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Measurement of the Magnetic Moment and Lifetime of the 1.131-MeV Level in F^{18}†

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The magnetic moment of the 1.131-MeV level in F^{18} has been measured, using the $O^{16}(He^3,p)F^{18}$ reaction and the differential time-delay technique, as $\mu=+(0.568\pm0.013)J$. The mean lifetime of this level has been remeasured. The measured magnetic moment agrees, to within the experimental uncertainties, with that predicted by the nuclear shell model for a level of spin-parity 5^+ resulting from the $1d_{5/2}{}^2$ configuration. Some information is also obtained about the effect on the original nuclear alignment of the stopping process for F^{18} ions of approximately 1-MeV energy in copper.

I. INTRODUCTION

THE structure of the nucleus F^{18} has been the subject of a number of recent theoretical and experimental investigations.[1–8] Experimentally the spins and parities of all the levels below 3.0 MeV have been determined except for the spin of the level at 1.131 MeV which decays by the emission of an $E2$ γ ray of 194-keV energy to the 3^+ state at 0.937 MeV. Shell-model[1] theoretical studies which consider the interaction of two particles in the $(2s,1d)$ shell have been successful in explaining many of the properties of the even parity levels below 3.1 MeV. One of the predictions of these shell-model calculations is that there should be a level of even parity with $J=5$ at about 1-MeV excitation energy. This has been identified with the 1.131-MeV level, but so far there has been no rigorous demonstration of its spin. The nuclear-structure description of this level is simple in both LS and jj coupling—it is either $|1d_{5/2}{}^2,5\rangle$ in the jj description or in LS language, $|d^24(S=1),5\rangle$, i.e., two d particles with $L=4$ and $S=1$ coupled to give $J=5$. This theoretical simplicity has so far contrasted sharply with the inadequacy of the experimental knowledge of the properties of the 1.131-MeV level.

The immediate aims of the experiments which we shall describe in this paper were twofold. The first was to remeasure the lifetime of the 1.131-MeV level in F^{18}. The properties of $E2$ transitions in nuclei near $A=16$ have been quite intensively studied recently[9,10]; however present electronic methods of measuring lifetimes in the 200-nsec range are capable of much higher accuracy than that[11] with which the lifetime of the 1.131-MeV level was known when this work began. The second was to measure the magnetic moment of the 1.131-MeV level. A measurement of the lifetime of the 1.131-MeV level of F^{18} gives the dynamic $E2$ matrix element $\langle 3\|E2\|5\rangle$ connecting that state with the 0.937-MeV level, while a measurement of its magnetic moment gives the static $M1$ matrix element $\langle 5\|M1\|5\rangle$. Both matrix elements can give important information on the nuclear structure of the states concerned. Another consideration is that the magnetic moments of both single particle $1d_{5/2}$ nuclei (O^{17},F^{17}) are known. A comparison of the magnetic moment of the F^{18} 5^+ level with that calculated from the O^{17} and F^{17} magnetic moments could (because of the simplicity of the F^{18} state) yield information on exchange terms in the magnetic-moment operator, or quenching of the magnetic moment by virtual meson currents in the nucleus.

Because of the relatively long lifetime of the 1.131-MeV state we were able to use the differential time-

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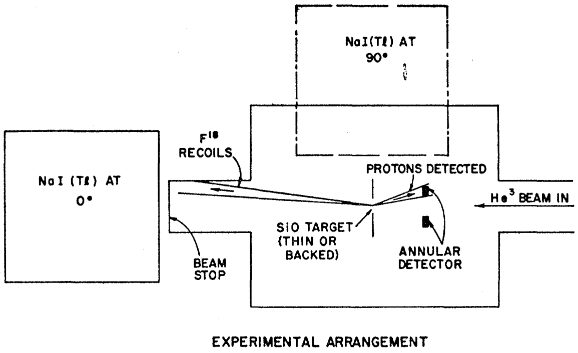

FIG. 1. Experimental arrangement for the lifetime measurement. The reason for using two different geometries is explained in the text.

