that could also be made is the measurement of the L/K ratio for V^{49}. The usual theoretical L/K ratio for V^{49} is 0.087; the exchange-corrected ratio is 0.101.

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Lifetime Measurements on the First Excited States of O^{17} and F^{18}†

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The mean life of the first excited state of O^{17} at 871 keV has been measured by a pulsed Van de Graaff beam technique. A value of $\tau_m = (0.263 \pm 0.008)$ nsec was found. Similar measurements on the first excited state of F^{18} at 940 keV established an upper limit to the mean life: $\tau_m < 0.2$ nsec.

I. INTRODUCTION

In a shell-model description, O^{17} consists of a single neutron outside a closed-shell O^{16} core. The $\frac{5}{2}+$ ground state and $\frac{1}{2}+$ first excited state of O^{17} correspond, respectively, to the $1d_{5/2}$ and $2s_{1/2}$ states of the odd neutron. The 871 keV, $E2$ gamma decay of the first excited state is on this model, therefore, a single neutron transition outside the core. The lifetime for this decay is of interest theoretically,[1] since the odd neutron makes no contribution to the matrix element for the transition, which takes place only through contributions from the O^{16} core. Many attempts have been made to calculate the core contributions, using both the shell model,[2] and also the weak-coupling collective model.[1] The importance of a measurement of this lifetime arises partly from the possibility of a direct experimental test of the theoretical work for this relatively simple nucleus, and also from the consequent availability of an empirical value of the O^{16} core contribution, for use in the interpretation of lifetime measurements in neighboring nuclei in the $1d-2s$ shell.

Several measurements of the lifetime for this transition have been published,[3–5] but in only two cases were the measurements made by direct observation of the exponential decay of the level using electronic timing. Lifetimes measured by this method are not subject to the uncertainties and systematic errors associated with recoil or centroid shift techniques. However, the two published measurements in which the decay was observed directly[4,5] differ substantially. Also, one of the measurements involved delayed coincidence techniques, in which the identification of the gamma responsible for the observed decay is somewhat less certain. The present paper reports a further measurement of this lifetime using pulsed beam techniques.

A detailed study of the properties of the low-lying states of F^{18} has been published by Kuehner, Almqvist, and Bromley.[6] Kuehner *et al.* compared their experimental data with the shell-model predictions for this nucleus calculated by Elliott and Flowers[7] and by Redlich,[8] and found that the shell model can give a reasonably satisfactory account of the levels below 3 MeV. Kuehner *et al.* set an upper limit of 5 nsec on the lifetime of the 3+ first excited state at 940 keV for $E2$ gamma decay to the 1+ ground state. An identical upper limit for this lifetime was set by Allen *et al.*[9] and

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[1] B. J. Raz, Phys. Rev. **120**, 169 (1960). This paper reviews other theoretical work on gamma transitions in nuclei in this mass region.

[2] For example, G. Barton, Nucl. Phys. **11**, 466 (1959); G. Barton, D. M. Brink, and L. M. Delves, *ibid.* **14**, 256 (1959).

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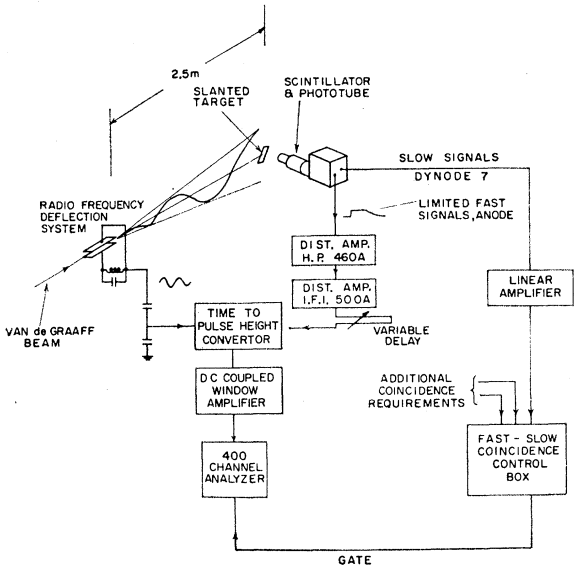

FIG. 1. Block diagram of the electronics.

a lower limit of 4×10^{-12} sec was set by Litherland *et al.*[10] using Doppler-shift techniques. The lifetime of this state is of interest for comparison with shell-model calculations, particularly since the predicted lifetime is surprisingly short in spite of the strong configuration mixing involved. The predicted speed of the transition arises from coherence between contributions to the matrix element from the strongest components of the wave functions. A measurement of the lifetime would provide an experimental demonstration of this appearance of a collective effect in the shell-model calculations.[11,12] The present paper describes the measurement of a new upper limit on this lifetime.

