the relative conversion coefficients were obtained:

$$L_{\rm I}:L_{\rm II}:L_{\rm III}=(2.51\pm0.24):(3.12\pm0.28):(1.00\pm0.11).$$

Our values for $(L_{\rm I}+L_{\rm II})/L_{\rm III}$ and L/M, respectively, are 5.63 ± 0.35 and 3.67 ± 0.25, and agree very well with the ratios found by Birkhoff *et al.*,[1] *viz.*, 5.9 and 3.61. However, the theoretical values obtained by interpolation from the tables of Rose[7] are

$$L_{\rm I}:L_{\rm II}:L_{\rm III}=2.23:2.45:1.00.$$

The seemingly large values for $L_{\rm I}$ and $L_{\rm II}$ relative to $L_{\rm III}$ may in part be attributed to the statistical uncertainty in the measurement of the latter. At present it is expected that the effect of finite nuclear size would be small for an $E2$ transition, and should decrease the $L_{\rm I}/L_{\rm III}$ and $L_{\rm II}/L_{\rm III}$ ratios.[8,9] Our results may therefore be an indication that this effect, if present, is small.

ACKNOWLEDGMENTS

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[7] M. E. Rose (privately distributed tables).

[8] M. E. Rose (private communication).

[9] K. W. Ford (private communication).

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Lifetime of the 6.14-Mev 3^- State of O^{16} by a Recoil Method*†

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The lifetime of the 6.14-Mev 3^- state of O^{16} has been measured by means of a recoil technique. The spatial distribution of decays of recoiling O^{16} nuclei, produced by the reaction $F^{19}(p,\alpha_1)O^{16*}$, was studied with a highly collimated γ-ray detector. Comparison with the corresponding distribution obtained when the O^{16} nuclei were stopped at the target surface by an evaporated metallic layer provided a means of determining the lifetime. A value for this half-life of $(8.6\pm4.0)\times10^{-12}$ second [mean life, $\tau=(1.2\pm0.6)\times10^{-11}$ sec] has been found, consistent with previously established limits. The measured value is compared with values predicted from various nuclear models.

I. INTRODUCTION

PREVIOUS investigations[1,2] had established an upper limit to the lifetime of the 6.14-Mev 3^- state of O^{16} by use of the recoil technique.[3] As used here, the expression recoil technique refers to a method of measuring the lifetime of an excited state by employing the motion of the recoiling nuclei to convert times of decay to corresponding positions of decay, the latter being studied by an appropriately collimated detector. In addition a lower limit to the lifetime had been established by the Doppler-shift technique.[1] These two limits together give for the half-life, $t_{\frac{1}{2}}$, the range: 5×10^{-12} sec $\leqslant t_{\frac{1}{2}}\leqslant 10\times10^{-12}$ sec.

Previous attempts in this laboratory to measure the O^{16*} lifetime demonstrated the necessity of having the target on a thick backing, since thin foils, necessary for looking at the forward recoils, fluttered sufficiently under bombardment to mask the effect of a short lifetime. Similarly, evaporated metallic layers to stop the recoils were found necessary, as no dependable method of cementing foils onto the target without subsequent blistering under bombardment was found. The present experiment was therefore designed[4] to use a target evaporated onto a rigid metal backing, the decay of the recoils in the backward hemisphere then being studied for evidence of an effect due to a small but nonzero lifetime. The evaporated metallic layer which stopped the recoils was used to provide an effective calibration of the apparatus. With these improvements in the target arrangement and with further improvements in collimation, it was felt that the technique could be used to measure lifetimes down to the order of a few times 10^{-12} second.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The apparatus, shown in Fig. 1, consisted in part of a thick brass target block mounted on the end of a differentially threaded shaft, by means of which the

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† A brief report of this experiment together with a preliminary value of the lifetime was given at the Monterey Meeting of the American Physical Society, December 27–29, 1956 [Bull. Am. Phys. Soc. Ser. II, 1, 390 (1956)].

[1] Devons, Manning, and Bunbury, Proc. Phys. Soc. (London) A68, 18 (1955).

[2] C. A. Barnes and J. Thirion, 1955 (private communication).

[3] J. Thirion and V. Telegdi, Phys. Rev. 92, 1253 (1953). This article contains references to earlier lifetime work by the recoil method.

[4] These modifications were suggested by C. A. Barnes.

target could be moved parallel to the beam direction in small steps across a highly collimated γ-ray detector. The collimation arrangement consisted of a $\frac{1}{8}$-inch thick plate of tungsten 2 inches wide by $7\frac{1}{2}$ inches long mounted on a rigid brass block normal to the beam direction and facing the incoming beam. The surface of the tungsten was an accurately ground flat face and one edge was placed within about 0.050 inch of the target block. The remainder of the collimator consisted of two lead blocks 2 in.×4 in.×6 in. mounted at the end of the tungsten face. One of the blocks formed a continuation of the tungsten face, with its 4 in. ×6 in. face carefully adjusted to be in the same plane; the other lead block then faced the first block with a separation of 0.006 inch at the end adjacent to the tungsten, and of 0.010 inch at the far end. The total length from the target to the end of the lead collimator was approximately 14 inches. The effective solid angle which this collimator provided was approximately 1.5×10^{-4} steradian. The target block itself was a thick, carefully polished brass disk, 3 inches in diameter. This target backing was a few mils smaller in diameter than the inside of the aluminum cylinder which formed part of the vacuum chamber. That section of the wall of the vacuum chamber which separated the target from the tungsten edge was about 20 mils thick and approximately 20 mils separated the aluminum from the tungsten edge. This then made it possible for the total separation of the target spot from the near edge of the tungsten face to be kept at about $\frac{3}{32}$ inch, it being essential to keep this separation small in order to make the collimation system as effective as possible.