delay technique[12] for the magnetic-moment experiment: that is, we observed the time dependence of a precession by a magnetic field of the angular correlation between protons populating the 1.131-MeV state in the $O^{16}(He^3,p)F^{18}$ reaction and the de-exciting γ rays. The magnetic moments of a number of excited nuclear states have previously been measured by using this technique to observe the precession of a γ-γ angular correlation from an unaligned radioactive source.[12] The magnetic moments of excited states in F^{19} and Na^{22} have also been measured by adaptations of this time-delay technique.[13,14] Its use in the observation of the precession of a particle-γ correlation in a static magnetic field has not previously been reported.

II. EXPERIMENTAL METHOD

A. Lifetime Determination

The $O^{16}(He^3,p)F^{18}$ reaction was used to populate the level of interest, the 1.131-MeV level of F^{18}. The experimental arrangement is shown in Fig. 1. A He^3 beam of 3.1-MeV energy passed through an annular particle detector which detected the reaction protons originating from a thin SiO target. This was either deposited on a thin copper backing (0.001 in.) which stopped the recoil F^{18} nuclei at the target site or else was self-supporting, in which case the F^{18} nuclei corresponding to the protons detected in the annular detector recoiled out of the target and reached the beam stop in a time that was small compared to the lifetime of the 1.131-MeV level. Elastically scattered He^3 particles were stopped before reaching the detector by a 5 mg/cm² aluminum foil. The two different detection geometries were used to see if there was any significant perturbation of the time-delay spectra by possible relaxation of the initial nuclear alignment in a time comparable to the lifetime of the level. In the first case the 3×3-in. NaI(Tl) detector was placed at 90° to the beam direction with its front face 1 in. from the target ($\Omega=0.4\pi$ sterad). In the second case the detector was placed at 0° so that the beam stop subtended a solid angle of $\Omega\approx 2\pi$ sr at the detector. In either case pulses from the particle detector corresponding to the protons populating the 1.131-MeV level triggered a conventional start-stop time-to-amplitude converter (T.A.C.) while the photopeak pulses from the NaI γ-ray detector corresponding to 0.937-MeV γ rays provided the stop pulses. The mean life of the F^{18} 0.937-MeV level[8] is $(6.8\pm0.7)\times10^{-11}$ sec which is short compared to the expected lifetime[11] of the 1.131-MeV level. Furthermore the 1.131-MeV level decays 100% to the 0.937-MeV level and it was advantageous, experimentally, to detect the 0.937-MeV γ rays originating from the 1.131-MeV level rather than those of 0.194 MeV energy. The start and stop pulses for the T.A.C. were derived from a crossover pickoff circuit following a bipolar amplifier. The time resolution of this system gave 10 nsec full width at half-maximum (FWHM) for a prompt p-γ coincidence. This was perfectly adequate for the lifetime involved. A typical time spectrum for each case is shown in Fig. 2. These time spectra were calibrated by insertion of a 60-nsec delay cable on either side of the T.A.C. A least-squares fit to the exponential slopes of these spectra gave $\tau_m=222\pm12$ and 215 ± 12

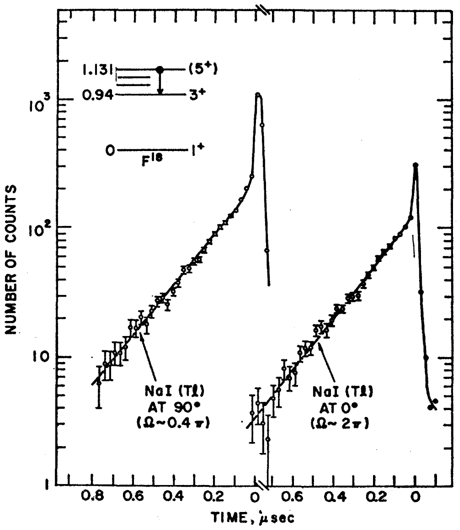

FIG. 2. Time-delay curves, between protons populating the 1.131-MeV state of F^{18} and γ rays de-exciting the 0.937-MeV level, obtained in the two geometries of Fig. 1. As explained in the text, the exponential slope of the left-hand sides of these curves are characteristic of the mean life of the 1.131-MeV level of F^{18}.

