\pm2)\times10^{-10}$ sec.

TABLE I. Assumptions on the transitions leading to the 720-kev level of B^{10} in $Be^9(d,n)B^{10}$.

B^{10} level (kev)	Contribution to the 720-kev γ ray (%)	C.m. distribution of neutrons
720	50	$1-\frac{1}{2}\cos^2\theta$
1740	8	1
2150	21	1
3580	21	1

In the IPM picture, the corresponding transition involving a single nucleon would lead a lifetime of 5×10^{-10} sec, which is a lower limit for the actual case in which two unpaired nucleons are coupled. A transition between two terms of a $(p_{\frac{3}{2}})^2$ configuration yields a value of 5×10^{-9} sec. The observed lifetime is thus compatible with the IPM picture.

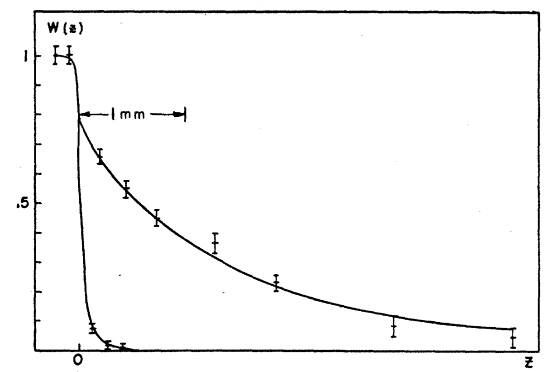

FIG. 4. Normalized intensity $W(z)$ *vs* target position x for 720-kev γ ray from $Be^9(d,n)B^{10*}$. Target 40 $\mu g/cm^2$ Be foil, $E_d=1.32$ Mev. Same notation as in Fig. 2. Theoretical curve calculated for $\tau=7\times10^{-10}$ sec.

It is a pleasure to express our gratitude for the kind hospitality received in this laboratory. We also wish to thank Professors C. C. Lauritsen, W. A. Fowler, and R. F. Christy for much assistance and helpful discussions. This experiment could not have been carried out without the electronic equipment built by Dr. H. H. Woodbury, to whom we are also indebted for much patient assistance.

[11] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 24, 347 (1952).