The differential screw which moved the target relative to the collimator included a hardened steel shaft, with a threaded section of 48 threads to the inch, which was fitted into a mild steel plate. This plate formed the back of the vacuum chamber and was bolted rigidly to the collimation system. The plate was threaded with 44 threads to the inch concentrically with the steel shaft and its threaded section. A bronze nut appropriately threaded was then fitted onto both the central shaft and the back plate. The shaft was prevented from rotating by an external clamp placed on its outer end. Rotation of the nut then provided a finely controlled motion to the shaft, with an effective 528 threads to the inch. Furthermore atmospheric pressure on the shaft provided a uniform load of about 26 lb working against the differential screw. This reduced in part the tendency of the shaft to move erratically because of the friction of the shaft against the cylinder wall and the O-ring in the wall.

The other end of the vacuum chamber was capped by a brass plate into which two electrically heated evaporating furnaces were mounted which permitted laying down either a target layer or an overlying metallic layer without mechanically disturbing the system. In addition this plate contained a Sylphon

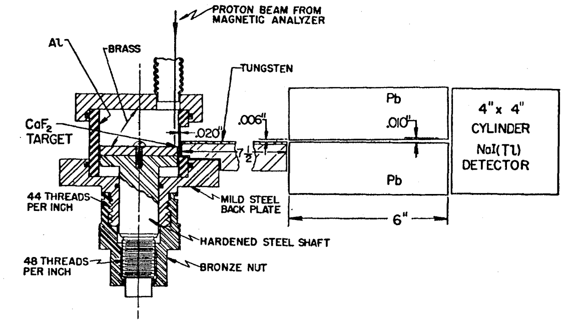

FIG. 1. Schematic diagram of apparatus for the O^{16} 6.14-Mev state lifetime experiment. Note the expanded scale for the separation of the lead collimator blocks.

bellows which served both as the vacuum outlet and the beam entrance channel to the target.

The γ-ray detector consisted of a cylindrical 4 in. ×4 in. NaI(Tl) crystal mounted on a DuMont 6364 photomultiplier, and placed directly behind the lead collimator with its axis toward the target. Conventional pulse amplifiers, discriminators, and associated electronic circuits were used with this detector.

The $F^{19}(p,\alpha_1)O^{16*}$ reaction at the 873-kev resonance provided the O^{16*} recoils. This resonance was chosen because of its favorable production of the 6.14-Mev state relative to the other two γ-ray emitting states at 6.9 Mev and 7.1 Mev, and also because of its large absolute cross section for the production of that state. It was also found that any higher bombarding energy would have seriously increased the general background from the accelerator. The targets used were evaporated layers of CaF_2, in which the energy loss for 873-kev protons varied from 8 to 30 kev. Optimum results were obtained for a target thickness of about 15 kev. Proton beam currents of 1 to 2 microamperes were ordinarily employed. The proton beam was produced by the Kellogg Laboratory 3-Mv electrostatic generator and a double-focusing magnetic analyzer was employed for energy regulation. It was possible in typical operation to place the beam current within an area of about $\frac{1}{32}$ in.$\times\frac{1}{16}$ in. approximately $\frac{1}{32}$ inch in from the edge of the target block.

The γ-ray pulses from the 4-in.×4-in. crystal were amplified and fed to a differential pulse-height analyzer which accepted pulse heights corresponding to energies in the range of about 4.5 Mev to 7.5 Mev. The γ-ray yield was also monitored by an independent NaI(Tl) detector.

The experimental runs consisted first in adjusting the screw to place the target somewhat ahead of the edge of the tungsten collimator, thus giving the maximum counting rate corresponding to the full transmission of the collimation system. The screw was then backed out in steps of 18° in rotation in the regions where the counting rate was slowly varying, i.e., either well in front of the edge or well behind it. In going across the edge, steps of 9° were taken, corresponding

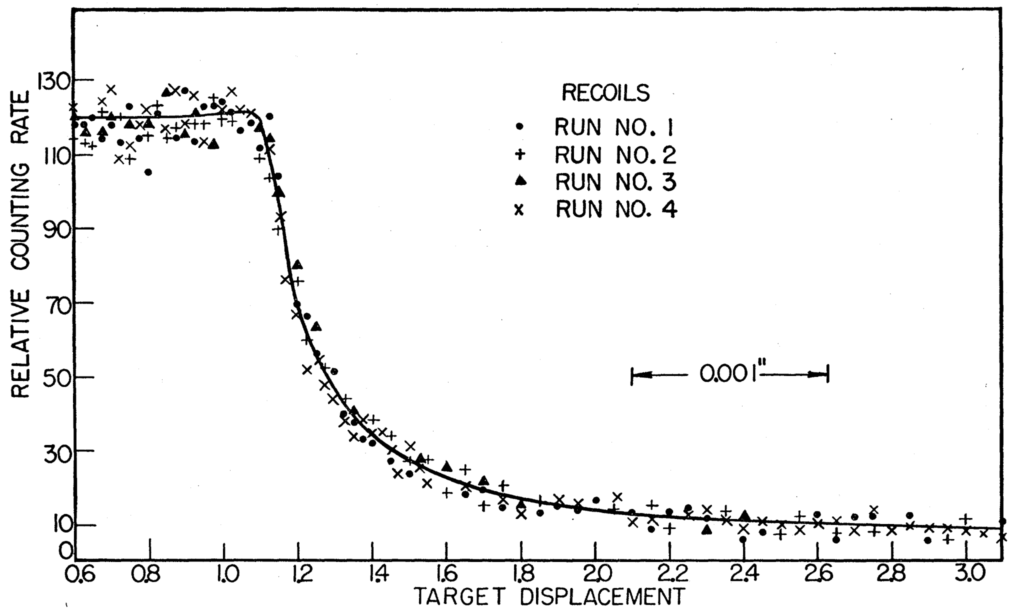

FIG. 2. The raw data for a set of recoil runs. The separate runs have been divided by the average monitor count for that run. Target displacement is measured in revolutions of the differential screw; 528 revolutions equal 1 inch.