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[13] A. W. Sunyar and P. Thieberger [Phys. Rev. **151**, 910 (1966)] have measured the magnetic moment of the 0.583-MeV level in Na^{22} by the use of the $F^{19}(Po^{210}\alpha,n)Na^{22*}$ reaction.

[14] The magnetic moment of the 0.198-MeV level in F^{19} has been measured by R. M. Freeman [Nucl. Phys. **26**, 446 (1961)] with the aid of a pulsed accelerator beam, while H. Schmidt, J. Morgenstern, J. Braunsfurth, H. J. Körner, and S. J. Skorka as quoted in Ref. 13 have used a similar technique to measure the magnetic moment of the 0.583-MeV level in Na^{22}.

Note added in proof. H. Schmidt *et al*. [Phys. Letters **24B**, 457 (1967)] have recently reported a measurement of the magnetic moment of the 1.131-MeV level in F^{18} using this pulsed-beam technique. Their results are in excellent agreement with ours.

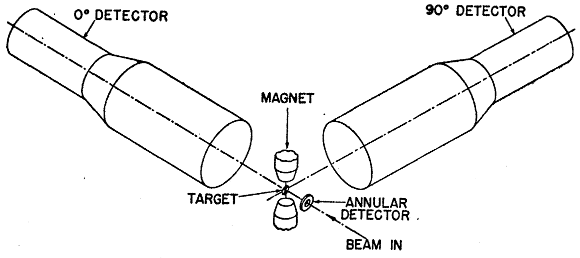

FIG. 3. Sketch of the experimental arrangement for the magnetic-moment experiment. The target and annular proton detector were both inside a small target chamber which is not shown in the figure. The front face of each NaI detector was 7.6 cm from the target spot while the annular detector was 2.5 cm from the target.

nsec for the 90° and 0° detection respectively, their average being $\tau_m = 219 \pm 10$ nsec. The agreement between the lifetimes determined for the 90° and 0° detection shows that any effect on the measured lifetimes by possible relaxation of the initial alignment can be neglected. The error limits quoted include the uncertainties due both to counting statistics and time calibration. We will later compare the above lifetime with that extracted from the magnetic-moment experiment, and with other determinations.

B. The Magnetic-Moment Experiment

A sketch which shows the general experimental arrangement used in this measurement is shown in Fig. 3. Again, the reaction $O^{16}(He^3,p)F^{18}$ was used to populate the 1.131-MeV level at a bombarding energy of 3.4 MeV. The target was a layer of SiO approximately 200 $\mu g/cm^2$ thick evaporated on a 0.001-in. thick copper foil. An estimate of the density of SiO gives $\rho = 2.5$ g/cm^3 with $\rho = 2.3$ g/cm^3 as a reasonable lower limit. With this density, the range of 1.3-MeV F^{18} ions is approximately 300 $\mu g/cm^2$. The thickness of the SiO film is sufficiently less than this so that all of the F^{18} recoils corresponding to protons detected at backward angles stop in the copper backing. An aluminum foil 5 mg/cm^2 thick placed in front of the annular detector stopped elastically scattered He^3 particles before the detector. Both the target and detector were inside a small target chamber (not shown) which was coupled directly to the machine vacuum. A tantalum collimator with an aperture $\frac{1}{8}$ in. in diameter backed by a lead cylinder 3-in. long with a $\frac{1}{4}$-in. axial hole restricted the beam to a small diameter before entering the chamber through the annular detector. The magnetic field was provided by a permanent magnet whose field at the target spot was measured using a flip-coil flux meter as 6100±60 G. The two γ-ray detectors were 3×3-in. NaI(Tl) crystals placed at 0° and 90° with respect to the incident beam. The target chamber walls in these two directions were 0.050-in. thick in order to minimize the absorption of the γ rays.

