Magnetic moment of the 97-ps, $I^{\pi}=3^{-}$ level in ^{14}C

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The nuclear gyromagnetic ratio of the 6728-keV $I^{\pi}=3^{-}$ level in ^{14}C has been determined by observation of the time-dependent intensity modulations caused by static, isotropic hyperfine fields occurring in hydrogen-like ^{14}C ions recoiling in vacuum. A value $|g|=0.272 \pm 0.007$ is obtained.

[NUCLEAR REACTION $^{3}H(^{13}C,p)$, $E=21$ MeV, measured $I_{\gamma}(\theta,t)$, hyperfine frequency. Deduced g, 6.728 MeV, 3^{-} level.]

1. INTRODUCTION

The shell closure at ^{16}O makes nuclei in this mass region amenable to shell-model calculations and precise measurements of magnetic moments may eventually provide new information on effective nucleon g factors and on mesonic exchange currents in light nuclei. Here we report on one such measurement which makes use of the perturbation of γ-ray intensities by hyperfine interactions in hydrogen-like ions.

The angular distribution of γ rays emitted from high-velocity ions recoiling in vacuum can be highly perturbed. The perturbation can arise if the static magnetic or quadrupole moment of the excited state interacts during its lifetime with the electrons remaining in atomic orbits around the nucleus. In general the perturbation is time-dependent and complex in origin. However, the perturbation in hydrogen-like ions is simple and the magnetic field acting on the nuclear moment can be calculated accurately.[1] To measure magnetic moments of excited nuclear levels with mean lifetimes in the ps range, magnetic fields of several MG are required to produce a measurable precession of the nuclear spin. Therefore there is considerable incentive to understand and use the MG hyperfine fields occurring naturally in highly stripped ions.

Recently, Randolph *et al.*[2] have shown that g factors of short-lived nuclear states can be obtained accurately using the randomly oriented static hyperfine fields produced in hydrogen-like ions after they recoil into vacuum with high velocities. If the ions recoil from the target foil at a velocity where the $q=Z$ (fully stripped), $Z-1$ (hydrogen-like), and $Z-2$ (helium-like) charge states predominate, then the major contribution to the perturbation is from hydrogen-like ions. There is no hyperfine field for the fully stripped ions and the ground-state helium-like ions. For the helium-like ions appreciable fields come only from configurations with unpaired S electrons.

The nuclear magnetic moment of the excited state can be determined from the frequency of the time-dependent intensity modulations of the emitted γ rays. The modulation is caused by the magnetic hyperfine coupling of the aligned nuclear level with the magnetic field produced by the electronic state of the ion. It is worth mentioning that this effect is similar to the quantum beats observed in optical spectroscopy using beam-foil techniques.[3]

In this paper we present the results of a measurement of the g factor of the $I^{\pi}=3^{-}$ 97-ps level in ^{14}C at 6728 keV. A brief description has already been given.[4] Here, additional data are presented that corroborate the interpretation of the modulation phenomenon. The magnetic moment of the 6728-keV level in ^{14}C was studied by observing the intensity modulation of the 6728-keV γ rays produced by the reaction $^{3}H(^{12}C,p\gamma)^{14}C$ ($Q_0=4.634$ MeV). This reaction was chosen to populate the $I^{\pi}=3^{-}$ level with good alignment and to give the recoiling ^{14}C ions sufficient velocity in vacuum ($v/c \simeq 0.04$) that an appreciable fraction (~44%) were in the hydrogen-like ion state. The 3^{-} level in ^{14}C is sufficiently long lived, $\tau=97\pm15$ ps,[5] for the experimental method of Randolph *et al.*[2] to be easily applied.

2. EXPERIMENTAL METHOD

The experiment was designed to measure the nuclear gyromagnetic ratio g of the 3^{-} level in ^{14}C. Since few experiments have been done, the experiment was also designed to obtain data to verify the interpretation of the modulation phenomena.