II. APPARATUS

The measurements were made using the pulsed-beam facility of the Brookhaven National Laboratory 3-MeV Van de Graaff. A detailed account of the apparatus has been published elsewhere[13–15]; only a brief description will be given here.

The Van de Graaff beam is pulsed after acceleration to produce pulses separated by about 134 nsec. These pulses are shortened by a slanted-target time-compression technique[13] to produce a duration of about 0.1 nsec on the target.

Figure 1 shows a schematic diagram of the detector and associated electronic equipment. The scintillation detector consists of a 1-in. long by $1\frac{1}{4}$-in. diam Pilot B scintillator mounted on a RCA-type C-7260-B photomultiplier. In each experiment the target to detector distance was long enough so that detection of the gammas was complete before the arrival at the detector of the highest energy neutron group from the target. The time resolution observed for prompt gammas of $\sim$900 keV was 0.5 nsec (full width at half-maximum), and the slopes of the sides of the peak were 0.07 nsec for a factor of 2 decrease in counting rate.

Time calibration of the apparatus is accomplished by the insertion of various lengths of RG63/U cable in the fast signal lead. The velocity of detector signals in this cable has been measured to an accuracy of 0.3% and a description of these measurements, and of tests of the over-all calibration of the system is given in Ref. 14.

III. EXPERIMENTAL PROCEDURE

O^{17}

The first excited state of O^{17} was produced in the $O^{16}(d,p)O^{17*}$ reaction by bombardment of a thick quartz target with 2.75-MeV deuterons. Observation of the spectrum of emitted gammas with a 2-in.$\times$2-in. NaI(Tl) scintillation counter confirmed that there were no prominent gammas in the region of 900 keV other than the strong 871-keV gamma from the first excited state of O^{17}.

The single-channel discriminator (Fig. 1) was channeled on the Compton edge of the 871-keV gamma. Gammas for a prompt comparison time spectrum were provided by the $C^{12}(d,p\gamma)C^{13}$ reaction on a graphite

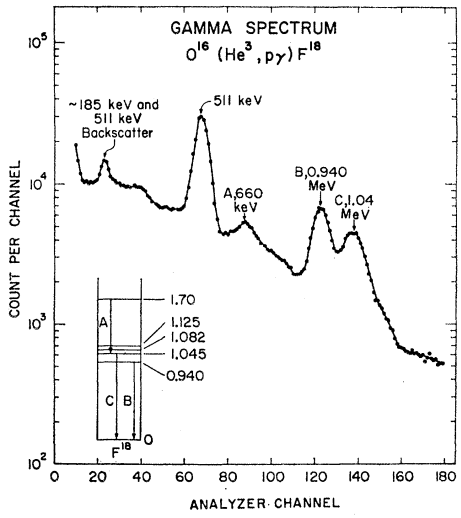

FIG. 2. Pulse-height spectrum of gammas from $O^{16}(He^3,p\gamma)F^{18}$ obtained using a 2-in.$\times$2-in. NaI(Tl) crystal as detector.

[10] A. E. Litherland, B. M. Adams, D. Eccleshall, and M. J. L. Yates, in *Proceedings of the Kingston Conference on Nuclear Structure*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960).

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target, with the single-channel discriminator channeled at 871 keV as before. The time spectra discussed below were obtained in a 4-h run. During the run, the O and C targets were alternated every 30 min to avoid errors due to a gradual drift of the centroid position.

F^{18}

F^{18} was produced in the reaction $O^{16}(He^3,p)F^{18*}$ by bombarding a quartz target with a 3-MeV He^3 beam. The spectrum of gammas from this reaction obtained using a 2-in.×2-in. NaI(Tl) crystal as detector is shown in Fig. 2, which also shows the level scheme for the low-lying states taken from Ref. 6. The pulse-height spectrum in the 1-in.×$1\frac{1}{4}$-in. plastic scintillator showed a composite Compton edge arising from gammas at 0.940 and 1.045 MeV. The single-channel discriminator was channeled on the Compton distribution for the 940-keV gamma. The channel, therefore, contained substantial contributions from the 940-keV and 1.045-MeV gammas, together with much smaller contributions from higher energy gammas.