to withdrawing the target in steps of approximately 0.047 mil. For the case with only the target layer evaporated onto the target backing, 3 to 5 such runs were made in this manner across the tungsten edge, where for each setting of the target position about 50 microcoulombs of charge were collected. Then a copper layer about 150 kev thick to 1-Mev protons was evaporated onto the target surface and the procedure was repeated for 3 to 5 runs with as much as 100 μcoul of charge being collected for each point. These will be referred to as the "recoil" and "no-recoil" runs respectively. It was found that the individual runs within the "recoil" and "no-recoil" groups were in general quite reproducible as to shape, but sometimes were displaced relative to each other by small amounts. Figure 2 shows the raw data for a group of recoil runs. In addition the recoil and no-recoil groups of curves, between which the evaporation of the stopping layer was carried out, were often shifted relative to one another by about 0.1 mil. The causes of these shifts were not isolated, and are discussed in Sec. IV. However the difference in shape of the recoil and no-recoil curves is the significant result of this experiment. Four such complete sets of data were accumulated which were regarded as suitable for analysis. In addition many runs consisting of groups of recoil or no-recoil runs alone were accumulated. These were individually consistent with the four sets of runs which were used, but were not included because the recoil and no-recoil runs were taken at different times and may well have represented slightly different conditions as to target spot size, location, etc. In analyzing the data, averages of the complete sets of runs were taken. A background equal to the counting rate observed with the target well behind the tungsten edge, amounting to 7 to 15% of the full transmission value was then subtracted, and the curves were normalized to the same arbitrary value at the flat maximum of the curves, corresponding to the target being in front of the tungsten edge. Such a curve is shown in Fig. 3. The theoretically constructed distribution of decays for different assumed values of the lifetime was then folded into the no-recoil curves and the resultant curves were compared with the recoil curves, as explained in Sec. III. Figure 7 shows such a comparison.

III. ANALYSIS

The measurement of the lifetime of an excited state by the recoil technique requires a comparison of the experimental decay distribution curves with curves calculated for various assumed lifetimes. If ideal geometry is assumed, in which the collimator is one-sided and 100% effective, then one must find the relative number of de-excitation γ rays emitted perpendicular to the incident proton beam direction as a function of the normal distance from the target to the point of emission. Since there is some penetration of the collimator edges by the γ rays, these calculated distribution curves must then be folded into the "no-recoil" curves, which measure the effectiveness of the collimator for a source identical with respect to its γ-ray spectrum, but with an effectively zero lifetime.

The distribution curve may be derived as follows, using Fig. 4 for reference. Because of the center-of-mass motion and the energy loss of the recoiling nuclei in the target and contaminating layers, as discussed below, the velocity is a function of the polar angle θ, θ being measured in the laboratory with respect to an axis along the proton beam direction. For an excited O^{16} nucleus with a mean life τ, moving at an angle θ with

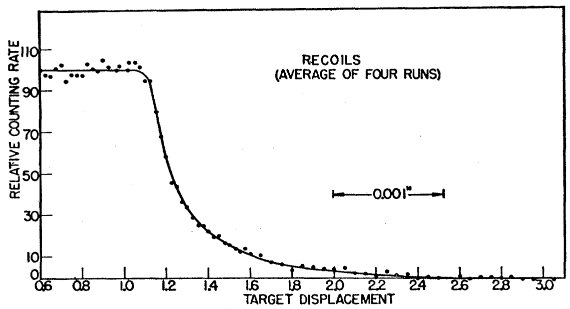

FIG. 3. The data of Fig. 2 averaged, with the background subtracted and then normalized to give the flat maximum an arbitrary value of 100.

respect to this axis, the probability of decay between r and $r+dr$, where $r=v(\theta)t$, is then given by

$$P(r)dr=\frac{dr}{\tau v(\theta)}\exp\left[-\frac{r}{\tau v(\theta)}\right]. \quad (1)$$

Next one must find the probability that an excited O^{16} nucleus will emit a γ ray into a solid angle $d\Omega_\gamma$ at θ_γ, ϕ_γ, while recoiling into a solid angle $d\Omega$ at θ, ϕ. The polar angle is measured with respect to the proton beam axis, and since by symmetry this probability can only depend upon the relative azimuthal angle, ϕ will be measured from the p-γ plane, so that $\phi_\gamma=0$. This joint probability, or correlation, will be written as follows:

$$U(\theta_\gamma,0;\theta,\phi)\frac{d\Omega_\gamma}{4\pi}\frac{d\Omega}{4\pi}.$$

From the definition of the function U, it follows that

$$\int_{4\pi}U(\theta_\gamma,0;\theta,\phi)\frac{d\Omega(\theta,\phi)}{4\pi}=W_\gamma(\theta_\gamma), \quad (2)$$

where $W_\gamma(\theta_\gamma)$ is the p-γ distribution function, normalized so that

$$\int_{4\pi}W_\gamma(\theta_\gamma)\frac{d\Omega_\gamma}{4\pi}=1.$$

In this experiment, only γ rays emitted perpendicular to the proton axis were detected, i.e., at $\theta_\gamma=\pi/2$. For convenience $U(\theta_\gamma=\pi/2, \phi_\gamma=0; \theta, \phi)$ will be written $U(\theta,\phi)$. Knowing this correlation $U(\theta,\phi)$, one may find the probability $n(r,\theta,\phi)drd\Omega$ of a γ ray, detected in a solid angle $\Delta\Omega_\gamma$ perpendicular to the proton beam, being emitted from an excited O^{16} nucleus recoiling into a solid angle $d\Omega$ at angles θ, ϕ and decaying between r and $r+dr$. This probability is

$$n(r,\theta,\phi)drd\Omega=\frac{dr}{\tau v(\theta)}\exp\left[-\frac{r}{\tau v(\theta)}\right]U(\theta,\phi)\frac{d\Omega}{4\pi}\frac{\Delta\Omega_\gamma}{4\pi}. \quad (3)$$

Changing variables to $z=r\cos\theta$, and $\mu=\cos\theta$, the following integral probability is found:

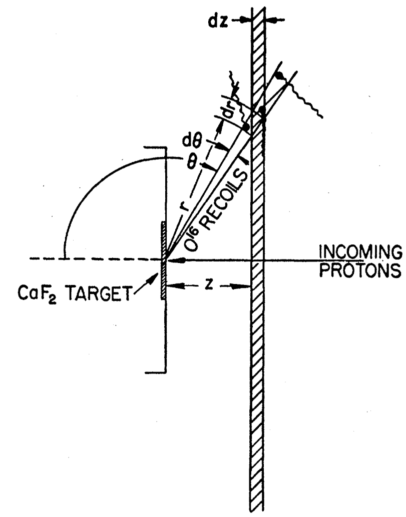

FIG. 4. Schematic diagram of the geometry for the analysis of the recoil distribution of decaying O^{16} nuclei.

$$N_\pm(a,\infty)=\pm\frac{\Delta\Omega_\gamma}{4\pi}\int_0^{\pm1}\bar{U}(\mu)\exp\left[\mp\frac{a}{\mu\tau v(\mu)}\right]\frac{2\pi d\mu}{4\pi}. \quad (4)$$

$N_\pm(a,\infty)$ is the probability of an excited nucleus decaying at a normal distance $|z|\geqslant a$ from the target, and emitting a γ ray into a solid angle $\Delta\Omega_\gamma$ perpendicular to the proton beam, the positive sign referring to recoils in the direction of the incident beam, and the negative sign to recoils in the backward direction. $\bar{U}(\mu)$ is the correlation averaged over the azimuthal angle of the recoiling nuclei, i.e.,

$$\int_0^{2\pi}U(\mu,\phi)d\phi=2\pi\bar{U}(\mu).$$

In the present experiment, F^{19} was bombarded with 873-kev protons, which also excite the 6.9- and 7.1-Mev states of O^{16}. The detection apparatus could not resolve this 7-Mev radiation from the 6-Mev radiation with which this experiment was concerned. The branching ratio $\alpha_1/(\alpha_1+\alpha_2+\alpha_3)$ has been measured at this resonance,[5–7] and was taken to be 0.70. Then if N is the total number of O^{16} nuclei produced in these three states, $N_1=0.70N$ and $N_{2+3}=0.30N$, where N_1 is the number excited to the 6.1-Mev state, and N_{2+3} is the number excited to the 6.9- and 7.1-Mev states. The lifetimes of these two states have been studied,[8] and the limits are $t_{\frac{1}{2}}\leqslant 1.7\times10^{-14}$ second for the 6.9-Mev state, and $t_{\frac{1}{2}}\leqslant 8\times10^{-15}$ second for the 7.1-Mev state.

[5] J. Seed and A. P. French, Phys. Rev. **88**, 1007 (1951).
[6] Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 188 (1950).
[7] J. M. Freeman, Phil. Mag. **41**, 1225 (1950).
[8] Devons, Manning, and Towle, Proc. Phys. Soc. (London) **A69**, 173 (1956).

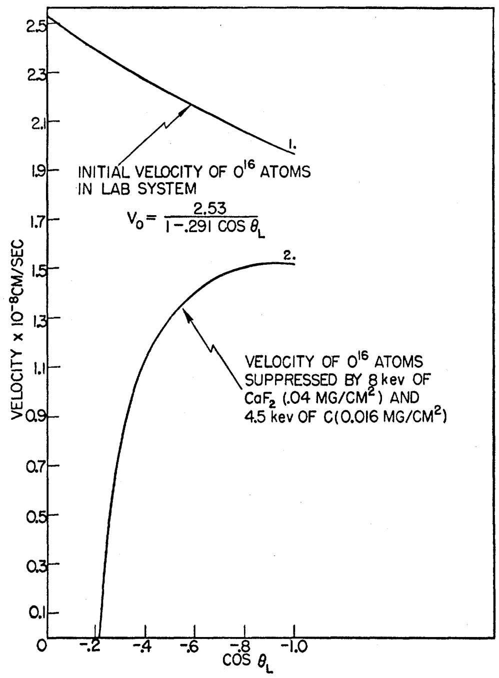

FIG. 5. The velocity of the recoil O^{16} nuclei in the backward hemisphere given by the nuclear reaction dynamics, curve 1, and the velocity corrected for the slowing down due to the CaF_2 and carbon layers, curve 2.

More recent measurements[9] give $t_{\frac{1}{2}}=(8.3\pm0.2)\times10^{-15}$ second for the 6.9-Mev state and $t_{\frac{1}{2}}=(6.9\pm0.2)\times10^{-15}$ second for the 7.1-Mev state. These two states thus decay promptly compared to the 6.1-Mev state, and therefore, within the linear resolution of the apparatus, simply add to the γ-ray yield from the target layer.

In this experiment the target backing stopped the excited O^{16} nuclei recoiling forward in a distance short compared with the linear resolution of the apparatus, and thus the forward recoils also contributed only to the γ-ray yield from the target layer. Upon combining the above results, the following expressions for the number of γ rays emitted perpendicular to the proton beam into a solid angle $\Delta\Omega_\gamma$ from the target layer, from normal distances $-z\geqslant a$, as well as the expression for the total number, are found:

$$N_{\text{target}}=N\frac{\Delta\Omega_\gamma}{4\pi}\left[0.70\int_{-1}^{0}\bar{U}(\mu)\frac{2\pi d\mu}{4\pi}+0.30W_\gamma^{2+3}(\pi/2)\right],\quad(5)$$

$$N_-(a,\infty)=N\frac{\Delta\Omega_\gamma}{4\pi}\left[0.70\int_{-1}^{0}\exp\left[+\frac{a}{\mu\tau v(\mu)}\right]\bar{U}(\mu)\frac{2\pi d\mu}{4\pi}\right],\quad(6)$$

$$N_{\text{total}}=N\frac{\Delta\Omega_\gamma}{4\pi}[0.70W_\gamma^{1}(\pi/2)+0.30W_\gamma^{2+3}(\pi/2)].\quad(7)$$

[9] C. P. Swann and F. R. Metzger, Phys. Rev. **108**, 982 (1957).