As the amplitude of the modulations depends strongly on the initial alignment of the decaying level, the unperturbed angular distribution was measured. To do this, a tritium target in the form of a 200-$\mu g/cm^2$-thick layer of titanium hydride on a thick tantalum backing was bombarded with a 21-MeV $^{12}C^{3+}$ beam. The 3^- level in ^{14}C nuclei produced by the $^3H(^{12}C, p)^{14}C$ reaction was found to be highly aligned. The $3^- \rightarrow 0^+$ γ-ray angular distribution was measured from 0 to 90° in 15° intervals with a 19% efficient Ge(Li) detector. The measured angular distribution is:

$$W(\theta) = 1 + \sum_{k=2,4,6} Q_k A_k P_k(\cos\theta) \tag{1}$$

with $Q_2A_2 = 0.72 \pm 0.05$, $Q_4A_4 = 0.09 \pm 0.06$, and $Q_6A_6 = 0.39 \pm 0.07$. For the g-factor measurement different targets with the same nominal thickness (200 $\mu g/cm^2$) of titanium hydride but on thin (~700-$\mu g/cm^2$) copper backings were used. This allowed the ^{14}C nuclei to recoil into vacuum through the copper foil. To be certain that the results were insensitive to the titanium hydride target thickness, angular distributions from backed targets were also measured at bombarding energies of 20 and 22 MeV. The distributions were found to be insensitive to the bombarding energy and similar to the distribution at 21 MeV. The unperturbed distribution obtained at 21 MeV with the Ta-backed target is shown in Fig. 1 and labeled $t = 0$, $2\pi/\omega$, ... The dashed curved labeled $t = \pi/\omega$, $3\pi/\omega$, ... in Fig. 1 is the expected perturbed angular distribution calculated as described below assuming all excited nuclei are perturbed. The hyperfine interactions cause the intensity $W(\theta, t)$ to oscillate between these two extremes at a frequency $\nu = \omega/2\pi$. In practice only a fraction of the recoiling nuclei f_5, where the subscript indicates the ionization state, are hydrogen like and the size of the modulation is considerably smaller than shown at the top of Fig. 1. The curves in the bottom graph in Fig. 1 show the peak-to-peak amplitude of the modulation as a function of the detector angle θ. The solid line assumes $f_5 = 0.44$ and the dashed line $f_5 = 0.55$. The points are data from measurements with two large Ge(Li) detectors.

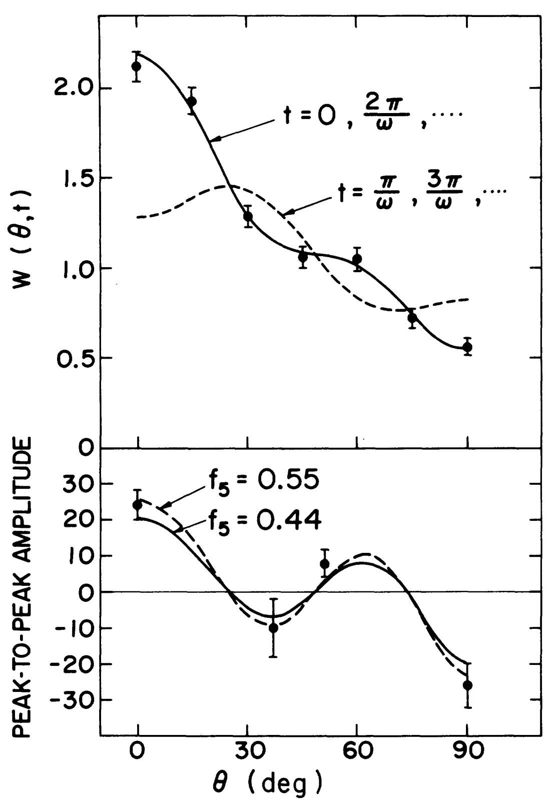

FIG. 1. $W(\theta, t)$, the angular distribution of 6728-keV γ rays from the 3^- level in ^{14}C excited in the $^3H(^{12}C, p)^{14}C$ reaction. The data points were observed using a Ta-backed target. The dashed curve labeled $t = \pi/\omega$, $3\pi/\omega$ ... is calculated from the experimental curve assuming a static hyperfine interaction due to $1s$ electrons. The observed and calculated peak-to-peak amplitude of intensity modulations are shown at the bottom of the figure. f_5 is the fraction of hydrogen-like ^{14}C ions.