Pulses from the particle detector corresponding to the protons populating the 1.13-MeV level started a T.A.C. In two separate experiments the photopeak stop pulses from the NaI(Tl) detectors corresponded either to a γ ray of 0.194 MeV or 0.937 MeV. The time-delay pulses from the T.A.C. were routed into one or the other of the two halves of a RIDL 400-channel analyzer depending upon whether the stop pulse originated in the 0° or 90° detector. In this way the precession of the angular correlation could be observed simultaneously at both 0° and 90° with respect to the beam. This was important not only because it effectively doubled the counting rate, but also because it facilitated the data analysis.

Copper was chosen as the target backing for three reasons: (1) Its atomic number is high enough so that He^3 reactions induced upon it at the bombarding energies which were used were insignificant compared to those resulting from $O^{16}+He^3$. (2) It is diamagnetic, thus the internal magnetic field is expected to be very close to the applied external field. (3) It has a cubic lattice, so that as long as the recoiling F^{18} nuclei come to rest in a lattice site, they experience essentially no electric quadrupole field. The only perturbing force acting on the F^{18} nucleus in this case would then be the applied magnetic field, aside from the very small diamagnetic correction.

C. Theory of Magnetic-Moment Experiment

The time-dependent correlation function $W(\theta,t)$ for the detection of a γ ray emitted from a nucleus aligned with respect to the axis 0z in a magnetic field B perpendicular to the plane defined by 0z and the direction of emission of the γ ray is[15]

$$W(\theta,t)=\sum_k A_k P_k[\cos(\theta\pm\omega_L t)]e^{-t/\tau_m}, \tag{1}$$

where $\omega_L = g\mu_N B/\hbar$ is the Larmor precession frequency, $P_k(\cos\theta)$ is a Legendre polynomial of order k ($k=0$, 2, $4\cdots$), and τ_m and g are the mean lifetime and gyromagnetic ratio of the state under consideration while μ_N is the nuclear magneton. For the case where the level is populated by a nuclear reaction and aligned by the detection of an outgoing particle in an annular detector[2,16] at 180°,

$$A_k=\sum_\alpha \rho_k(a,\alpha)P(\alpha)F_k(ab), \tag{2}$$

provided the γ ray is emitted directly from the level of concern. The coefficients $\rho_k(a,\alpha)$ and $F_k(ab)$ are defined in Ref. 2 while $P(\alpha)$ is the population of the magnetic substates. For the $O^{16}(He^3,p)F^{18}$ reaction $|\alpha_{\max}|=1$ for detection in a point detector at 180°. If an annular detector is used, higher substates are expected to be populated to some small degree, the next in importance to $\alpha=0$, and ±1 are $\alpha=\pm2$. The degree of alignment of the initial level which is possible by the use of this

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[15] Equation (1) is an application to p-γ correlations (with axial symmetry) of the corresponding formula for γ-γ correlations given in Ref. 12 above.

[16] A. E. Litherland and A. J. Ferguson, Can. J. Phys. 39, 788 (1961).

method is generally higher than that obtained for the intermediate level in a γ-γ correlation. The actual alignment coefficients A_k observed in the experiment could be attenuated from those predicted by Eq. (2) through changes in the alignment resulting from interactions between the F^{18} recoils and the copper backing.

In the present case, terms in Eq. (1) up to $k=4$ were expected (and found), so that the most convenient way of extracting ω_L from the raw data was to generate the functions,

$$F_{\pm}=[Y(\theta=90,\,t)\pm\epsilon Y(\theta=0,\,t)]\exp(t/\tau_m)\,, \quad (3)$$

where $\epsilon(\approx 1)$ is an efficiency normalization constant introduced so that $A_0(90°)=A_0(0°)$. These two functions have the following form:

$$F_{-}\sim B\cos(2\omega_L t+\varphi_1)\exp(-t/\tau_r) \quad (4)$$

and

$$F_{+}\sim C+D\cos(4\omega_L t+\varphi_2)\exp(-t/\tau_r)\,, \quad (5)$$

where

$$B=-(3A_2/2+5A_4/8)\,,$$
$$C=+(2+A_2/2+9A_4/32)\,,$$
$$D=35A_4/32\,.$$

The phase factors φ_1, φ_2 depend upon the position of the zero of the time scale and A_0 has been taken as unity. The factor $\exp(-t/\tau_r)$ has been added to take account of any possible relaxation of the alignment due to perturbations other than the magnetic field: For example, any interaction between the electric-quadrupole moment of the 1.13-MeV level and electric-field gradients in the stopping material. Detection at 0° and 90° and the formation of expressions (4) and (5) above gives no information however about the sign of g. For this, detection at some intermediate angle (generally 45°) is required. A preliminary experiment in which the γ-ray detector was placed at 45° with respect to the beam established the sign of g for the 1.13-MeV level to be positive.

III. RESULTS

As mentioned earlier, we observed the precession of the angular distributions of both the direct (0.194-MeV) and cascade (0.937-MeV) γ rays. The perturbed decay curves for the case where the 0.937-MeV γ ray provided the stop signals are given in Fig. 4. The perturbed decay curves for the other case were quite similar. The results of forming the functions (4) and (5) from the data of Fig. 4 are shown in Fig. 5. Also shown are the curves which have been obtained by a least-squares fit to the data points of these functions. Dealing first with the sum function F_+ shown in Fig. 5, it can be seen that there is definite evidence for a finite value of A_4 [cf.

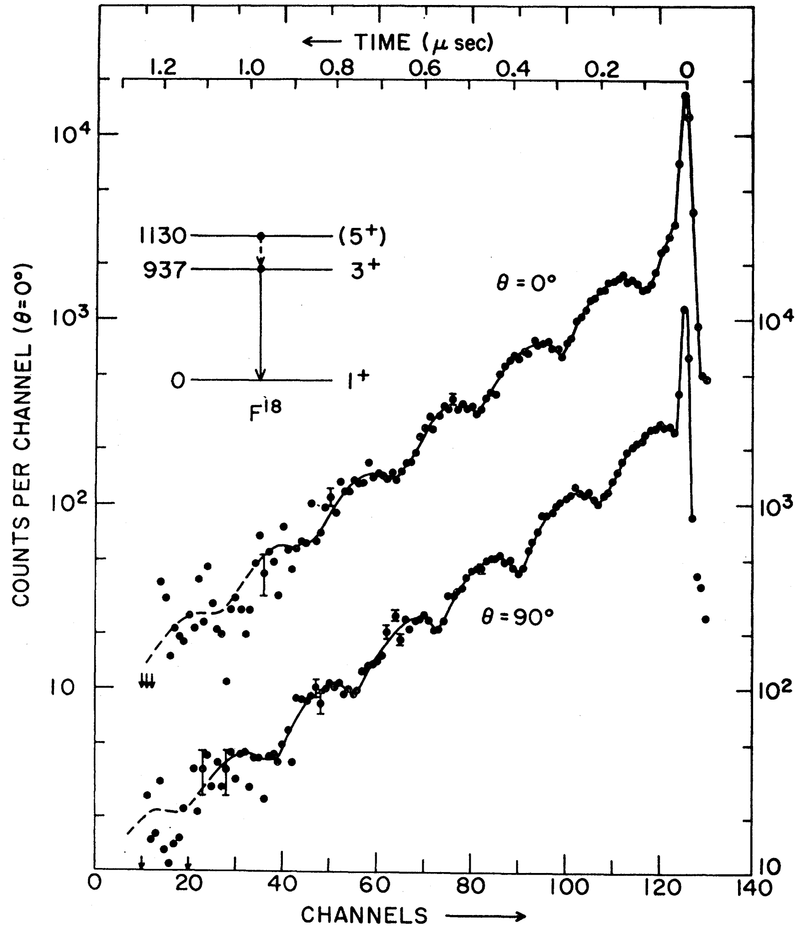

FIG. 4. The perturbed time-delay curves, between protons populating the 1.131-MeV state of F^{18} and γ-rays de-exciting the 0.937-MeV level, obtained using the experimental arrangement shown in Fig. 3. The modulations on the 0° and 90° time-delay curves are exactly out of phase. The effect of the finite value of the A_4 coefficient in Eq. (2) is to round the maxima and sharpen the minima seen on each curve.