The first excited state of F^{18} is populated directly in the $O^{16}(He^3,p)F^{18}$ reaction, and is also formed from cascade decay of higher states. Of the higher states which are known[6] to de-excite through the first excited state, all are expected from their known spins and parities to be fast, except the 5+ state at 1.125 MeV. The mean life of this state has been measured[9] as 190 nsec, and its decay is 100% through the first excited state.[6,9] Gammas of 940 keV arising from this cascade will not exhibit the lifetime characteristic of the first excited state, and it is important for the analysis of the data to know the fraction of the observed 940-keV peak that arises from this cascade. The 1.125-MeV level is not excited strongly[6] in $O^{16}(He^3,p)F^{18}$ at energies below 3 MeV, and it does not seem to be involved in the cascade decay of higher states.[6] A direct measurement of the contribution from this level under the conditions of the present experiment is provided by observation of the 185-keV gammas from its decay. The peak at 185 keV in Fig. 2 arises mainly from backscattered 0.511-MeV gammas. If it arose entirely from decay of the 1.125-MeV state, then the associated, long-delayed 940-keV gammas would comprise 10% of the 940-keV photopeak. Therefore, 10% is an upper limit to the long-delayed fraction of the observed 940-keV peak.

Gammas for a prompt comparison time spectrum were obtained from the $C^{12}(He^3,p\gamma)N^{14}$ reaction with the channel set at 940 keV as before. The time spectra discussed below were obtained during a 12-h run. As in the O^{17} experiment, the O and C targets were alternated many times during the run.

IV. RESULTS

O^{17}

The time spectrum after subtraction of background is shown in Fig. 3. The region of the exponential decay

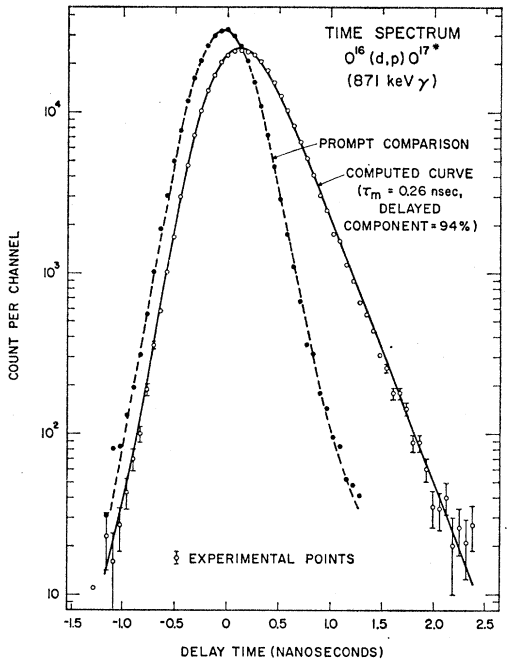

FIG. 3. Time spectrum of 871-keV gammas from $O^{16}(d,p\gamma)O^{17}$ (open circles). A prompt comparison spectrum is also shown (solid circles). The lifetime was determined by a least-squares fit to the straight part of the exponential decay. The solid curve shown is the computed response of the system to a gamma with a mean life of 0.26 nsec.

clear of the influence of the prompt peak (the region between delays of 0.8 and 2.3 nsec) was analyzed by carrying out a least-squares fit to an exponential decay. The slope corresponded to a mean life of 0.265 nsec, with a statistical accuracy of 1%. The dominant source of error is the uncertainty of 2% in the time calibration, as discussed in Ref. 14. The final value for the mean life, calculated from this result and from a subsequent run, is

$$\tau_m = (0.263 \pm 0.008) \text{ nsec}.$$

The solid curve in Fig. 3 shows the calculated response of the system to a gamma with a mean life of 0.26 nsec. The curve was computed using the experimental prompt comparison as the prompt response curve of the system, and it was found necessary to assume that 94% of the counting rate in the channel was due to the delayed gamma. The fit to the experimental delayed time spectrum excludes the possibility that the exponential decay arises from the weaker, higher energy gammas present in the spectrum.