The curves in Fig. 1 were calculated by considering the following. In the $^3H(^{12}C, p\gamma)^{14}C$ reaction, the ^{14}C ions recoil within a cone of half-angle $= 5.1°$ with an average velocity of $v \simeq 0.04c$ and form a large fraction ($f_5 \approx 0.44$ [6]) of hydrogen-like ions $^{14}C^{5+}$ if they recoil into vacuum. For these ions, hyperfine interactions perturb the angular distribution. The result of the perturbation can be detected as a function of time by stopping the ions in a metal stopper placed at a distance $d = vt$ from the target foil. The perturbation quickly terminates when the ions enter the metal since rapid charge exchange effectively decouples the nuclear moment from the hyperfine fields. The intensity of the γ rays from nuclei in the hydrogen-like ion state which have traveled for a time t in vacuum before decaying is given by[7]:

$$I_0(\theta, t) = N_0 e^{-t/\tau}\left[1 + \sum_k G_k(t) Q_k A_k P_k(\cos\theta)\right], \tag{2}$$

where

$$G_k(t) = \left[1 - \frac{k(k+1)}{(2I+1)^2}\right] + \frac{k(k+1)}{(2I+1)^2}\cos\omega t,$$

$$\omega = (2I+1)g\frac{\mu_N H(0)}{\hbar},$$

$$H(0) = 0.167Z^3 = 36.07 \text{ MG} \quad \text{(Ref. 1)}.$$

Similar expressions can be derived for other states of ionization of the recoiling ion. If one assumes that the perturbation comes only from the hydrogen-like ions, then the observed intensity of γ rays in the "stopped" peak is:

$$I(\theta, t) = f_5 I_0(\theta, t) + (1 - f_5) I_0(\theta, 0),$$

where f_5 is the fraction of hydrogen-like ions and $I_0(\theta, 0)$ is the unperturbed intensity [at $t=0$ Eq. (2) reduces to Eq. (1)].

The peak-to-peak amplitude of the modulation caused by the hydrogen-like ions in the population expressed as a fraction of the average intensity is then given by:

$$2S(\theta) = \frac{I_0(\theta, 0) - I_0(\theta, \pi/\omega)}{1/2[I_0(\theta, 0) + I_0(\theta, \pi/\omega)] + [(1 - f_5)/f_5] I_0(\theta, 0)}. \tag{3}$$

As can be seen from Fig. 1, there are angles θ where the modulation is zero, positive, or negative.

The target chamber containing the plunger apparatus[8] was modified such that movement of the gold stopper is accomplished by a differential micrometer driven by a stepping motor controllable by an on-line PDP-1 computer. The plunger was programmed to step (minimum step = 1.27 μm) through a set of prescribed distances and to recycle for repeated observations. γ rays were detected in a 5% efficient Ge(Li) detector placed at 0° and in a 12.7-cm-diam by 15.2-cm-long NaI(Tl) detector placed at 90°. In a second series of runs, two Ge(Li) detectors of 19 and 10% efficiency were used to observe the γ ray at angles of 0, 37, 90, and 129°. The γ-ray spectra were accumulated in the PDP-1 computer memory. For each plunger setting the electrical capacity between the target and stopper was recorded in a pulse-height spectrum.[8] Both this capacity and the γ-ray spectra were written on magnetic tape automatically after a preset time interval had elapsed. The yield of the 6728-keV γ rays from ^{14}C was normalized to the yield of the isotropic, 2313-keV γ rays from the first excited level ($I^\pi = 0^+$) in ^{14}N populated in the ^{3}H(^{12}C, n)^{14}N reaction.

Typical Ge(Li) spectra obtained at three distances are shown in Fig. 2. The bottom spectrum was taken at a large distance so that the velocity distribution of the recoiling ions and its mean value could be experimentally determined from the Doppler-shifted line shape.

3. RESULTS AND ANALYSIS PROCEDURE

The data from a 10% efficient Ge(Li) detector placed at 0° during a set of measurements are

