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Lifetimes of the First Excited States of B^{10} and Al^{28}†

J. C. SEVERIENS AND S. S. HANNA*
Department of Physics, The Johns Hopkins University, Baltimore, Maryland
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The lifetimes of the first excited states of B^{10} and Al^{28} have been measured by a recoil technique which incorporates coincidence counting. Recoil nuclei are produced in a unique manner which facilitates an accurate determination of the recoil velocity. Corrections to the velocity for target thickness were investigated experimentally. Lifetimes of $(8.5\pm2.0)\times10^{-10}$ sec and $(3.0\pm0.5)\times10^{-9}$ sec were obtained for the first excited states of B^{10} and Al^{28}, respectively.

INTRODUCTION

THE recoil motion imparted to a nucleus in a nuclear reaction or disintegration has been utilized by a number of investigators[1–4] in the measurements of nuclear lifetimes in the range 10^{-6} to 10^{-15} sec. As has been discussed by Devons *et al.*,[4] the various techniques fall into two categories: (1) a direct measurement of the mean distance traversed by the recoiling nuclei before radiating, and (2) observations on the Doppler energy shift produced by the recoil motion. The direct method has been used successfully for lifetimes down to about 10^{-11} sec; with the techniques involving the Doppler shift, the range has been extended to about 10^{-15} sec.

In this paper we describe a method for determining the mean distance traveled by a group of excited nuclei before radiating. The technique was devised in order to obtain greater sensitivity and to provide for a more straightforward determination of the recoil velocity than achieved in previous experiments. The method has been used to measure the lifetimes of the first excited states in B^{10} and Al^{28}. In addition, a negative result was obtained for the first excited state in Li^7 indicating, as expected, a lifetime too short for a technique involving a direct measurement of distance.

METHOD

The technique in its most useful form is illustrated in Fig. 1. In this application the radiation is preceded by the emission of a heavy particle. Consider, for example, a $(d,p\gamma)$ process. The thin target is oriented so that the beam traverses the backing (if a backing is required) before entering the active target. Recoil nuclei are therefore free to leave the target and travel in vacuum in the forward hemisphere. The state under study is isolated by observing $(p\text{-}\gamma)$ coincidences. This mode of detection provides two advantages: (1) recoiling, excited nuclei are produced in a unique manner so that the recoil velocity can be computed simply and accurately, and (2) the protons can be detected in a backward direction so that one utilizes only those recoils traveling in the forward direction and having the maximum velocity. The proton counter, therefore, is placed at 180° to the beam. The coincident gamma rays emitted by the forward moving nuclei are detected in a counter mounted at 0° to the beam. Between the target and the gamma counter a movable recoil stopper is inserted. The function of the stopper is to control mechanically the range of the recoil nuclei. As the stopper is moved the source of gamma radiation is effectively displaced resulting in a change in solid angle of detection. This change in yield can be easily related to the mean distance traveled by the excited nuclei which in turn is a function of the lifetime.

The method is not restricted to disintegrations in which the radiation is preceded by emission of heavy particles. In the B^{10} problem, for example, it was more convenient to detect gamma-gamma rather than neutron-gamma coincidences. Since the gamma-gamma process is itself preceded by neutron emission the recoils are not unidirectional, and it is necessary to know their angular distribution in order to interpret the measurements accurately.

There is in principle no need to confine the method to the use of coincidence detection. If the radiation under observation can be detected without excessive background and if the velocity distribution of the recoils is known, the technique of obtaining the yield of radiation as a function of recoil stopper position can be applied directly. Two possible applications of this direct approach would be to a (p,γ) capture process or

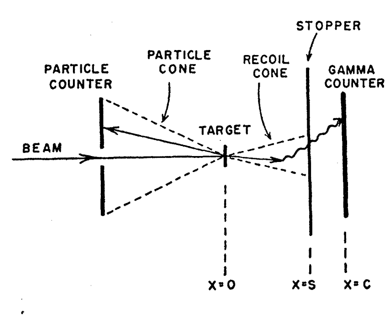

FIG. 1. Schematic diagram of the method, illustrating the notation. In addition, b = radius of gamma counter and δ = mean distance traversed by a recoil during its mean life.