F^{18}

The time spectrum, after subtraction of background, is shown in Fig. 4. The solid line in this figure is a smooth curve drawn through the experimental prompt comparison spectrum. The experimental points for the delayed spectrum do not show any significant delay

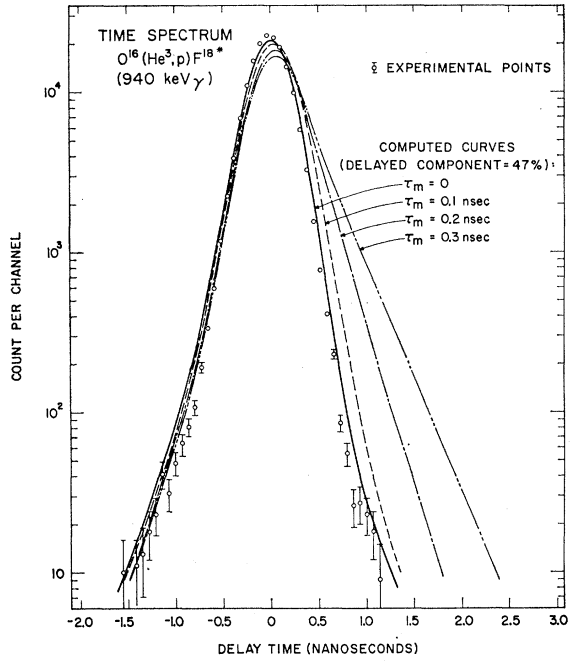

FIG. 4. Time spectrum of 0.940 and 1.04 MeV gammas from $O^{16}(He^3,p\gamma)F^{18}$ (open circles). The solid curve is derived from the experimental prompt comparison spectrum. The broken curves show the calculated response of the system to gammas of 0.1, 0.2, and 0.3 nsec, respectively.

relative to this curve; thus, the lifetime is too short to be measured with the present equipment. In order to set an upper limit on the lifetime, the expected response of the system to gammas with $\tau_m=0.1$, 0.2, and 0.3 nsec was computed in the same way as in the O^{17} analysis. To carry out this computation, a knowledge of the fraction of prompt component in the gamma channel is required. Analysis of Fig. 2 and of the pulse-height spectrum in the plastic scintillator indicates that approximately 50% of the counting rate in the channel arises from the 1.045-MeV and higher energy gammas. As discussed above, up to 10% of the remaining 50% consists of 940-keV gammas with a long lifetime characteristic of the 1.125-MeV state. Thus, an estimated 47% of the counting rate in the channel arises from 940-keV gammas with a lifetime characteristic of the 3+ first excited state.

The computed time spectra for three values of the mean life are shown in Fig. 4. Comparison of these with the experimental data for F^{18} indicates an upper limit to the mean life of

$$\tau_m<0.2 \text{ nsec}.$$

V. DISCUSSION

O^{17}

The present result is in good agreement with that of Kane *et al.*[4] who found $\tau_m=(0.255\pm0.013)$ nsec. It does not agree with that of Gale *et al.*[5] who obtained (0.430 ±0.021) nsec. The reason for this discrepancy is not known.

Since the present result is identical with that found by Kane *et al.*,[4] the theoretical analysis of Raz,[1] which is based on the experimental result of Kane *et al.*, is also relevant to the present experimental work.

F^{18}

As discussed in Sec. I, the mean life of the 940-keV state of F^{18} was known[6,10] to lie in the range 4×10^{-12} sec$<\tau_m<5\times10^{-9}$ sec. The present result reduces this upper limit by a factor of 25.

The dominant feature of the low-lying $T=0$ levels predicted in the shell-model calculations of Elliott and Flowers[7] and Redlich,[8] is a triplet of levels with spins 1+, 3+, and 5+. It has been shown by Kuehner *et al.*[6] that these three levels very probably correspond to the ground state, the 940-keV state, and the fourth excited state at 1.125 MeV, respectively. The lifetime predicted for the 3+ state can be calculated from the wave functions published by Redlich[8,16] using standard techniques.[17] In carrying out these calculations, values for the radial integrals computed by Arnurius *et al.*[18] were used. These integrals were evaluated using wave functions computed in a well of Saxon-Woods shape, using parameters which reproduce correctly the binding energies of the odd proton and neutron in F^{18}. In the calculations, the collective enhancement arising from excitation of the O^{16} core was allowed for in the conventional manner by the assignment of an effective charge to the nucleons outside the core. The transition in O^{17} discussed above proceeds entirely through these collective effects, and the value of the effective charge, $0.5e$, calculated from the present lifetime measurement was used in the analysis of the F^{18} result.