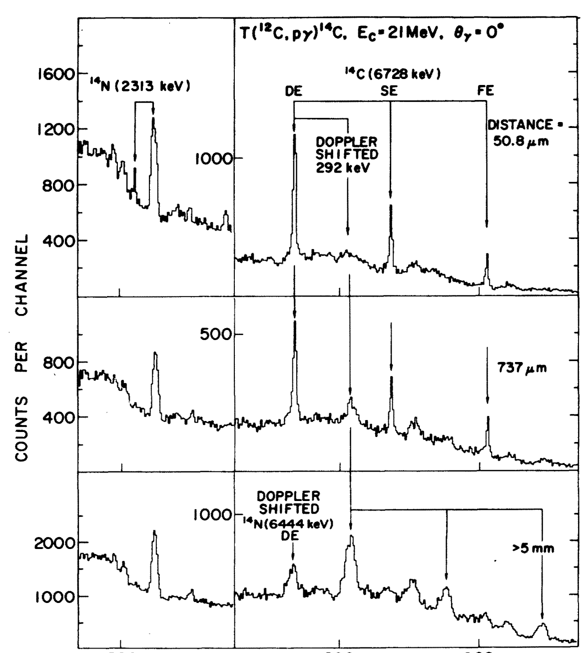

FIG. 2. Portions of the γ-ray spectra observed with a 40-cm^3 Ge(Li) detector at $\theta_\gamma = 0°$. The "stopped" and Doppler-shifted γ rays from the 3$^-$ 6728-keV level of ^{14}C and the 0$^+$ 2313-keV level of ^{14}N are indicated for various target-to-stopper distances.

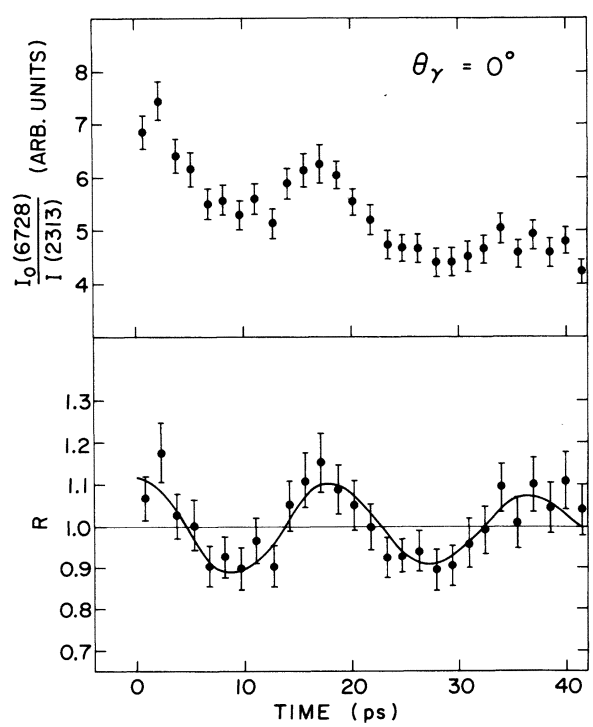

FIG. 3. The experimental data and the fitted curve for the intensity modulation of the 6728-keV γ rays observed at $\theta_\gamma = 0°$. The top curve shows the intensity normalized to the isotropic 2313-keV γ ray from ^{14}N. The ratio R in the bottom graph is explained in the text.

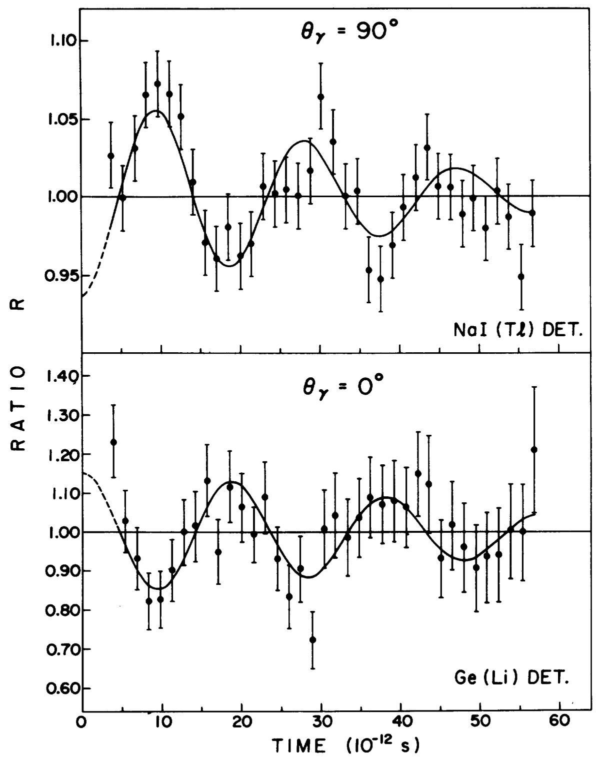

FIG. 4. The experimental data and the fitted curves for the intensity modulation of the 6728-keV γ rays observed at $\theta_\gamma = 90$ and 0°. The ratio R is explained in the text.

