Lifetime of the 1.042-MeV State in ^{18}F†

A. E. BLAUGRUND,* D. H. YOUNGBLOOD, G. C. MORRISON, AND R. E. SEGEL‡
Argonne National Laboratory, Argonne, Illinois
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The lifetime of the 1.042-MeV $T=1$ state in ^{18}F was measured by use of the attenuated-Doppler-shift method. Analysis of the measurements by use of the universal stopping cross section given by Lindhard, Scharff, and Schiott give a mean life $\tau=(0.4_{-0.2}^{+0.3})\times10^{-14}$ sec. The experimental lifetime agrees with the value calculated from the corresponding Gamow-Teller β transition according to a relation given by Kurath. The accuracy of the universal stopping cross section is discussed.

INTRODUCTION

FOR transitions involving an isospin change $|T_f-T_i|=1$, Kurath[1] has shown that a simple relation exists between the strength of the Gamow-Teller β transition $(J_i=J_f,\ J_f\pm1;\ T_f\pm1;\ T_z\pm1)\rightarrow(J_f;\ T_f;\ T_z)$ and the $M1$ γ transition from the analog state $(J_i;\ T_f\pm1;\ T_z)$ to the same final state. Physically, this relationship comes about because both the Gamow-Teller β decay and the $M1$ γ decay can be described as a single nucleon making a spin flip. The moment due to the orbital motion will also contribute to the $M1$ transition, but this contribution is smaller by a factor of 5 and plays an important role only when the spin flip is suppressed. In several cases this relation has been verified experimentally by comparing the γ lifetime with the ft value of the corresponding β transition.[1] The discrepancy that existed in the mass-10 nuclei has been removed as a result of a recent measurement[2] of the lifetime of the 1.74-MeV level in ^{10}B.

For the 1.042-MeV $(J=0^+,\ T=1)$ level in ^{18}F, only an upper limit for the lifetime has been reported.[3] This upper limit was 50 times the mean life calculated from the ft value of the β decay. A measurement of the lifetime of this level by use of the attenuated-Doppler-shift technique is reported here.

MEASUREMENTS

In lifetime measurements employing the attenuated-Doppler-shift technique, two basic variants of the experimental arrangement are possible.[4] In the first, the difference between the energies of γ rays emitted at two different angles ϕ_1, ϕ_2 with respect to the recoil direction is measured for one stopping material. In order to maximize this difference, ϕ_1-ϕ_2 is chosen as large as possible. In the second, the difference in γ-ray energies is measured for the recoiling nuclei slowing down in different stopping materials while the emission angle of the γ-rays is kept constant, usually at 0° with respect to the recoil direction in order to maximize this energy difference. In either method, the lifetime is calculated from the observed shift in γ-ray energy.

The types of situation to which the two variants are applicable can be compared by considering the following simplified case in which it is assumed that all recoiling nuclei move in the direction $\phi=0°$ with velocity $v=v_0e^{-t/\alpha}$, where v_0 is the initial velocity of recoil and α is the slowing-down time in the stopping material. An example of the first variant is the determination of the attenuated Doppler shift from measurement of the shifted γ-ray energy $E_{\gamma\alpha}$ at $\phi=0°$ and the unshifted γ-ray energy $E_{\gamma0}$ at $\phi=90°$. The attenuated Doppler shift $E_{\gamma\alpha}-E_{\gamma0}$ is related to the lieftime τ of the level by

$$\frac{E_{\gamma\alpha}-E_{\gamma0}}{\Delta E_{\gamma\infty}}=\frac{1}{1+\tau/\alpha}=\frac{\alpha/\tau}{1+\alpha/\tau},\qquad(1)$$

where $\Delta E_{\gamma\infty}=(v_0/c)E_{\gamma0}=E_{\gamma\infty}-E_{\gamma0}$, and $E_{\gamma\infty}$ is the fully shifted γ-ray energy (realized by letting the nuclei recoil into vacuum).