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* Present address: Argonne National Laboratory, Lemont, Illinois.
[1] J. C. Jacobsen, Phil. Mag. **47**, 23 (1924); Nature **120**, 874 (1927); A. W. Barton, Phil. Mag. **2**, 1273 (1926).
[2] L. G. Elliot and R. E. Bell, Phys. Rev. **74**, 1869 (1948); **76**, 168 (1949); Rasmussen, Lauritsen, and Lauritsen, Phys. Rev. **75**, 199 (1949).
[3] Devons, Hereward, and Lindsey, Nature **164**, 586 (1949); J. Thirion and V. L. Telegdi, Phys. Rev. **92**, 1253 (1953).
[4] Devons, Manning, and Bunbury, Proc. Phys. Soc. (London) **A68**, 18 (1955).

to a $(p,n\gamma)$ reaction just above threshold, where p might be any heavy particle. In both these cases the excited nuclei are projected forward and it might easily be possible to isolate the radiation under study by straightforward energy discrimination in the gamma-ray detector.

In order to determine the optimum experimental conditions for the proposed technique, we may use expressions derived under the simplifying assumption of a point source and ideal collimation. It is also convenient here to assume that the gamma-ray counter can be represented by an ideal circular aperture having constant efficiency over its area. The notation used is given in Fig. 1.

If there are N_0 nuclei with constant velocity V being produced per sec at the source, then the number of these nuclei which travel a distance at least s before radiating is given by

$$N=N_0e^{-t/\tau}=N_0e^{-s/\delta},$$

where τ is the mean life and $\delta=V\tau$ the mean distance traveled by the excited nuclei. The counting rate from nuclei caught on the stopper is therefore

$$Y_s(s)=2\pi N_0e^{-s/\delta}\{1-[1+b^2/(c-s)^2]^{-\frac{1}{2}}\}. \quad (1)$$

The expression within the curly brackets (times 2π) gives the solid angle subtended by the gamma counter at the stopper, a distance $c-s$ away, where b is the radius of the counter. The counting rate from nuclei which decay before reaching the stopper is obtained by an integration

$$Y_q(s)=(2\pi N_0/\delta)\int_0^s e^{-x/\delta}\{1-[1+b^2/(c-x)^2]^{-\frac{1}{2}}\}dx. \quad (2)$$

The total yield, $Y(s)=Y_q+Y_s$, is a sensitive function of the stopper position s, provided the parameters b and c are properly chosen.

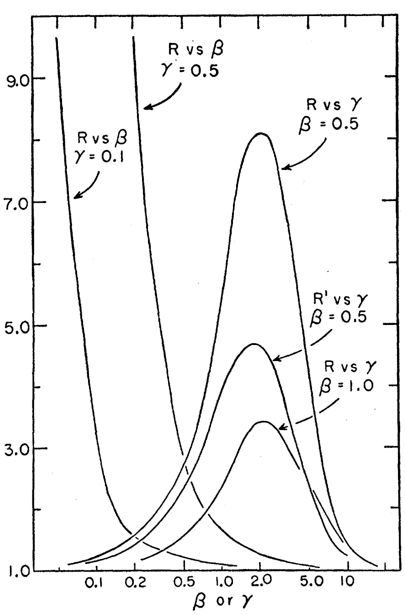

FIG. 2. Theoretical curves illustrating the sensitivity of the method as a function of various parameters.
$R=Y(c)/Y(0)$.
$R'=Y(0.8c)/Y(0)$.
$\beta=b/\delta$ and $\gamma=c/\delta$.

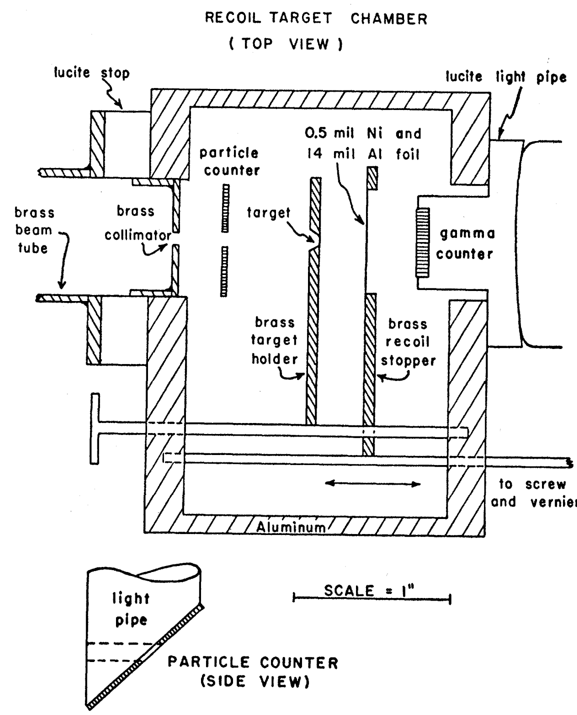

FIG. 3. View of the target chamber. The light pipe for the particle counter, with a beam hole passing through it, is also shown.