The value calculated for the mean life is 0.61×10^{-10} sec, which is consistent with the upper limit of 2×10^{-10} sec established above. The predicted mean life is short in spite of the substantial mixing of $d_{5/2}$, $d_{3/2}$, and $2s_{1/2}$ states in the wave functions, and the consequently large number of terms in the matrix element. The predicted speed of the transition arises from the fact that the strongest contributions to the matrix element from different configurations are all in phase. The present upper limit, which is relatively close to the shell model

[16] In the calculation of Ref. 8 the Serber exchange force was used. This exchange mixture does not reproduce correctly certain features of the level spectrum (see Ref. 7). However, the wave function for the 1+ state given in Ref. 7, calculated using a Rosenfeld exchange force, is very close to the Serber force wave function given in Ref. 8. Also, in a private communication, Elliott has confirmed that lifetime calculations using his Rosenfeld force wave functions give results close to those presented here.

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[18] D. E. Arnurius, B. Buck, and G. R. Satchler, in *Proceedings of the Conference on Electromagnetic Lifetimes and Properties of Nuclear States, Gatlinburg, Tennessee, 1961*, Nuclear Science Series Report No. 37 (National Academy of Science–National Research Council, Publication 974, Washington 25, D. C., 1962), p. 28; and private communication from Dr. Satchler through Dr. B. J. Raz.

prediction, supports qualitatively this appearance of collective effects in the shell model calculations. This effect is discussed in detail by Elliott[11,12] who demonstrates certain collective features in shell-model wave functions which form representations of the group $U(3)$. The mean life for the 3+ to 1+ transition in F^{18} can be calculated from the $U(3)$ wave functions given in Ref. 11, and the value obtained, using the same values of the parameters as in the shell-model calculations above, is $\tau_m = 0.54 \times 10^{-10}$ sec, which is close to the shell-model value and is again consistent with the present upper limit. Clearly, an actual measurement of this lifetime would be valuable.

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Fine Structure Effects in the Fission of U^{235}†

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By the use of a Frisch-gridded double ionization chamber the energy and mass distribution of U^{235} fission fragments under thermal neutron fission have been studied in coincidence with relatively high-energy prompt-fission γ rays. The data were electronically analyzed and the results printed on paper tape, transferred to IBM cards, and analyzed by the campus IBM-7074 computer. Runs were taken for fission fragments in coincidence with prompt-fission γ's>2 MeV and γ's>3 MeV and the results were compared with fission fragments corresponding to all γ rays. Pronounced structural effects were noted in the kinetic-energy distribution and in the mass ratio, the magic-number nucleus $N=82$, $Z=50$ perferentially emitting higher energy γ rays. The symmetric fission yield was found to increase the γ-ray energy, thus offering the possibility that the extra excitation energy of symmetric fission fragments may be carried off in the form of higher energy γ rays.

INTRODUCTION

RECENTLY, several experiments have been performed with the purpose of looking for fine structure effects in fission. Gibson *et al.*[1] found such an effect in the kinetic-energy spectrum of the heavy fission fragments of U^{235} in coincidence with different light-fragment energies. It was also noticed that the total kinetic-energy release for symmetric fission is approximately 30 MeV less than for asymmetric fission,[2] and that the number of neutrons emitted for symmetric fission of U^{235} is ~ 6 (compared to the average of 2.5). This higher rate of neutron emission may help carry away some of the extra excitation energy in the case of symmetric fission but possibly some of it might also appear as higher energy γ radiation. In addition, Vandenbosch[3] suggests that the dip in the kinetic energy and the sawtooth structure in the prompt neutron yields[4] result from the influence of the shell structure of the eventual fragments at the scission configuration. Milton and Fraser[5] found that for Cf^{252} the yield of γ rays showed a pronounced dip at the doubly magic-number nucleus $N=82$, $Z=50$ with the average γ-ray energy being slightly higher in this region. In this experiment the kinetic energy, mass, and angular distribution of the fission fragments arising from the thermal neutron fission of U^{235} have been studied in coincidence with relatively high-energy prompt fission γ rays with the purpose of looking for fine structure effects if they exist.

EXPERIMENTAL METHOD AND PROCEDURE

In carrying out this experiment a Frisch-gridded double ionization chamber was constructed in a manner similar to one developed previously by one of the authors.[6] The gas mixture in the chamber consisted of

† Work supported in part by the U. S. Atomic Energy Commission.

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[3] R. Vandenbosch (private communication).

[4] J. S. Fraser and J. C. D. Milton, Phys. Rev. **93**, 818 (1954).

[5] J. C. D. Milton and J. S. Fraser, in *Proceedings of the Second United Nations Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, P/199.

[6] R. R. Roy, in *Proceedings of the Second United Nations Conference on the Peaceful Uses of Atomic Energy, Geneva 1958* (United Nations, Geneva, 1958), Vol. 15, P/694.