An example of the second variant is the measurement of the energy difference of the γ rays emitted in the forward direction for two stopping materials with slowing-down times α and ∞. The energy difference $E_{\gamma\infty}-E_{\gamma\alpha}$ is related to the lifetime of the level by

$$\frac{E_{\gamma\infty}-E_{\gamma\alpha}}{\Delta E_{\gamma\infty}}=\frac{\tau/\alpha}{1+\tau/\alpha}.\qquad(2)$$

The appropriate variant to use in a given situation can be seen by considering the measurement of lifetimes for the two extreme cases of very short lifetime $(\tau/\alpha\ll1)$ and very long lifetime $(\tau/\alpha\gg1)$. The quantities of interest in the two experiments are $E_{\gamma\alpha}-E_{\gamma0}$ and $E_{\gamma\infty}-E_{\gamma\alpha}$, respectively. Each is obtained as a difference between two measured γ-ray energies and therefore the absolute errors in the two quantities are the same. For very short lifetimes $(\tau/\alpha\ll1)$, either Eq. (1) or Eq. (2) leads to

$$\frac{\tau}{\alpha}\approx\frac{E_{\gamma\infty}-E_{\gamma\alpha}}{\Delta E_{\gamma\infty}}=\frac{\Delta E_{\gamma\infty}-(E_{\gamma\alpha}-E_{\gamma0})}{\Delta E_{\gamma\infty}}.\qquad(3)$$

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* On leave of absence from the Weizmann Institute of Science, Rehovoth, Israel.
‡ Presently also at Northwestern University, Evanston, Illinois.
[1] Dieter Kurath, Argonne National Laboratory Report No. ANL-7108, 1965, p. 61 (unpublished).
[2] T. R. Fisher, S. S. Hanna, and P. Paul, Phys. Rev. Letters 16, 850 (1966).
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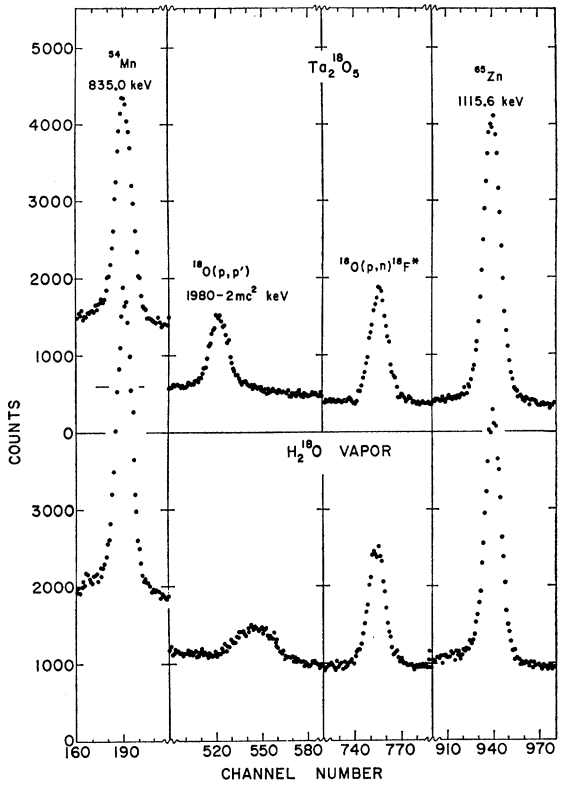

FIG. 1. Relevant portions of the γ-ray spectra from a solid $Ta_2{}^{18}O_5$ and a $H_2{}^{18}O$ vapor target at 0°. The energy dispersion is 0.374 keV/channel.

In this case $(E_{\gamma\alpha}-E_{\gamma 0})$ will differ only slightly from $\Delta E_{\gamma\infty}$. Thus, the more accurate method of obtaining τ would be a direct measurement of their difference $(E_{\gamma\infty}-E_{\gamma\alpha})$, i.e., the second variant above. A value for $\Delta E_{\gamma\infty}$ may then be calculated from the reaction kinematics. Several errors, particularly in detector solid angle and position, may be eliminated by fixing the γ detector at 0° and alternating fast and slow stopping materials.

For long lifetimes $(\tau/\alpha\gg 1)$, however, the applicable approximate expression is

$$\frac{\alpha}{\tau}\approx\frac{E_{\gamma\alpha}-E_{\gamma 0}}{\Delta E_{\gamma\infty}}. \tag{4}$$

In this case, the situation is reversed and the first variant becomes the more appropriate to use. For best experimental accuracy, the slowing-down time α should be as large as possible. Care should be taken to avoid additional errors caused by uncertainty in the detection angle, particularly $\phi=90°$ because of the $\cos\phi$ dependence of the Doppler shift.