Eq. (5)]. Furthermore, from the least-squares fitting for this function we concluded that for the 1.131-MeV level $\tau_m=234\pm10$ nsec. (This is the average of fitting the sum function for the cases where the stop pulses corresponded either to γ rays of 0.937 or 0.194 MeV.) Considering now the difference function, F_-, one of the results of the least-squares fitting of expression (4) was that at the 10% confidence limit, $\tau_r>750$ nsec. The value of the quantity ω_L was completely insensitive to the magnitude of τ_r for $\tau_r>750$ nsec and was found to be $\omega_L=(1.66\pm0.03)\times10^7$ rad/sec (averaging the 0.937- and 0.194-MeV data which were in excellent agreement). A value of ω_L could be extracted from the sum function though with less accuracy. This also was in good agreement with the above value. From the above value of ω_L, the gyromagnetic ratio $g=\omega_L\hbar/\mu_N B$ for the 1.131-MeV level of F^{18} was calculated as, $g=0.568\pm0.013$. For $J=5$, this gives $\mu=2.840\pm0.065$ nm. The coefficients A_2 and A_4 (of Eq. 1) could be estimated quite well by fitting the function $W(\theta=90,t)\exp(t/\tau_m)$ to an expansion $A_0+A_2P_2[\cos(\omega_L t+\varphi_0)+A_4P_4[\cos(\omega_L t+\varphi_0)]$. This gave $A_2=0.30\pm0.02$ and $A_4=-0.15\pm0.02$ for the 0.937-MeV γ ray and $A_2=0.27\pm0.02$ and $A_4=-0.13\pm0.02$ for the 0.194-MeV γ ray. [These results have been corrected for the finite size of the NaI(Tl) detector. For this experiment the attenuation coefficients defined, for example, in Ref. 16 were $Q_2=0.90$ and $Q_4=0.69$ for a 937-keV γ ray and $Q_2=0.88$ and $Q_4=0.63$ for a 194-keV γ ray.]

IV. DISCUSSION

A. The Stopping Process

From a knowledge of the spins involved (assuming the spin of the 1.131-MeV state to be 5) and the alignment expected as a result of detecting the protons in an annular detector at 180°, we estimated that without any perturbation except the static magnetic field $(A_2)_{\text{est}}=0.44\pm0.03$ and $(A_4)_{\text{est}}=-0.22\pm0.03$. The observed values are significantly smaller than these, furthermore the attenuation must take place in a time small compared to $1/\omega_L$, i.e., $\ll6\times10^{-8}$ sec. If it is assumed that this attenuation is caused by a certain fraction f, of the recoiling F^{18} nuclei finally coming to rest in interstitial sites where there could be large electric-field gradients and consequently short relaxation times, then an estimate of f can be made: $f=1-A_k/(A_k)_{\text{est}}\approx0.33\pm0.1$.

B. Nuclear Structure, Comparison with Theory and Other Experiments

To assign a spin of $J=5$ to the 1.131-MeV level of F^{18} is to invoke circumstantial evidence. There has so far been no rigorous spin assignment for this level; however, the case is a strong one. The pieces of evidence are: (1) The nuclear shell model which is quite successful in explaining the positions and decay modes of the other known levels in F^{18} belonging to the $(s,d)^2$ configuration predicts a 5^+ level at about 1 MeV.[1] (2) The parity of