It is convenient to use the mean distance, $\delta=V\tau$, as a unit for measuring counter size and distance: $\beta=b/\delta$ and $\gamma=c/\delta$. We also define $R=Y(c)/Y(0)$. A measurement of this ratio is the simplest way of obtaining information from which the lifetime may be deduced.

For any given set of conditions, R is increased by making β as small as possible, as shown in Fig. 2, the only limitation being one of maintaining sufficient intensity. In practice values of β between one and three have been used. The optimum value of γ depends on β as well as being limited by the necessity of maintaining an adequate counting rate. For $0.02<\beta<3$, R is a maximum for $\gamma\simeq 2$, as illustrated in Fig. 2. For $\beta>3$, one obtains roughly $\gamma\simeq\beta$ as the optimum condition. In general, these values of γ are readily obtained experimentally.

In practice it is not possible to measure $Y(c)$. If a scintillating crystal is used for the gamma counter, the effective aperture is within the crystal, and the stopper position is limited by the front face of the crystal, as well as by the thickness of the stopper itself. For this reason it is desirable to use crystal detectors which are as thin as possible, the only limitation being that of maintaining an adequate counting efficiency. The effect of crystal thickness on the ratio R can be seen in Fig. 2. Fortunately, the requirement of thinness is compatible with keeping background from neutrons and high-energy gamma radiation at a minimum.

The stopper should be inert to the beam and as thin as possible to allow maximum displacement. In addition to stopping the recoil nuclei, it should also absorb the particles in the beam and all charged particles from the reaction as well. On the other hand, the stopper must be fairly transparent to the radiation emitted by the recoil nuclei, a requirement which is not always trivial when very low-energy radiations are studied.

A point source and ideal collimation of the recoils are not attainable experimentally. Under conditions for which the active spot on the stopper does not greatly exceed in area the aperture of the gamma counter, the simplified formulas given above are not greatly in error and the necessary corrections can be made in fairly straightforward fashion.[5] More importantly, good collimation is desirable for maximizing the ratio R and in

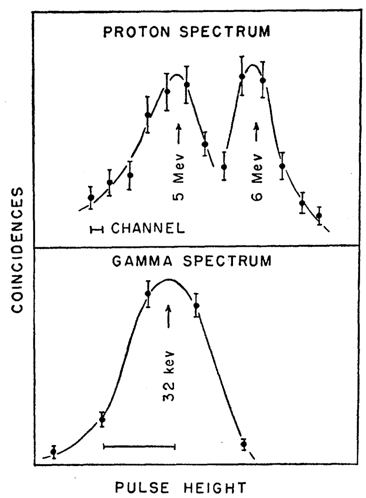

FIG. 4. Coincidence spectra obtained with the $Al^{27}(d,p)Al^{28}$ reaction. The proton spectrum was recorded with the gamma channel set on 32 kev. The gamma spectrum was recorded with the proton channel on 6.0 Mev. The proton group at 5.0 Mev represents an unresolved doublet. The coincidence response for this doublet arises from cascades through the 32-kev state. The lifetime data were obtained with the proton channel set on the 6.0-Mev group.

reducing the effect of an unknown anisotropy in the directional distribution of the recoils.

The dependence of the recoil velocity on the angle of emission of the recoil is easily calculated. The velocity in the vacuum, however, depends also on the amount of target material previously traversed by the recoil particle, and hence on the angle of emission as well as on the depth in the target at which the reaction occurred. The velocity distribution is further affected by scattering of the recoil before leaving the target. These effects of target thickness introduce the largest uncertainty into the lifetime measurement, since so little is known of the passage of heavy ions through various media. Insofar as it was possible, energy loss data were accumulated from the literature and reasonable extrapolations were made to the problem at hand. In addition, the measurements were carried out on targets of several