Since the lifetime of the 1.042-MeV level in ^{18}F is very short compared with the available slowing-down times, the second variant was chosen for this measurement. The level was populated through the 3.76-MeV resonance in the $^{18}O(p,n)^{18}F^*$ reaction. Since this is only ~70 keV above the threshold for the 1.042-MeV level, the neutrons were emitted with low energies and, therefore, the ^{18}F* nuclei recoiled in the forward direction with little spread in angle and velocity. The solid targets were $Ta_2{}^{18}O_5$ made by anodizing tantalum metal with 96% enriched ^{18}O. The thickness of ~200 μg/cm^2 was much larger than the distance traveled in the time τ so that the observed slowing down occurred entirely in the target material. The gas target $(\alpha\approx\infty)$ consisted of $H_2{}^{18}O$ vapor in a chamber with windows of either nickel or Mylar foil. Because of these windows, the energy of the protons from the 4-MeV Van de Graaff accelerator was raised by ~40 keV to again reach the 3.76-MeV resonance. Some measurements were also made with $^6Li^{18}OH$, $H_2{}^{18}O$ ice, and $Ca(^{18}OH)_2$ targets.

A 9-cm^3 planar germanium counter having a resolution width of 4.5 keV was placed at 0° with respect to the proton beam and at a distance of 5 cm from the target. The γ-ray spectra were fed through a biased amplifier and recorded in 1024 channels covering the energy range 0.760–1.140 MeV. The radiation coming from the target was registered along with two reference γ lines[5] from radioactive ^{54}Mn (0.8350 MeV) and ^{65}Zn (1.1156 MeV). Runs with $Ta_2{}^{18}O_5$ and $H_2{}^{18}O$ vapor were alternated to eliminate effects of drift. The background, measured for each target by lowering the proton energy below threshold, was flat under the line of interest for each target and hence could not contribute to a measurable shift in the line position.

RESULTS

Figure 1 shows spectra obtained with targets of $Ta_2{}^{18}O_5$ and $H_2{}^{18}O$ vapor. In addition to the reference lines and the 1.042-MeV line from ^{18}F*, the $^{18}O(p,p')$ line at (1.980 MeV$-2mc^2$) was observed. After background subtraction, the spectral lines were fitted by Gaussian curves by means of the Argonne variable-metric program.[6] In each case, the energy of the ^{18}F line was calculated by linear interpolation from the energies of the ^{65}Zn (1.1156 MeV) and ^{54}Mn (0.8350 MeV) lines. The energies obtained for the various runs are shown in Fig. 2 together with their statistical standard deviations. Also included are some data (with much poorer statistics) obtained with $Ca(^{18}OH)_2$, $^6Li^{18}OH$, and $H_2{}^{18}O$ ice targets. The slowing-down times in both the LiOH and H_2O ice targets are considerably longer than the slowing-down time in $Ca(OH)_2$. It should be noted that in all measurements with $\alpha\approx\infty$ (triangles) the energy of the γ rays was found to be higher than for the corresponding measurements with finite α (circles). Variations in the absolute γ-ray energies between different

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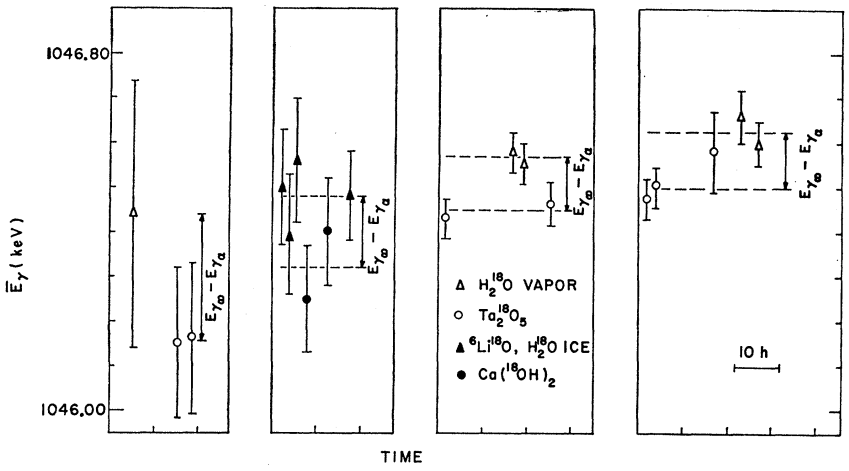

FIG. 2. Survey of γ-ray energies measured at 0° with various targets. Triangles refer to stopping materials with long stopping times. Circles represent measurements with short stopping times. The four plots refer to different runs.

runs are due to slightly different experimental conditions. The mean energy difference between the tantalum oxide and water vapor targets was found to be

$$E_{\gamma\infty}-E_{\gamma\alpha}=0.124\pm0.035 \text{ keV},$$

TABLE I. The correction factors f_n to be applied to the theoretical atomic stopping powers in order to fit the experimental values for the ranges of recoils in the different stopping materials. In each case, a 16% correction was added to the theoretical value of the electronic stopping power.