Sanders[10] has measured the $(p,\gamma_2+\gamma_3)$ distribution at the 873-kev resonance, and Seed and French[5] have calculated it. The correlation was taken to be $I^{2+3}(\theta_\gamma)=1+0.34\cos^2\theta_\gamma$, leading to $W_\gamma^{2+3}(\pi/2)=0.90$.

In the center-of-mass coordinate system, the (γ_1,O^{16}) and the (γ_1,α_1) correlations will be the same, since the α particles and the O^{16} nuclei recoil in opposite directions. In this coordinate system, the (γ_1,α_1) correlation, averaged over the azimuthal angle Φ_α of the α particle, between a γ ray at $\Theta_\gamma=\pi/2$, $\Phi_\gamma=0$, and an α particle at Θ_α is given by

$$\begin{aligned}\bar{U}(\Theta_\gamma=\pi/2,\,\Theta_\alpha)=&\frac{3}{1024}\left(\frac{1}{1+B^2}\right)\\&\times[438-284\cos^2\Theta_\alpha-138\cos^4\Theta_\alpha\\&+(10)^{\frac{1}{2}}B\cos\beta(17+291\cos^2\Theta_\alpha\\&-1185\cos^4\Theta_\alpha+861\cos^6\Theta_\alpha)\\&+\tfrac{5}{2}B^2(165+388\cos^2\Theta_\alpha-2196\cos^4\Theta_\alpha\\&+3864\cos^6\Theta_\alpha-2205\cos^8\Theta_\alpha)].\end{aligned}\quad(8)$$

This correlation is derived from a knowledge of the angular momenta involved. $Be^{i\beta}$ measures the relative amplitude and phase of the outgoing g-wave and d-wave α particles. The derivation is discussed in the Appendix.

The magnitude of $\cos\beta$ is determined from the barrier factors,[5] leaving the magnitude of B and the sign of $\cos\beta$ to be determined experimentally. Martin *et al.*,[11] from a study of the (α_1,γ_1) correlation, combined with the results of the (p_1,α_1) distribution studied by Peterson *et al.*[12] and the results of the (p,γ_1) distribution, studied by Sanders,[10] found $B=0.85$, $\cos\beta=+0.242$, with $B=0.2$, $\cos\beta=-0.242$ as possible but less likely. Seed and French[5] found $B=0.54$, $\cos\beta=-0.245$. In these calculations the values $B=0.85$ and $\cos\beta=+0.242$ were used, but the other values give quite similar results, as will be shown later.

Having found $\bar{U}(\Theta_\gamma=\pi/2,\,\Theta_\alpha)$, one may transform to the laboratory coordinate system, using $Q=1.98$,[13] and remembering that we are interested in the O^{16*} recoils, thus obtaining $\bar{U}(\mu)$, where $\mu=\cos\theta$.

TABLE I. Measured half-life values.

Number of run group	$t_{\frac{1}{2}}$ (in 10^{-12} second)	Relative weight on basis of number of points taken
1	3	7
2	11	14
3	5	16
4	12	18
Weighted mean	8.6	

[10] J. E. Sanders, Phil. Mag. **43**, 630 (1952).
[11] Martin, Fowler, Lauritsen, and Lauritsen, Phys. Rev. **106**, 1260 (1957).
[12] Peterson, Fowler, and Lauritsen, Phys. Rev. **96**, 1250 (1954).
[13] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

The velocity dependence upon $\cos\theta$ may be calculated from the kinematics of the reaction, and for backward angles is given approximately by the following expression:

$$v(\cos\theta) = \frac{2.53}{1-0.291\cos\theta} \times 10^8 \text{ cm/sec.} \qquad (9)$$

A correction must be made for the reduction of velocity of the recoiling nuclei in the calcium fluoride layer itself and also in the layer of carbon contamination. The over-all average depth of production of the $F^{19}(p,\alpha_1)O^{16*}$ reaction in the CaF_2 target layer for all recoil runs was about 8 kev. In addition a layer of carbon was formed during each set of recoil runs with an average total thickness of 9 kev. The average carbon layer during the set of recoil runs was then taken to be 4.5 kev thick. Upon taking the stopping power for protons in CaF_2 and C as 190 kev/mg/cm^2 and 284 kev/mg/cm^2 respectively,[14] average thicknesses of 0.04 mg/cm^2 of CaF_2 and 0.016 mg/cm^2 of carbon were found.

To calculate the velocity loss of the O^{16} recoils in traversing these layers, a range-velocity curve for O^{16} in air was constructed from the data of Blackett and Lees.[15] The Bragg-Kleeman rule[16] was then used to adjust the range scale for the two materials CaF_2 and carbon. This rule states that for a given particle the range is approximately given by $R_1 = (A_1/A_0)^{\frac{1}{2}} R_0$, where R is in units of mass per unit area.

Extrapolation by the Bragg-Kleeman rule over the rather greater range from the O^{16} data for air to copper gives a value for the range of O^{16} in copper too large by about 30% compared to the range computed from the relation $R=\alpha v$ with a value for α(Cu) of $(1.8\pm0.2)\times10^{-13}$ second[8] measured at a velocity of 2.8×10^8 cm/sec. Hence the errors in constructing the range-energy relations in CaF_2 and C may be of the order of 15 to 20%.

From these curves the velocity loss in bringing the recoils out through the two layers successively could be found for a series of angles, given the initial velocity

TABLE II. Effect of the relative amplitude and phase $Be^{i\beta}$ of outgoing d- and g-wave α particles on $N_-(0,\infty)$, the number of γ rays emitted perpendicular to the beam direction from nuclei recoiling in the backward direction, and on $\bar{v}_z$, the mean z component of velocity of these recoils.