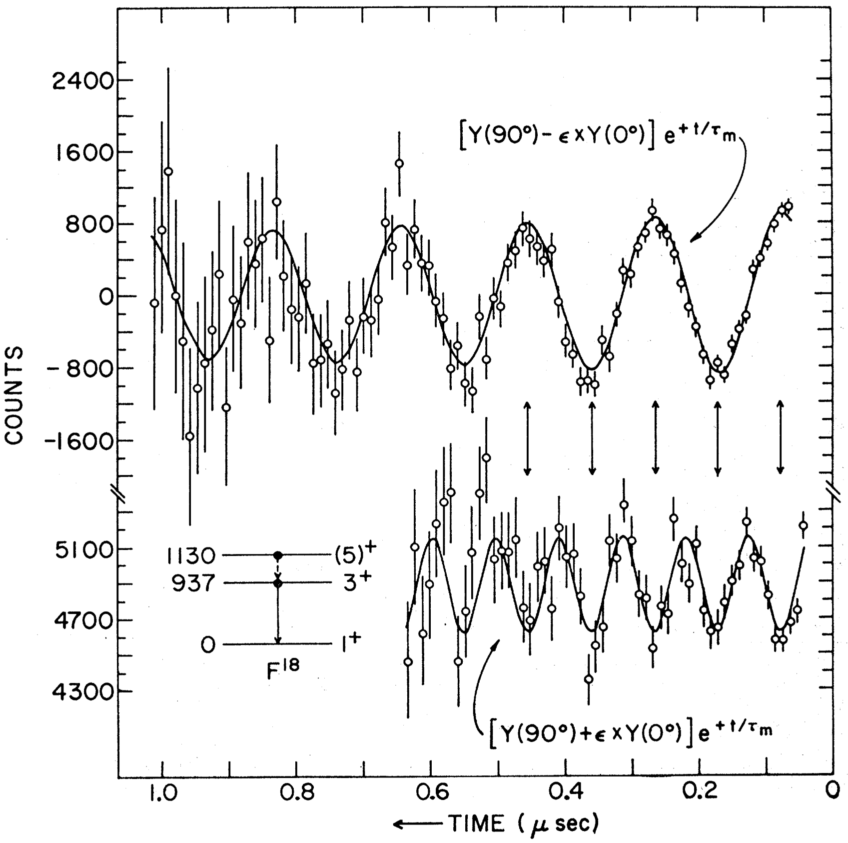

FIG. 5. The experimental points in the upper portion of this figure have been obtained by taking the difference (see text) $[Y(90)-\epsilon Y(0)]\exp(t/\tau_m)$, where $Y(90)$, $Y(0)$ are given in Fig. 4. The continuous damped sine curve is a least-squares fit to the data points as explained in the text. The particular curve shown had a normalized χ^2 of 0.81 and corresponds to $\tau_r=3.2$ μsec; for $\tau_r=\infty$, $\chi^2=0.84$, while for $\tau_r=750$ nsec, $\chi^2=0.98$. The points in the lower portion of the figure have been obtained by taking the sum $[Y(90)+\epsilon Y(0)]\exp(t/\tau_m)$. As shown in Eqs. (4) and (5) the frequency of the upper curve is twice, while the lower curve's frequency is 4 times, the Larmor precession frequency ω_L.

TABLE I. Measurements of the mean life of the 1.131-MeV level of F^{18}.

Measurement	Mean life (nsec)	Adopted mean life (nsec)
[a]	190±45	
[b]	221±21	225±8
Present work	219±10[c] 234±10[d]	

[a] Reference 11.
[b] Reference 9.
[c] This value results from a more accurate analysis (see Sec. IIA) of the data from which the preliminary value $\tau_m=215\pm10$ nsec was extracted. See A. R. Poletti and D. B. Fossan, Bull. Am. Phys. Soc. 11, 368 (1966).
[d] Calibration of the T.A.C. in two independent ways using a 60-nsec delay cable or with the aid of a time-mark generator gave results which agreed within 1%.