Recoiling nucleus	Stopping material	f_n (for $f_e=1.16$)	References
N	Be	1.1	a
···	C	1.1	a
···	Al	0.85	a
Ne	Be	0.6	a
···	C	0.7	a
···	Al	0.6	b
Na^{24}	Al	0.7	c, d
Si^{30}	Ta+2Si^{30}	0.4	d, e
···	Cu+Si^{30}	0	d, e
Ar	Be	1.0	a
···	B^{10}	1.1	a
···	B	1.1	a
···	C	1.1	a, d
K^{42}	Al	0.7	c, d
Cu	Cu	0.5	d, f
Ga^{66}	Cu	0.7	g
···	Ar	0.6	g
Kr	Be	0.9	a, d
···	Al	1.0	a, d
Rb^{86}	Al	0.6	c, d
Ag	Ag	0.6	d, f
Xe	Be	1.0	a, d
···	Al	1.0	a, d
Cs^{137}	Al	0.8	c, d
Au	Au	1.0	d, f
Al+Po	Au	0.6	d, h

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[d] Insensitive to the value of f_e.
[e] M. I. Guseva, E. V. Inopin, and S. P. Tsytho, Zh. Eksperim. i Teor. Fiz. 36, 1 (1959) [English transl.: Soviet Phys.—JETP 9, 1 (1959)].
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[h] L. Winsberg and J. M. Alexander, Phys. Rev. 121, 518 (1961).

and hence

$$(E_{\gamma\infty}-E_{\gamma\alpha})/\Delta E_{\gamma\infty}=0.025\pm0.007.$$

From the measurements with the $Ca(OH)_2$, LiOH, and H_2O ice, the value found was

$$(E_{\gamma\infty}-E_{\gamma\alpha})/\Delta E_{\gamma\infty}=0.032\pm0.020.$$

The value $\Delta E_{\gamma\infty}=4.9$ keV, which appears in the denominator, was calculated from the kinematics of the reaction. A measurement of the γ-ray energies at emission angles $\phi=0°$ and $\phi=90°$ for the vapor target confirmed this value. The energy of the transition is 1041.7±0.6 keV.

The relation $v=v_0e^{-t/\alpha}$ is valid only for a limited range of recoil energies. One of the conditions to be satisfied is that atomic collisions can be neglected. Since this condition certainly is not true here, energy loss due to atomic collisions as well as the scattering of the recoiling nuclei must be taken into account. A relation between the lifetime τ and the observed Doppler shift has been derived by Blaugrund,[7] who employed the universal cross section given by Lindhard, Scharff, and Schiott[8] and took account of the energy loss of the recoiling nucleus in collisions with atoms and electrons as well

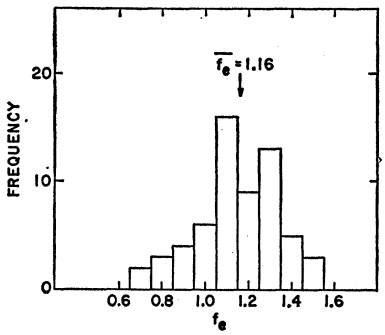

FIG. 3. A histogram of the ratio of experimental to theoretical electronic stopping powers. $\bar{f}_e$ is the average value of f_e.

[7] A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).
[8] J. Lindhard, M. Scharff, and J. E. Schiott, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. 33, No. 14 (1963).

as the effect of angular scattering. The measured electronic stopping powers[9] seem on the average to be 16% higher than predicted by Lindhard's expression. Figure 3 is a histogram of f_e, the ratio of experimental to theoretical electronic stopping powers. The width of this distribution may be due to a systematic dependence of f_e on the type of moving ion.[10] On the other hand, a comparison of measurements reported by different groups shows a similar spread.