B	$\cos\beta$	$N_-(0,\infty)$ (in %)	$\bar{v}_z$ (in 10^{+8} cm/sec)
0.85	+0.242	16.8	0.62
0.54	−0.242	16.7	0.63
0.20	−0.245	15.4	0.59

[14] From a compilation of stopping cross sections by Ronald Fuchs and Ward Whaling (unpublished).
[15] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. (London) **A134**, 658 (1932).
[16] R. D. Evans, *The Atomic Nucleus* (McGraw-Hill Book Company, Inc., New York, 1955), p. 652.

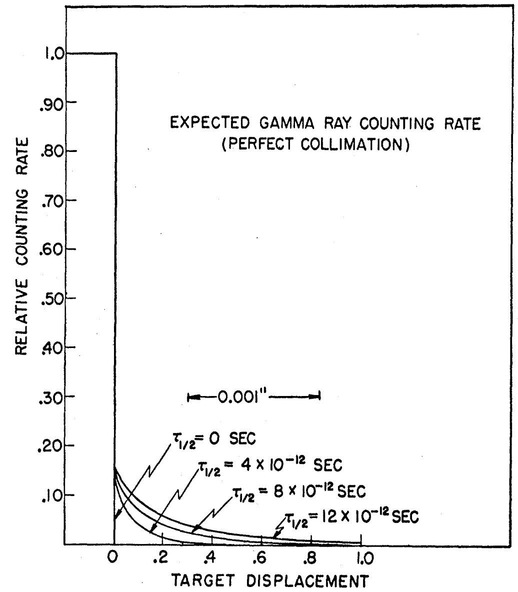

FIG. 6. The theoretically constructed decay distributions for a perfect collimation system. The ordinate represents the total number of decays occurring beyond the given position.

of the ion determined by the reaction dynamics. The results are shown in Fig. 5, which gives both the initial velocity and the corrected velocity as a function of the angle.

The suppressed velocity distribution shown in Fig. 5 was difficult to approximate analytically. Hence the integration of Eq. (6) was carried out numerically, using Eq. (7) for normalization to 100. Figure 6 shows the curves computed for a perfect one-sided collimator with assumed half-lives of 0, 4×10^{-12}, 8×10^{-12}, and 12×10^{-12} second.

IV. RESULTS AND DISCUSSION

Table I lists the half-life values determined by comparing the experimental decay curves with curves computed as in Sec. III. One such comparison is illustrated in Fig. 7. The over-all mean value of the half-life, weighted as indicated, is 8.6×10^{-12} second, where the standard deviation of the above values is 3.6×10^{-12} second. However, because of the approximations in the construction of the theoretical recoil distributions, resulting primarily from uncertainties in the range-velocity relations for the O^{16} ions, and the uncertainty in the determination of the best fits of the folded distributions to the observed distributions, the probable error is quoted as 4.0×10^{-12} second.

A further source of uncertainty in the analysis arises from the ambiguity in the choice of the relative amplitude and phase $Be^{i\beta}$ for the outgoing d- and g-wave α particles as already discussed. A measure of the effect of the various values of B and $\cos\beta$ is given in Table II, where $N_-(0,\infty)$ is the relative number of γ rays emitted perpendicular to the beam direction from nuclei recoil-

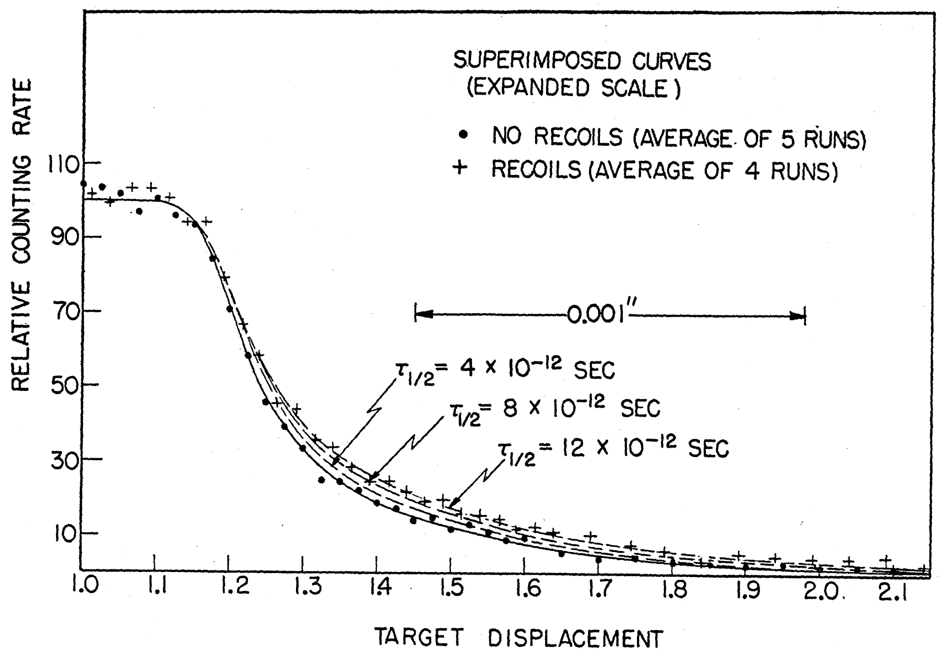

FIG. 7. The differential decay distributions constructed from the curves of Fig. 6 have been folded into a "no-recoil" curve and the significant portion presented on an expanded scale with the corresponding "recoil" curve superimposed. The value for $t_{\frac{1}{2}}$ taken corresponding to this set of runs was 12×10^{-12} sec.

ing in the backward direction ($N_{\text{total}}=100.0$), and $\bar{v}_z$ is the mean z component of velocity of these recoils in the backward direction.