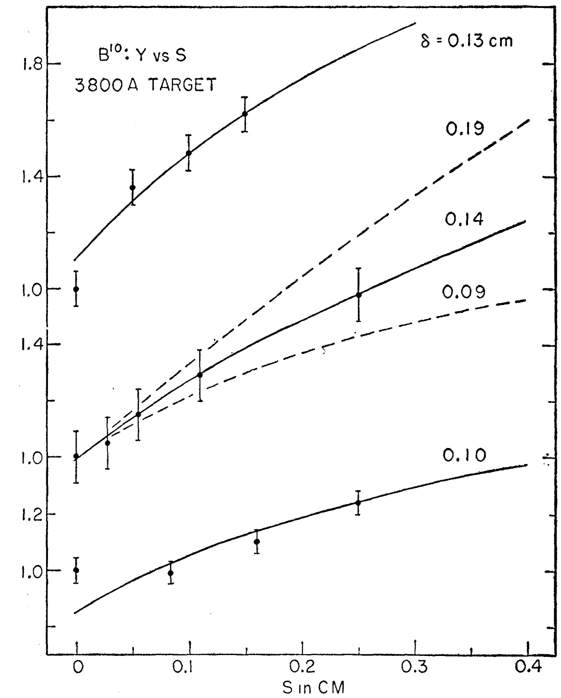

FIG. 5. Coincidence yield as a function of stopper position for the B^{10} recoils. The curves are calculated using the point source approximation.

different thicknesses and the results were compared with the energy loss data.

EXPERIMENTAL ARRANGEMENT

The target chamber is shown in Fig. 3. The incoming beam, collimated to a diameter of about 0.25 cm, passes through a hole in a vertical light pipe. The light pipe has an oblique end, to which is attached the scintillating

TABLE I. Measured ratios and corresponding values of the mean distance δ for the first excited state of B^{10}.

Target thickness A	Counter distance cm	R	δ cm
3800	0.15	1.48±0.09	0.13 ±0.05
	0.15	1.43±0.14	0.11 ±0.06
	0.16	1.24±0.06	0.05 ±0.02
	0.17	1.38±0.22	0.09 ±0.07
	0.25	1.41±0.11	0.09 ±0.03
	0.25	1.33±0.12	0.07 ±0.03
	0.25	1.54±0.08	0.12 ±0.03
	0.25	1.54±0.08	0.12 ±0.03
	0.26	1.33±0.07	0.07 ±0.02
	0.27	1.52±0.14	0.12 ±0.04
	0.27	1.45±0.14	0.10 ±0.03
	0.27	1.60±0.13	0.14 ±0.05
	0.45	1.42±0.16	0.10 ±0.03
			Av=0.10 ±0.01
7600	0.16	1.18±0.05	0.04 ±0.01
	0.24	1.09±0.06	0.03 ±0.01
			Av=0.035±0.01
Thick target	0.24	1.02±0.19	0.00 ±0.04

[5] Formulas for an extended source may be found in B. P. Burtt, Nucleonics 5, 28 (1949); Calvin, Heidelberger, Reid, Tolbert, and Yankwich, *Isotopic Carbon* (John Wiley and Sons, Inc., New York, 1949).

crystal for detection of the charged particles (in the Al^{28} problem). The target holder could be rotated from outside the chamber so that several targets could be used without breaking vacuum. The recoil stopper consists of 0.5 mil of nickel foil to stop the beam and then 14 mils of aluminum foil to protect the gamma counter from energetic charged particles. This stopper absorbs about 20% of the 32-kev radiation encountered in the Al^{28} problem. The scintillating crystal for detection of the gamma radiation is mounted behind the stopper in a well in a Lucite light pipe. The recoil stopper could be moved from outside the chamber by means of a precision screw, equipped with a scale and vernier which were accurate to about 0.05 mm. The target itself could also be displaced horizontally so that the crystal to target distance could be varied.

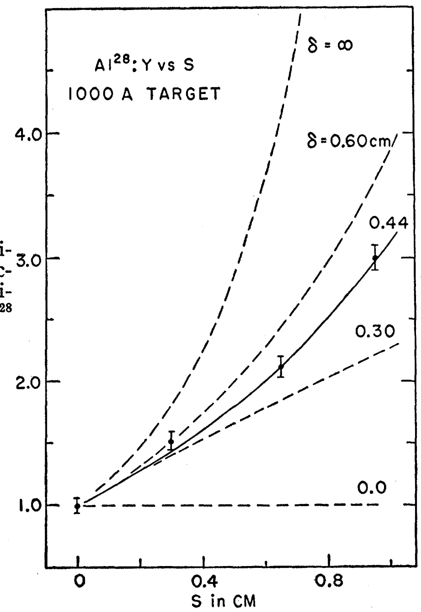

FIG. 6. Coincidence yield as a function of stopper position for the Al^{28} recoils.