The validity of the expression for the atomic stopping power given by Lindhard *et al.* was checked by evaluating

$$R_p=\int_0^\infty \langle v\cos\phi\rangle_{av}dt$$

with the aid of the approximation for $\langle v\cos\phi\rangle_{av}$ derived in Ref. 7 and comparing the results with published experimental ranges. The value $f_e=1.16$ was assumed in each case. In approximately half of the cases, the measured projected ranges were considerably longer than the calculated ones. The experimental ranges could be fitted well (in many instances over considerable intervals of energy) by multiplying the theoretical atomic stopping power by a factor f_n. The values of f_n giving best fits are shown in Table I. It seems that the values of f_n fall into two groups centered, respectively, around 1.0 and 0.6. Also, f_n appears to depend on the nature of the moving ion and not on the stopping material. However, the experimental data available at the present time are too scant and, in general, too inaccurate to draw far-reaching conclusions.

The lifetime of the 1.042-MeV state is much shorter than the effective slowing-down time in $Ta_2{}^{18}O_5$. Hence, according to Eq. (23a) of Ref. 7, the relation between the Doppler shift and the lifetime has the form

$$\frac{E_{\gamma\infty}-E_{\gamma\alpha}}{\Delta E_{\gamma\infty}}=(1+C_n+C_\phi)\frac{\tau}{\alpha}.$$

The three terms in the right-hand side of the above expression represent the contributions of energy loss by electronic and atomic collisions and of angular scattering. Expressions for the quantities C_n, C_ϕ, and α are given in Ref. 7 for the universal scattering cross section. Unfortunately, there are no experimental data on the slowing down of low-energy ^{18}F ions. Assuming $f_e=1.16$ and $f_n=1.0$, one gets $C_n=0.21$, $C_\phi=1.34$, and $\alpha=4.4\times10^{-13}$ sec for $Ta_2{}^{18}O_5$ (whose density[11] is 8.0 g/cm^3) and $C_n=0.20$, $C_\phi=0.30$, and $\alpha=6.0\times10^{-13}$ sec for $Ca(^{18}OH)_2$. With $f_e=1.16\pm0.20$ and $f_n=1.0_{-0.4}{}^{+0.1}$, the $Ta_2{}^{18}O_5$ data lead to the value

$$\tau=(0.41_{-0.20}{}^{+0.30})\times10^{-14}\text{ sec}$$

for the mean life of the 1.042-MeV level in ^{18}F. The indicated error is largely due to the uncertainty in the stopping power. A lifetime $\tau=(1.2_{-0.8}{}^{+1.2})\times10^{-14}$ sec was deduced from the $Ca(^{18}OH)_2$ data. The value adopted for the lifetime of this level is

$$\tau=(0.4_{-0.2}{}^{+0.3})\times10^{-14}\text{ sec.}$$

DISCUSSION

According to Kurath,[1] the relation between the $M1$ transition probability and the ft value of the corresponding β decay is given by

$$\Gamma_{M1}=\frac{129}{ft}E^3\frac{(T\pm1,\,1,\,T_z,\,0\,|\,TT_z)^2}{(T\pm1,\,1,\,T_z\pm1,\,\mp1\,|\,TT_z)^2}\times\left[1+0.2125\frac{\langle J_fT\|l\tau\|J_iT\pm1\rangle}{\langle J_fT\|\sigma\tau\|J_iT\pm1\rangle}\right]^2,$$

where T, T_z refer to the final state populated by the γ decay, Γ_{M1} is the width of the level in eV, and E is the γ transition energy in MeV. The reduced matrix elements are reduced both with respect to angular momentum and isospin. For $T=T_z=0$, the ratio of the Clebsch-Gordan coefficients is 1 and one finds from the above expression that

$$\tau=5.10\times10^{-18}ftE^{-3}\left[1+0.2125\frac{\langle J_fT\|l\tau\|J_iT\pm1\rangle}{\langle J_fT\|\sigma\tau\|J_iT\pm1\rangle}\right]^{-2},$$

where τ is the mean life of the level in seconds. For $\log ft\lesssim3.5$, the spin-dependent part of the $M1$ interaction is expected to be considerably larger than the orbital part.