the 1.131-MeV level is even[1,17] and the 0.194-MeV γ ray is $E2$ in nature.[17] (3) The lifetime is characteristic of the enhancement predicted by the effective-charge shell-model calculations[18] for an $E2$ transition between the $J=5$ and (lowest) $J=3$ members of the $(s,d)^2$ configuration. (4) The 1.13-MeV level shows a pure $l=2$ stripping pattern in the $O^{17}(He^3,d)F^{18}$ reaction.[19] (5) In the $O^{16}(\alpha,d)F^{18}$ reaction at about 50-MeV bombarding energy[20] a strong peak in the deuteron spectrum has been observed at an excitation energy which corresponds to the 1.13-MeV level. This has been interpreted as due to the preferential excitation of the $(d_{5/2})^2$ $J=5$ configuration in this reaction. The present work adds some further evidence: The experimentally observed g factor is in excellent agreement (see below) with that calculated from the shell model for the $J=5$ state belonging to the $(1d_{5/2})^2$ configuration. It also rigorously excludes the possibility $J=1$ for the first time. Furthermore the identity of the $1.131\rightarrow0.937$ and $(1.131\rightarrow)0.937\rightarrow0$ angular correlations although attenuated from the expected result (see discussion above) is characteristic of a $5\rightarrow3\rightarrow1$ transition, in which both transitions are quadrupole.

The lifetime of the 1.131-MeV level has now been measured in four independent experiments. The results of these are compared and a weighted mean is given in Table I. All four measurements are in good agreement though the present result is somewhat more accurate than previous measurements. This result is in good agreement with that[11] calculated by Elliott ($\tau_m=200$ nsec) on the assumption that the two levels concerned belonged to the $(2s,1d)^2$ configuration of F^{18}.

The value, measured in the present experiment, of $g=0.568\pm0.013$ for the 1.131-MeV level in F^{18} can be very easily compared to the shell-model predictions. For two particles in the $(1d,2s)$ shell there is only one $J=5$ state and the jj and LS coupling models give identical theoretical g factors for this state. The jj-coupling result is[21]

$$g=\tfrac{1}{2}[(g_p)_{5/2}+(g_n)_{5/2}]=0.575\,, \qquad (6)$$

where just the free nucleon g factors have been used for both the proton and neutron. The experimental and theoretical values for the g factor of this state agree to within the 2% experimental uncertainties.

The question regarding quenching of free-nucleon g factors for this state in F^{18} is interesting since the configurations involved are believed to be relatively pure. The possibility of quenching is thought to depend on the interaction of virtual meson currents within the nucleus (exchange effects). Experimental g factors for the $1d_{5/2}$ neutron and proton single-particle states in O^{17} and F^{17} have been measured.[22,23] The g factor for these two states, both of which are ground states, are less than the free-nucleon g factors by only 1–2%. This slight quenching suggests a limited meson-current interaction between the O^{16} core and the $1d_{5/2}$ nucleons. In fact the g factor for the 5^+ F^{18} state obtained by substituting the empirical $1d_{5/2}$ F^{17} and O^{17} g factors into (6) gives $g_{\rm emp}=0.566$ which also agrees with the experimental value. The agreement between theory and experiment for the g factor of this F^{18} state along with the essentially free nucleon g factors observed for the $1d_{5/2}$ states in F^{17} and O^{17} then suggests, that either there is no quenching due to the interaction between the $1d_{5/2}$ neutron and $1d_{5/2}$ proton, or that the quenching from this interaction is equal and opposite for the neutron and proton; that is, of course, to within the 2% experimental uncertainties. This feature of equal and opposite quenching for neutrons and protons with parallel spins is consistent with the theoretical and experimental information regarding the magnetic moment of the deuteron.[24]

Note added in proof. E. K. Warburton (private communication) has shown by using the ratios $A_k(0.194)/A_k(0.937)$ that all spin possibilities for the 1.131-MeV level except $J=5$ are inconsistent with the data of the present experiment. This method of analysis overcame the problems associated with the loss of alignment in the copper backing.

ACKNOWLEDGMENTS

It is a pleasure to thank Dr. A. W. Sunyar for his encouragement and interest in the magnetic-moment experiment.

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