The B^{10} nuclei were produced by means of the $Be^9(d,n)B^{10*}(\gamma)B^{10*}$ reaction, at $E_d=0.85$ Mev. The neutron angular distribution has been measured at this energy.[6] The targets were unsupported beryllium foils, either 15 or 30 microinches, The detector for 720-kev radiation from the first excited state was a NaI(Tl) crystal, approximately 2.2 mm thick and 6 mm in diameter. Coincidences were obtained between this radiation and the preceding 2.86-Mev gamma ray, which was detected with a NaI(Tl) crystal, 2 in. thick and 1.5 in. in diameter, mounted outside the target chamber.

The Al^{28} recoils were produced with the $Al^{27}(d,p)Al^{28*}$ reaction at $E_d=1.2$ Mev. Aluminum targets of thickness 500, 1000, 2000, and 4000 A were evaporated on nickel foils 1000 A thick. The scintillator for 32-kev

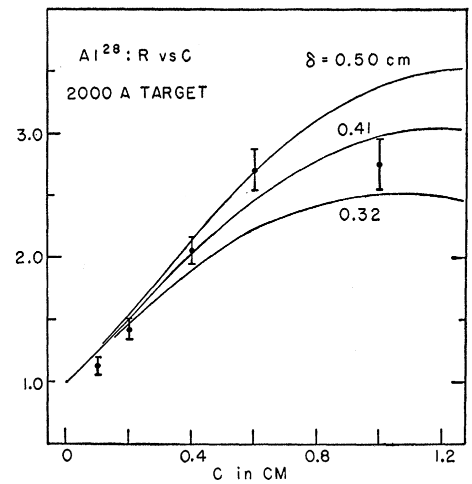

FIG. 7. The measured ratio R as a function of target to counter distance for Al^{28} recoils.

radiation from the first excited state was a NaI(Tl) crystal, 0.5 mm thick and 9 mm in diameter. In this reaction, p-γ coincidences were detected. The proton counter was a KI(Tl) crystal about 0.5 mm thick mounted on the oblique end of the light pipe. Energy discrimination was obtained with single channel discriminators, the outputs of which were analyzed in a coincidence circuit with a resolving time of about 10^{-7} sec. A monitor for accidental coincidences was also provided. Before each run, coincidence spectra were obtained in order to select the desired coincidences. Two such spectra are shown in Fig. 4.

RESULTS

The results for B^{10} are given in Fig. 5 and Table I. The curves in the figure and the values of δ in the table were computed with the point-source relationship:

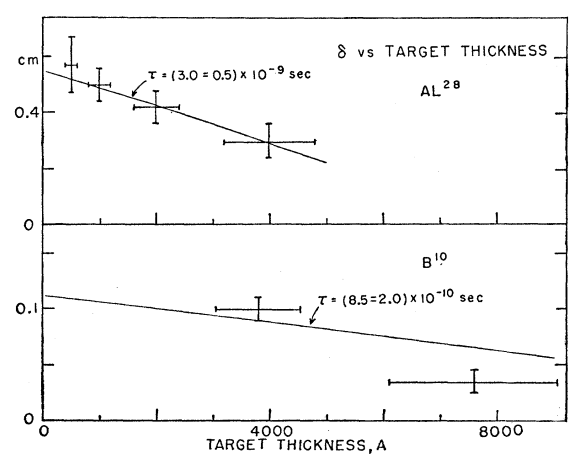

FIG. 8. Observed values of δ plotted against target thickness (in angstroms) for the Al^{28} and B^{10} problems. An error of 20% has been assigned to each foil thickness. The curves are based on available energy loss data and on the indicated value of the lifetime.

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[6] Pruitt, Swartz, and Hanna, Phys. Rev. 92, 1456 (1953); Green, Scanlon, and Willmott, Phil. Mag. 44, 919 (1953).

TABLE II. Measured ratios and corresponding values of the mean distance δ for the first excited states of Al^{28}.