Neglecting the orbital part of the interaction and using the ft values given by Ajzenberg-Selove and Lauritsen,[12] one obtains

$$\tau=(0.50\pm0.03)\times10^{-14}\text{ sec}$$

from the $^{18}Ne\rightarrow{}^{18}F$ transition and

$$\tau=(0.59\pm0.04)\times10^{-14}\text{ sec}$$

from the $^{18}F\rightarrow{}^{18}O$ decay after correcting the above equation by $(2J_f+1)/(2J_i+1)$ to account for the fewer magnetic substates available for this β decay. These values certainly fall within the rather wide experimental limits established in the present experiment. With a more accurate experimental value for this lifetime, it would be possible to say something about the magnitude and the relative phase of the orbital part of the interaction. However, a more accurate determina-

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tion of this lifetime is impossible as long as the slowing-down process is not better understood. This is true for most measurements employing the attenuated-Doppler-shift technique.

The lifetime for this transition has been predicted by Arima *et al.*[13] who used the $(d_{5/2},s_{1/2})$ model of oxygen, fluorine, and neon. Their value

$$\tau=0.48\times10^{-14}\text{ sec}$$

is well within the experimental limits.

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We are grateful to Dr. Kurath for many enlightening discussions.

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Lifetimes of the First Two Levels in ^{30}P†

E. F. KENNEDY,* D. H. YOUNGBLOOD, AND A. E. BLAUGRUND‡
Argonne National Laboratory, Argonne, Illinois
(Received 9 February 1967)

The lifetimes of the first two levels in ^{30}P were measured by the attenuated-Doppler-shift technique. The measurements were analyzed by use of the universal stopping cross section given by Lindhard, Scharff, and Schiott, and a mean life $\tau=(1.55\pm0.30)\times10^{-13}$ sec was obtained for the first level; for the second level only a lower limit ($\tau\geq3.0\times10^{-12}$ sec) was obtained. The experimental result for the first level is compared with the value calculated from the corresponding Gamow-Teller β transition according to the relation given by Kurath. Slightly revised energies of 677.0±1.0 and 709.0±1.0 keV are assigned to these levels.

INTRODUCTION

THE probabilities of $M1$ transitions involving an isospin change $|T_f-T_i|=1$ can be calculated from a simple relation derived by Kurath[1] and discussed in the preceding paper.[2] When used to calculate the lifetime of the first excited state of ^{30}P($T=1$, $J^\pi=0^+$), this relation yields a mean life $\tau=4\times10^{-13}$ sec if the orbital part of the interaction is neglected. This value is in the range measurable by use of the attenuated-Doppler-shift technique.

MEASUREMENTS

In the present experiment, the two lowest levels in ^{30}P were populated by means of the ^{27}Al$(\alpha,n)^{30}$P reaction at a resonance located at 3.95 MeV, which is 130 and 100 keV above the thresholds for production of these states. Both lifetimes could be measured at the same resonance because the second level is known[3] to decay to the ground state only. Since the neutrons were emitted with low energies, the ^{30}P nuclei recoiled in the forward direction with little spread in angle and initial velocity. The Al metal targets were inclined at an angle of 45° to the α beam from the Argonne 4-MeV Van de Graaff accelerator; they ranged in thickness from 10 to 50 μg/cm^2 and were evaporated onto carbon deposited on the tantalum beam stop. The intermediate layer of carbon, in thicknesses of 50 and 125 μg/cm^2, assured a stopping material with a slowing-down time similar to that of aluminum. For vacuum recoil measurements, 10-μg/cm^2 Al metal was evaporated onto a 20-μg/cm^2 carbon backing which faced the incident α beam.

A 9-cm^3 planar germanium counter having a resolution width of 4.5 keV was placed 4.5 cm from the target. The γ-ray spectra were fed through a biased amplifier and recorded in 1024 channels covering the energy range 0.540–0.920 MeV. The radiation coming from the target was registered along with two reference γ lines from radioactive ^{137}Cs(0.66162 MeV) and ^{95}Zr (0.7240 MeV). Runs at 0° and 90° were alternated to eliminate effects of drift. The background, measured carefully by lowering the proton energy below threshold, was flat under the lines of interest and hence could not contribute a measurable shift in the line positions.

The energy of the ^{95}Zr line was measured to be 0.7240 ±0.0007 MeV, with ^{137}Cs(0.66162 MeV) and ^{54}Mn (0.8350 MeV) sources[4] as energy standards. The ^{95}Zr

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* On leave of absence from College of the Holy Cross, Worcester, Massachusetts.
‡ On leave of absence from the Weizmann Institute of Science, Rehovoth, Israel.
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