A source of error not considered so far is a possible blistering of the covering layer of copper due to the heating during bombardment. This would allow the recoils to leave the target layer to some extent. After the runs were completed, the target spots were examined visually under a microscope and they appeared to be free of such effects at the time of inspection. This does not completely eliminate the possibility of the blistering appearing only during the bombardment, but that would seem unlikely. Another possible effect having to do with the target structure was indicated by the noticeable decline in counting rate as the bombardment continued. This may have been due to loss of fluorine from the target layer which was therefore probably changing in effective composition. This could well give rise to a somewhat different energy loss for the escaping O^{16*} recoils than was actually allowed for in the analysis. Temperature changes in the various parts of the mechanism could cause changes in the relative positions of the target and collimator during a run. Temperatures were not monitored; however, because of the large cross section of the shaft it is difficult to see how any significant temperature differences could be maintained along the shaft. Effects due to over-all temperature changes were also believed to be insignificant because, to a reasonable approximation, the thermal expansion of the shaft supporting the target was in turn compensated by a corresponding expansion of the shaft holder. The over-all shift of one run relative to another run sometimes seen, as noted already, might have been due at least in part to a slight realignment of the shaft in its supporting block, which occurred during the resetting of the target position preceding each run. Such effects were not believed serious because it was consistently observed that the shapes of the curves were in good correspondence, i.e., the unexplained shifts did not occur during a run which involved only a slight turning of the bronze nut for each successive point, but rather, when they did occur, it was between runs which involved completely repositioning the nut, amounting to about 10 full turns. The evaporation of the metallic recoil-stopping layer which took place between the groups of recoil and no-recoil runs involved a considerable, though temporary, increase in temperature. This might have introduced some of the shift between the recoil and no-recoil groups through a redistribution of the lubricating layer in the threads of the differential screw. A thinning of the lubricating layer occurring between the two groups of runs would have been consistent with the direction of the observed shift. Again this should not be regarded as serious because the experiment requires an analysis only of the shape of the curves.

Some possible means of improving the accuracy of the recoil technique should be pointed out. The collimator lead blocks could be moved closer together, provided of course that the reaction under study was sufficiently prolific. A factor of two reduction in the separation of the blocks would steepen the slope of the transmission curve by a factor of two near the top of the edge, and would give a much larger difference in transmission at the toe of the curve. This would provide a much greater distinction in the shapes of the curves given by the recoil and no-recoil runs. In addition it would be desirable to make some arrangement, perhaps optical, to measure independently the relative separation of the target and collimator rather than to use only the setting of the differential screw to determine this quantity.

Other critical features of the technique are the target flatness, beam position relative to the collimator, target thickness, and carbon deposition on the target. With the suggested changes in the collimator and measuring system, and with careful attention to the above-noted critical items, it should be possible to reduce the uncertainty in measurement of lifetimes of this order of magnitude by a factor of two or three. Similarly this would allow the measurement of correspondingly shorter lifetimes.

V. COMPARISON WITH THEORETICAL ESTIMATES OF THE MEAN LIFE

The single-particle limit for this mean life, as given by the Weisskopf formula[17] for γ-ray transition rates, is 2.1×10^{-10} second, where the radius of the O^{16} nucleus has been taken to be $1.30\times(16)^{\frac{1}{3}}\times10^{-13}$ cm. A radius of about this value seems indicated by the results of recent electron scattering experiments with light nuclei. The measured value of the mean life, $(1.2\pm0.6)\times10^{-11}$ second, is shorter than this estimate by a factor of about 17 and hence indicates very strongly that this transition is not of a single-particle nature.

The α-particle model for the O^{16} nucleus has been worked out in considerable detail by Kameny.[18] He gives an estimate of 3.2×10^{-11} second for the 6.14-Mev state mean life, using α-particle wave functions which had already been adjusted to give a quite reasonable fit to the known O^{16} level scheme. The experimental lifetime is still somewhat shorter than this value and would indicate that, while the static properties of the O^{16} states can be accounted for fairly well by α-particle wave functions, their dynamical aspects may still be in error. This is further confirmed by Kameny's calculations of the γ-ray transition rates for the other low-lying O^{16} states and the corresponding experimental values and limits for these rates.

Shell-model estimates of the mean life of this state have been about an order of magnitude too long. Elliott and Flowers give a value of 1.2×10^{-10} second, based on their shell-model calculations.[19] This result and a similar result by R. A. Ferrell[20] indicate that the shell-model wave functions as developed so far still do not give a sufficiently detailed description of the O^{16} ground and 6.14-Mev excited states.

In view of the apparent difficulty in finding nuclear wave functions which will give this very fast transition rate, Ferrell[20] and Lane[21] have calculated the maximum possible transition rate using two different sum rules. The first sum rule,

$$\sum_\lambda \left\langle 0 \left| \sum_{i=1}^{Z} |r_i^3 Y_3^m| \lambda \right.\right\rangle^2 = \frac{e^2 A}{16\pi}\langle 0|r^6|0\rangle, \qquad (10)$$

assumes no nucleon-nucleon correlations, is independent of the energy of the excited states, and requires the expectation value of $\langle r^6\rangle$ in the ground state. Its derivation is similar to an electric dipole sum rule given by Blatt and Weisskopf.[22] The second sum rule,

$$\sum_\lambda (E_\lambda - E_0)\left\langle 0 \left| \sum_{i=1}^{Z} r_i^3 Y_3^m |\lambda \right.\right\rangle^2 = \frac{21\hbar^2 e^2 A}{32\pi M}\langle 0|r^4|0\rangle, \qquad (11)$$