shown in Fig. 3. The top curve shows the ratio of the intensity of the 6728-keV "stopped" peak I_0 to the total intensity of the 2313-keV γ rays. A considerable deviation from a pure exponential decay is observed in the data. In the lower half of Fig. 3, the exponential decay of the intensity has been removed so that the percentage amplitude of the intensity modulated by $\cos\omega t$ can be easily seen. To accomplish this, the data from the Ge(Li) detector were fitted by a least-squares procedure to a function of the form:

$$I = \sum_i \left[A + B\cos\left(\omega\frac{d-d_0}{v_i\tau} + \phi\right)\right] a_i e^{-(d-d_0)/v_i\tau} + K, \tag{4}$$

where: A is the unmodulated intensity; B is the modulated intensity; d is the micrometer setting; d_0 is the micrometer setting for zero distance; ϕ is the phase angle; τ is the mean lifetime of the nuclear level; and K is the constant that accounts for systematic inaccuracies in background subtraction. (a_i, v_i) is the velocity distribution where $v_{\rm mean} = \sum_i a_i v_i, \sum_i a_i = 1$, and a_i is the fraction of ions with velocity v_i. The velocity distribution (a_i, v_i) was derived from the Doppler-shifted line shape observed at 0° taking into account relativistic effects. If the line-shape spectrum has intensity A_i at energy E_i, then

$$a_i = A_i\left(1 - 2\frac{v_i}{c}\right)\frac{1}{\epsilon(E_i)}, \tag{5}$$

$$v_i = \frac{E_i^2 - E_0^2}{E_i^2 + E_0^2}c,$$

where E_0 is the energy of the unshifted γ ray. The first relation takes into account the change in solid angle subtended by the detector due to the moving source and the change in the detector efficiency $\epsilon(E_i)$ with γ-ray energy. The second relation in (5) is the relativistic Doppler-shift formula.

In the bottom half of Fig. 3, the ratio

$$R = (I - K)/\left\{A\sum_i a_i \exp[-(d-d_0)/v_i\tau]\right\}$$

is plotted for both the experimental (points) and fitted (curve) values of I. In both cases the fitted values of the parameters are used. At $t = 0$, $R = 1 + B/A\cos\phi$ and $B/A = S(\theta)$, the percentage amplitude of the oscillation. In the fitting procedure A, B, ω, ϕ, τ, and K could be determined by the fitting or held at a preset value. The parameter K accounts for the intensity of the Doppler-shifted 6444-keV γ ray from ^{14}N since it lies close to the 6728-keV transition (see Fig. 2) at $\theta_\gamma = 0°$. The velocity distribution (a_i, v_i) accounts for the significant "damping" of the cosine term caused by time-of-arrival spread, in the fit shown for the Ge(Li) detector in Figs. 3 and 4.

The NaI(Tl) data were fitted to a similar function which takes into account that the shifted and unshifted γ rays both contribute to the intensity. For this case:

$$I = A + B\left(\frac{d\Omega}{d\Omega'}\left(\frac{\cos\phi - \omega\tau\sin\phi}{1+(\omega\tau)^2}\right) + \sum_i\left\{\cos\left(\omega\frac{d-d_0}{v_i\tau} + \phi\right) + \frac{d\Omega}{d\Omega'}\frac{1}{1+(\omega\tau)^2}\right.\right.$$

$$\left.\left.\times\left[\omega\tau\sin\left(\omega\frac{d-d_0}{v_i} + \phi\right) - \cos\left(\omega\frac{d-d_0}{v_i} + \phi\right)\right]\right\} a_i e^{-(d-d_0)/v_i\tau}\right) + K, \tag{6}$$

where $d\Omega/d\Omega' = [1-(\bar{v}/c)\cos\theta_\gamma]^2/[1-(\bar{v}/c)^2]$ is the ratio of the solid angle subtended by the γ detector for the Doppler-shifted peak (moving source) to that for the stopped peak.

$$I \simeq A + B\sum_i \left[\cos\left(\omega\frac{d-d_0}{v_i}+\phi\right)\right] a_i e^{-(d-d_0)/v_i\tau} + K$$

when $\omega\tau \gg 1$ and $\theta_\gamma = 90°$. Thus the amplitude of the oscillation in the NaI(Tl) data is also damped by the mean lifetime τ. This is illustrated in Fig. 4 where data from a set of measurements with a 5% efficient Ge(Li) detector and a NaI(Tl) detector at 0 and 90° for distances from 50.8 to 737 μm in 19.05-μm steps are shown. The modulation at $t=0$ is positive at $\theta_\gamma = 0^6$ and negative at 90° as predicted by Eq. (3) for the angular distribution shown in Fig. 1. The time scales shown in Figs. 3 and 4 were derived from the distance scale and the measured velocity obtained from the Doppler shift of the 6728-keV γ rays (see Fig. 2) and the relativistic Doppler formula. The zero of the distance scale was determined by measurement of the target-stopper capacity.