Target thickness A	Counter distance cm	R		δ cm
500	1.00	3.90±0.55		0.63±0.14
	1.00	3.40±0.55		0.51±0.14
			Av=	0.57±0.10
1000	0.73	3.50±0.25		0.75±0.16
	0.95	3.00±0.12		0.44±0.03
			Av=	0.50±0.08
2000	0.10	1.12±0.07		
	0.20	1.42±0.09		
	0.40	2.05±0.11		
	0.60	2.70±0.16		
	1.00	2.74±0.19		
			Av=	0.41±0.06
4000	1.00	2.85±0.23		0.40±0.04
	1.00	2.22±0.15		0.30±0.03
	1.00	1.74±0.15		0.22±0.03
			Av=	0.30±0.06
>25 000	0.95	1.07±0.11		0.03±0.04
	0.95	1.20±0.12		0.08±0.04
	1.00	1.12±0.04		0.05±0.02
	1.00	0.93±0.06		−0.03±0.03
			Av=	0.03±0.03

(1) plus (2). The average values of δ from Table I are plotted against target thickness in Fig. 8. The curve in Fig. 8 was derived in the following manner. The velocity distribution of the recoils was computed from the associated neutron distribution,[6] and an approximate range-energy relationship for B^{10} particles was constructed by accumulating data for other nuclei[7] and making reasonable interpolations. An effective forward velocity for the recoils was calculated, as a function of target thickness, by numerical integration, taking into account deviations from the point source formula. By using $\delta = V\tau$ and a value of $\tau = 8.5\times10^{10}$ sec, the curve in Fig. 8 was obtained. In selecting a value of the lifetime to fit the data, more reliance was placed on the datum for the thinner targets. Many more runs under varying conditions were made with the thin targets. In addition, in our experience the buildup of surface layers of carbon was slower on the thinner foils. In general a fresh target was used after every run or two.

The value of $(8.5\pm2)\times10^{-10}$ sec is in good agreement with the result, $(7\pm2)\times10^{-10}$ sec, obtained by Thirion and Telegdi,[3] who used quite a different technique to determine the mean distance traversed by the recoils. As pointed out by these authors, the lifetime is compatible with estimates based on the independent-particle model.

The Al^{28} results are displayed in Figs. 6, 7, and 8 and in Table II. The treatment of the data is very similar to that for B^{10}. Since δ turned out to be greater for Al^{28}, it was possible to carry out the series of measurements depicted in Fig. 7. The agreement between these data and the theoretical curve would be improved if departures from the point source formula were included. It was also possible to obtain measurements for a greater variety of target thicknesses. Since energy loss data for particles as heavy as aluminum were not available, a range-energy curve, having the same functional dependence on velocity as for B^{10}, was adapted to fit the Al^{28} data in Fig. 8. As the Al^{28} recoils were confined to a 20° cone, the collimation was considerably better than for the B^{10} recoils, and the distribution within the cone was assumed isotropic. Deviations from the point source formula, however, were comparable in the two cases, since the stopper was moved farther from the target and closer to the gamma counter in the Al^{28} runs.

The internal conversion coefficient for the 32-kev transition is less than one,[8] indicating either dipole or quadrupole radiation. From a study of the angular distributions in the $Al^{27}(d,p)Al^{28}$, Al^{28*} reactions,[9] agreement is obtained with spin and parity assignments of 3^+ and 2^+ for the ground and first excited states of Al^{28}, respectively. The radiation is therefore either $M1$ or $E2$. The measured value of the lifetime, $\tau = 3.0\times10^{-9}$ sec, is compatible with the assumption of $M1$ radiation in estimates[10] of the lifetime ($\sim10^{-9}$ sec) based on the independent-particle model.

TABLE III. Measured ratios for the first excited state of Li^7.

Counter distance cm	R
0.1	0.95±0.12
0.6	1.00±0.15

In Table III is given briefly the outcome of an attempt to determine the lifetime of the first excited state in Li^7, as a test of the method. As expected, the technique fails in this case because the lifetime ($\sim10^{-13}$ sec) is too short.[2]

We would like to acknowledge the assistance of Mr. P. W. Milich in operating the Van de Graaff generator. We are grateful also to Mr. William G. Fastic for his skillful preparation of the aluminum targets.

[7] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. (London) **A134**, 658 (1932); N. Feather, Proc. Roy. Soc. (London) **A141**, 194 (1933); R. L. Anthony, Phys. Rev. **50**, 726 (1936); J. T. McCarthy, Phys. Rev. **53**, 30 (1938); W. Hansen and G. A. Wrenshall, Phys. Rev. **57**, 750 (1940); G. A. Wrenshall, Phys. Rev. **57**, 1095 (1940).

[8] R. D. Smith and R. A. Anderson, Nature **168**, 429 (1951); A. H. Wapstra and A. L. Veenendaal, Phys. Rev. **91**, 426 (1953).

[9] Enge, Buechner, Sperduto, and Mazari, Bull. Am. Phys. Soc. Ser. II, **1**, 212 (1956).

[10] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).