is independent of nucleon-nucleon correlations, is dependent upon the energy of the excited states, and requires the expectation value of $\langle r^4\rangle$ in the ground state. Its derivation is similar to an electric monopole sum rule derived by Ferrell.[23] Since the 6.14-Mev state is $T=0$, the above sum rules have been restricted to $T=0$ to $T=0$ transitions. The matrix elements of $\langle r^4\rangle$ and $\langle r^6\rangle$ were evaluated using shell model wave functions (a $(1s)^2(1p)^6$ proton configuration) adjusted to give an rms radius to the proton distribution of 2.54×10^{-13} cm as indicated by the electron scattering results on O^{16} at Stanford.[24,25] One obtains for the limits on the mean life, $\tau\geqslant2.2\times10^{-11}$ sec from the first rule, and $\tau\geqslant3.8\times10^{-12}$ sec from the second. Ferrell[20] points out that these limits might be lowered by the inclusion of an exponential tail in the wave function, the effect being greater in the first sum rule than the second due to the dependence upon a higher power of r. The measured mean life is $\tau=(1.2\pm0.6)\times10^{-11}$ sec. This violates the first sum rule by approximately a factor of two and indicates that the assumption of no nucleon-nucleon correlations is not valid, which is not surprising. The measured value is about three times the second sum rule limit, and indicates that there exist possible wave functions which could give this fast transition rate. Furthermore, the second sum rule limit indicates that the 6.14-Mev transition accounts for at least one-third of the total $E3$ width to the ground state from $T=0$ states, and observing that the next known 3^- state is at 11.62 Mev,[13] this limit may be as much as one half.

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APPENDIX

The reaction studied in this experiment is $F^{19}(p,\alpha_1\gamma_1)O^{16*}$ at a proton bombarding energy of 873 kev. A compound nucleus, $Ne^{20}(J_r=2^-)$ is formed by p- and f-wave protons ($l=1, 3; s=\frac{1}{2}^+$) and $F^{19}(J=\frac{1}{2}^+)$. The proton and F^{19} spins combine to form channel spins $j=0$, 1. $Ne^{20}(J_r=2^-)$ then decays into d- and g-wave α particles ($l'=2, 4$) and $O^{16*}(J_s=3^-)$, which then emits an electric octupole γ ray. The designation of the states follows Seed and French.[5]

The correlation function $U(\Theta_\gamma,\Phi_\gamma,\Theta_\alpha,\Phi_\alpha)$ gives the probability per de-excitation of the simultaneous emission of a γ ray into a solid angle $d\Omega_\gamma$ at Θ_γ, Φ_γ, and an α particle into a solid angle $d\Omega_\alpha$ at Θ_α, Φ_α, where the capital Greek letters refer to the center-of-mass coordinate system, with the proton beam direction as the z axis. Furthermore, this correlation has the property that if it is integrated over the coordinates of the α particle the γ-ray distribution is obtained, and vice versa.

In the present experiment one is interested in γ rays emitted perpendicular to the proton beam, so a new axis z' is chosen perpendicular to the proton beam and along the γ-ray direction. In this coordinate system, the coordinates of the proton are $\Theta_p'=\pi/2$, $\Phi_p'=0$, and the coordinates of the α particle are Θ_α', Φ_α', where Θ_α' is the angle between the α particle and the γ ray, and Φ_α' is the angle between the p-γ plane and the α-γ plane. The correlation now may be written as a function only of the α-particle coordinates, and is

$$\begin{aligned}U'(\theta_\alpha',\Phi_\alpha')=\frac{3}{64}\left(\frac{1}{1+B^2}\right)\{&25+46\cos^2\Theta_\alpha'\\&-55\cos^4\Theta_\alpha'-\cos^2\Phi_\alpha'(24-24\cos^4\Theta_\alpha')\\&+(10)^{\frac{1}{2}}B\cos\beta[10-151\cos^2\Theta_\alpha'+440\cos^4\Theta_\alpha'\\&-315\cos^6\Theta_\alpha'-\cos^2\Phi_\alpha'(11-77\cos^2\Theta_\alpha'\\&+185\cos^4\Theta_\alpha'-119\cos^6\Theta_\alpha')]\\&+\tfrac{5}{2}B^2[4+109\cos^2\Theta_\alpha'-286\cos^4\Theta_\alpha'+189\cos^6\Theta_\alpha'\\&-\cos^2\Phi_\alpha'(3-42\cos^2\Theta_\alpha'+340\cos^4\Theta_\alpha'\\&-742\cos^6\Theta_\alpha'+441\cos^8\Theta_\alpha')]\}.\qquad\text{(A1)}\end{aligned}$$

This correlation is normalized so that

$$\int_{4\pi}U'(\Theta_\alpha',\Phi_\alpha')\frac{d\Omega_{\alpha'}}{4\pi}=\frac{74+95B^2}{80(1+B^2)},\qquad\text{(A2)}$$

which is equal to $W_\gamma(\Theta_\gamma=\pi/2)$, where Θ_γ is the polar angle of the γ-ray measured with respect to the proton beam direction. Transforming to the proton axis, and averaging over the azimuthal angle of the α particle in the unprimed system, one is led to Eq. (8).

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Inelastic Scattering of Photons in Y^{89}†

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The cross section for the inelastic scattering of photons in Y^{89} has been measured from 4 to 22 Mev. Two peaks were observed, and their significance is discussed.

It has been found recently that the cross section for the formation of isomeric states by inelastic scattering of photons shows two resonances instead of one, as is usual in photonuclear work.[1,2]

Schützmeister and Telegdi[2] tried to explain the high-energy peak as due to electric quadrupole emission and the lower energy one as electric dipole. On the other hand, Fuller and Hayward[3] measured the elastic scattering of photons and found two peaks at the same locations as the inelastic ones.

We have measured the cross section as function of energy for the formation of the isomeric state of Y^{89} ($9/2^+$; $T^{\frac{1}{2}}=14$ sec; $E=0.913$ Mev) from 4 to 22 Mev with the University of São Paulo betatron. The results are shown in Fig. (1) [curve (a)].

Samples of pure pressed Y_2O_3 of weight 10 grams were irradiated for one minute and transferred to a counting system, using a one-channel crystal spectrometer set at the 0.913-Mev line. The absolute value was determined by comparison with the $Al^{27}(\gamma,n)Al^{26}$ activation curve as measured by Katz and Cameron.[4] Tests were made with a strong Ra−Be source and it was found that the rise in the excitation function above 15 Mev was not due to inelastic scattering of neutrons either from the betatron

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