A summary of the results from the first series of measurements is shown in Table I. Sets of data, as shown in Fig. 4, from the Ge(Li) detector at 0° and the NaI(Tl) detector at 90° were obtained concurrently. The last entry in Table I gives the result of an independent lifetime measurement with a Ge(Li) detector at 51° and $\tau = 98 \pm 20$ ps in good agreement with the previously published value of $\tau = 97 \pm 15$ ps.[5] For the purpose of extracting ω from the data at 0 and 90°, the lifetime was fixed at 97 ps. Assuming a field $H(0) = 36.07$ MG, the weighted average of the values of $|g|$ is 0.272 $\pm$ 0.007, where the uncertainty includes the statistical errors from Table I and the uncertainty in the measured value of $v_{\mathrm{mean}} = (0.0425 \pm 0.0003)c$. The value $v_{\mathrm{mean}} = 0.042c$ calculated from the kinematics and foil thicknesses is in good agreement. In Table I the value of $S = B/A$ for the NaI(Tl) detector at 90° cannot be compared with the prediction shown in Fig. 1. This occurs because the constant K cannot be determined in an unambiguous way for the NaI(Tl) data.

A second series of measurements was obtained for the purpose of measuring the ratio S at angles of 0, 37, 129, and 90°. Ge(Li) detectors were used at all angles. The results of these measurements are shown as the experimental points in the bottom graph of Fig. 1. The data fit reasonably well with the calculated curve for a charge fraction f_5 equal to the empirically derived value $f_5 = 0.44$.[6] A larger value $f_5 = 0.55$ gives a better fit to the data.

In the analysis of the data, allowance has been made for an arbitrary phase ϕ for the oscillation. If the hyperfine interaction begins as soon as the ions leave the foil and is quenched when the ions enter the metal stopper, then ϕ would be zero. The determination of the zero of distance from capacity measurements together with the fitted values of ϕ allows us to estimate that the apparent time when the perturbation begins after the ions leave the foil is 1.8 ± 0.4 ps.

4. DISCUSSION

The 3^- 6728-keV level of ^{14}C is believed to have a dominant configuration $(p_{1/2}^{-3}d_{5/2})$ relative to a closed-shell ^{16}O core. If the configuration were pure, then one would expect the magnetic moment to be $\mu[^{14}C(3^-)] \simeq \mu(^{13}C) + \mu(^{17}O)$, yielding $g = -0.40$. It is seen that this naive interpretation is not adequate to predict the small g factor observed. A detailed shell-model calculation based on an ^{16}O core with three holes in the $1p_{3/2}$ and $1p_{1/2}$ orbitals and one particle in the $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ orbitals has been carried out.[9] The Cohen and Kurath[10] two-body matrix elements were used for the residual interaction between the p-shell nucleons and the Gillet[11] particle-hole force was used for the p-shell to sd-shell interaction. This calculation is shown in Fig. 5 where the absolute value of the gyromagnetic ratio of the 3^- level in ^{14}C is shown

TABLE I. Summary of data analysis.

$\theta\gamma$ (deg)	B/A (%)	ω (10^{12} rad/s)	ϕ (deg)	τ (ps)	K (%)	χ^2 norm	$\lvert g \rvert$
90	-8.2 ± 1.6	0.325 ± 0.021	22 ± 21	97	...	4.5	0.269 ± 0.018
0	12.2 ± 2.6	0.320 ± 0.023	3 ± 24	97	0.06 ± 0.14	1.4	0.265 ± 0.019
90	-6.3 ± 0.9	0.329 ± 0.011	-5 ± 13	97	...	1.2	0.272 ± 0.009
0	15.0 ± 3.0	0.332 ± 0.016	-13 ± 20	97	0.50 ± 0.08	0.8	0.275 ± 0.013
						$\langle g \rangle_{\mathrm{ave}} =$	0.272 ± 0.007
51	...	...	...	98 ± 20	0	5.6	...

as a function of the strength of the particle-hole force V_0. The calculation yields $g = -0.261$ for $V_0 = 40$ MeV in good agreement with experiment. The value $V_0 = 40$ MeV agrees with that obtained by Gillet and Vinh Mau[11] who fitted energy levels in ^{12}C and ^{16}O. The calculated[9] and measured[2] absolute values for the g factor of the 3^- level in ^{16}O are also shown. It is seen that the ^{14}C magnetic moment is quite sensitive to the strength of the particle-hole potential V_0 in contrast to the ^{16}O moment. The reason is that for ^{14}C, a $T_z = 1$ nucleus, there is a cancellation between the positive isoscalar and the larger but negative isovector contributions to the moment, whereas only the isoscalar component contributes in ^{16}O.

The present investigation also gives some information on the atomic physics involved in highly stripped ions. The form of the time-dependent perturbation agrees with the formula (2) and the amplitude of the oscillation agrees with the accepted value[6] for the fraction of hydrogen-like ions at the recoil velocity used. These points are illustrated in Fig. 1.

We have shown from the phase of the oscillations that the perturbation begins 1.8 ± 0.4 ps after the ions leave the foil. This time interval is difficult to interpret, but can be regarded as an upper limit on the time necessary to populate the atomic ground state of the $^{14}C^{5+}$ ions. It is interesting to note that the field produced by a $2p$ electron is weak compared to that of a $1s$ electron and the lifetime of the $2p_{1/2} \rightarrow 1s_{1/2}$ transition in C^{5+} is 1.2 ps.[12] This time is short enough that the proportion of the recoiling atoms that start out in the $2p$ state cannot be determined from the present experiment. The $2s_{1/2} \rightarrow 1s_{1/2}$ lifetime is 2.6 μs,[12] but the magnetic field generated at the nucleus from an electron in the $2s$ state would be about an order of magnitude smaller than that for a $1s$ electron.[13] If this state were populated, then our experiment would be insensitive to its static field. However the amplitude of the observed oscillations is consistent with the empirically derived[6] value of the charge fraction f_5. Thus only a negligible fraction of the hydrogen-like ions are in the $2s$ metastable state. This is consistent with the results of Kugel, Leventhal, and Murnick[12] who found that the pickup cross section for $2s$ electrons is only $(2.2 \pm 1)\%$ of the total cross section. The lifetimes of higher atomic levels are longer than ~5 ps. Our data would indicate that these states are formed in only a small fraction of the ions. The experiment of Faessler, Povh, and Schwalm,[14] who measured time-integrated attenuation coefficients for the decay of the short lived ^{20}Ne first excited level, indicates a feed time to the atomic ground state of less than 1 ps. The present value of 1.8 ± 0.4 ps for $^{14}C^{5+}$ ions is not inconsistent with these results since the dipole transition rates are proportional to Z^4. The feed-time value would then be 0.2 ps in ^{20}Ne.

The fraction of helium-like ions in the present

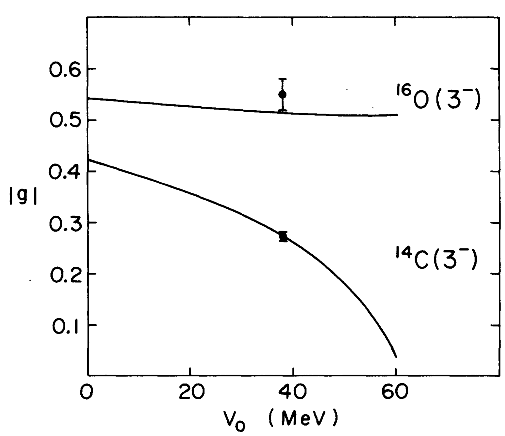

FIG. 5. The theoretical absolute values of the g factor of the 3^- levels in ^{16}O and ^{14}C as a function of the strength of the particle-hole force V_0. The experimental values of $|g|$ are also shown.

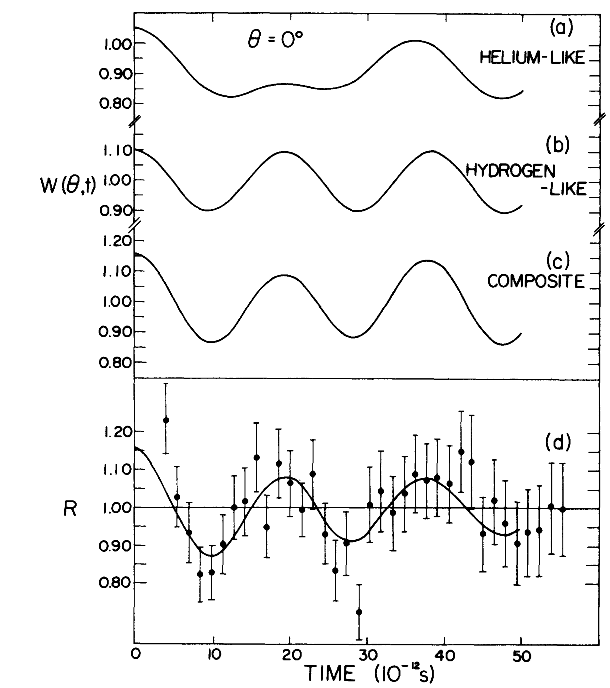

FIG. 6. Calculations of the effect of excited helium-like ions on the angular distribution. Curve (a) is for only helium-like ions in the ^3S state, W_4. Curve (b) is for only hydrogen-like ions, W_5. Curve (c) combines (a) and (b) as described in the text. Curve (d) is the result of folding in time-of-flight spread into curve (c). Data are shown for comparison.

experiment is expected to be large, $f_4 = 0.48$.[6] From their data on ^{18}O, Goldring *et al.*[15] have estimated that between 14 to 37% of the He-like ions will be in configurations with an unpaired $1s$ electron. These configurations can produce fields at the nucleus of the same order as hydrogen-like ions and have atomic lifetimes long enough to be considered static.[16] To investigate possible effects on our data from the presence of excited helium-like ions, the attenuation factors $G_k(t)$ associated with the $(1s2s)\ ^3S$ term have been calculated. The method described by Bethe and Salpeter[17] was used to calculate the hyperfine frequencies. The fraction of excited helium-like ions α_4 was assumed to be composed only of the ^3S term and to be ≤ 0.37.[15] The remaining fraction was assumed to be in the ground state or in configurations with no hyperfine interaction. The $W_4(\theta, t)$ resulting from this calculation is plotted in Fig. 6(a) as a function of time for $\theta = 0°$. The shape of $W_4(\theta, t)$ is determined by three hyperfine frequencies $\omega_{FF'}$, and is not like the pure cosine function observed. In Fig. 6(a) the nuclear g factor has been taken to be 0.272 resulting in the frequencies $\omega_{43} = 0.195 \times 10^{12}$, $\omega_{32} = 0.146 \times 10^{12}$, and $\omega_{42} = 0.341 \times 10^{12}$ rad/s.

The perturbation from both hydrogen-like and helium-like ions can be approximated by

$$W(\theta, t) = f_5 W_5(\theta, t) + f_4 \alpha_4 W_4(\theta, t) + (1 - f_5 - f_4\alpha_4) W(\theta, 0), \tag{7}$$

where the charge fractions $f_5 = 0.44$ and $f_4 = 0.48$. In Fig. 6(b) the perturbation due only to hydrogen-like ions $W_5(\theta, t)$ is plotted for comparison with $W_4(\theta, t)$. Figure 6(c) shows the composite as expressed by Eq. (7) with $\alpha_4 = 0.37$. It is seen that the dominant frequency is still the hyperfine frequency from the hydrogen-like ions even when $\alpha_4 = 0.37$. To estimate the effect of ignoring the presence of excited helium-like ions in determining $|g|$, the fitting procedure used in analyzing the experimental data was also applied to curve (c) of Fig. 6. The single frequency which was the best fit to this curve differed by less than 1% from that due to the hydrogen-like component alone, indicating that the helium-like ions have little effect even for $\alpha_4 = 0.37$.

The composite curve shown in Fig. 6(c) has been folded with the appropriate time-of-flight spread and compared directly with experimental data in Fig. 6(d). It is clear that the theoretical curve including fields from helium-like ions agrees with the data. An experiment with better statistical accuracy and smaller time-of-flight spread would be required to determine if excited helium-like ions were playing a role. However, as described above, it is our belief that the presence of such ions does not add uncertainty to the g factor extracted from the data.

In summary it has been found that the method of Randolph *et al.*[2] can be successfully applied in a singles γ-ray measurement. The observed modulations are entirely consistent in amplitude, phase, and frequency with the interpretation that they result from randomly-oriented static hyperfine interactions in hydrogen-like ions and, therefore, provide a powerful method of measuring magnetic moments of short-lived nuclear levels.

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