foil interaction at 40 kV. The alignment was found to be 12%.

In conclusion, the beam-foil level-crossing method combines the best features of the beam-foil and level-crossing techniques. On the one hand, beam foil offers a universal means of producing coherently excited states, bypassing the technical difficulties of electron excitation in magnetic fields; on the other hand, level crossing is inherently more accurate for lifetime determinations. Furthermore, the alignment induced in the beam-foil interaction process can be determined simultaneously with the lifetimes. It is of interest that the measured lifetimes tend to be lower than the theoretical value which is based on calculated oscillator strengths[11] and this may indicate that systematic effects are still of importance. The method is being extended, in the case of the triplet states, to high-field level crossing.[12] In the case of high-field level crossing, cascading can be significant only if in addition to alignment transfer from the upper state to the state under observation level crossings occur in the upper state at the same magnetic field value as for the state under observation. Since the latter is highly unlikely, high-field level crossing should be largely free from the influence of cascades.

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Observations with Oriented Nuclei of One-Electron Atoms of F^{19}†

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Substantial nuclear orientation of excited F^{19} has been preserved in flight through vacuum at velocities where only a few electrons remain bound. Identification of the fraction of atoms with one electron has been made by applying a weak field and observing the effect of the atomic precession in flight on the γ-ray angular correlation.

The strong hyperfine interactions observed in highly ionized atoms have been previously used to measure g factors of short-lived nuclear states.[1-3] In particular, few-electron systems have shown promise for such measurements because of the possibility of static interactions and calculable hyperfine fields. The present work elucidates the interactions taking place in vacuum and reports measurements of the fraction of atoms traversing the flight region in a particular atomic state.

A beam of F^{19} ions from the Stony Brook FN tandem impinges on a Au scattering foil as shown in Fig. 1. The projectile is Coulomb excited to the $I=\frac{5}{2}$, $\tau_{1/2}=89$ nsec level at 197 keV, and the F^{19} nuclei scattered through an average angle of 40° pass down a flight path to a Cu catcher foil. Because the scattering process detected in this experiment does not have symmetry around the beam direction, the excited nuclear state is oriented perpendicular to the scattering plane. If this orientation is preserved in flight to the catcher foil, an anisotropic γ-ray angular distribution is observed.

The beam energy is chosen so that the scattered F^{19} are stripped to few-electron atoms in

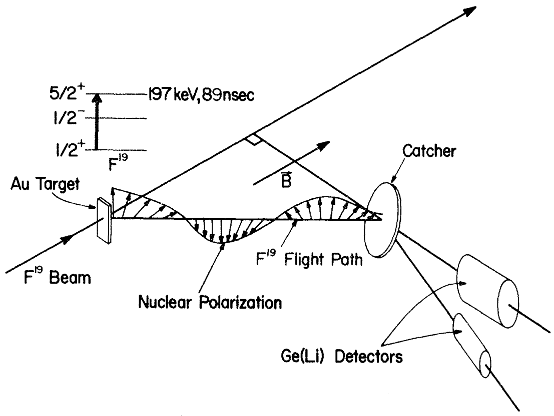

FIG. 1. Experimental geometry. The Z axis is along the beam direction and the X axis points toward the counter in the scattering plane. Pb shielding which allows only γ rays coming from the catcher to be counted is not shown.

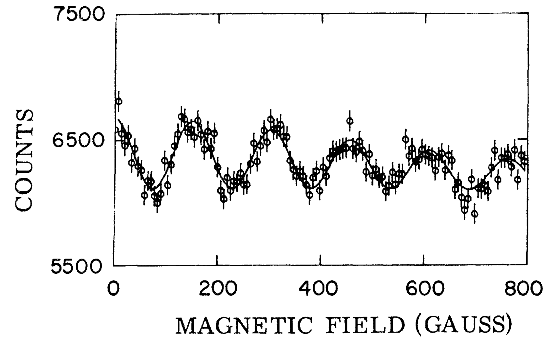

FIG. 2. Counting rate in 197-keV γ-ray window as a function of axial magnetic field for an incident energy of 45.0 MeV.

the gold foil. The one-electron atom in its ground state has $J=\frac{1}{2}$ and can couple to the $I=\frac{5}{2}$ nucleus to make $F=2, 3$. During the flight time of $t\approx 10$ nsec, the precession of I around F at the hyperfine frequency ($\sim 10^{11}$ Hz) modulates the anisotropy of the γ-ray angular correlation. Although the target is tilted and the catcher curved to make all flight times constant to within 100 psec, the phase of this fast modulation when averaged over the catcher is random, and only the "hard-core" anisotropy of the free-atom perturbation is transferred to the catcher.

A weak field of less than 10^3 G applied along the beam axis couples to the magnetic moment of the hydrogenlike atom and generates a precession of the atom around the field direction at the Larmor frequency. The nuclear orientation follows the atomic precession because of the strong hyperfine coupling. Nuclei with no electrons and singlet heliumlike atoms have no hyperfine interaction and precess at the nuclear Larmor frequency. When the atom enters the catcher foil, it quickly slows down and regains its electron shell, turning off the strong hyperfine interaction. The external field can then interact only with the small nuclear moment before the nuclear state decays: Thus the nuclear orientation is essentially "frozen" at the time of implantation in the catcher foil. A Ge(Li) detector in the scattering plane at 90° to the beam axis detects the 197-keV decay radiation. At zero field, the orientation direction (averaged over the fast modulation) stays fixed in flight, while at higher fields, the orientation is rotated in flight through larger angles. By sweeping the magnetic field, the angular correlation pattern is rotated past the fixed counter, thus modulating the singles counting rate as shown in Fig. 2.

The oscillations have been observed with different incident beam energies and different target thicknesses. The precession angle at maximum field in each run was observed to be proportional to the flight time, indicating that the same atomic g factor was being observed over the wide range of energies. A careful mapping of the field profile with an NMR probe allowed us to determine the atomic g factor as $|g|=0.33\pm 0.01$. The atomic g factors, g_F, for hydrogenlike F^{19} are $g_2=-0.3324$ and $g_3=0.3340$. The precision of the g factor is limited by uncertainties in the velocity due to the rather large energy loss in the target. By using thinner targets, it might be possible to achieve a precision of 0.1% for the g factor. Further improvements would require a precise measurement of the velocity.

The damping of the oscillation observed at high field can be explained by the interaction of the external field with the nuclear moment in the catcher. This small perturbation integrated over the nuclear lifetime both attenuates the angular correlation and produces a small precession. Since the two F states have g factors of opposite sign, the precession angle in flight adds to the small precession angle in the catcher for one value of F and subtracts for the other, yielding a beat pattern from two cosines differing slightly in frequency. The smooth curve shown in Fig. 2 is of the form[4]

$$W(B) = \sum_F f_F \sum_N b_N(F)[1 + (N\omega_I \tau)^2]^{1/2} \cos[N(g_F \mu_B Bt/\hbar + \Delta\varphi_N + \varphi_\gamma)], \quad (1)$$

where μ_B is the Bohr magneton, ω_I is the nuclear Larmor frequency in the field B, and $\tan(N\Delta\varphi_N) = N\omega_I \tau$. The coefficient f_F is the fraction of atoms emitted in a particular F state, and the coefficient b_N is given by

$$b_N(F) = \sum_k (2k+1)^{-1} A_k \{\rho_N{}^k\} \sqrt{4\pi}\, Y_{kN}(\theta_\gamma, 0) G_{kk}{}^\infty(F) G_{kk}(\text{Cu}) Q_k, \quad (2)$$

where the coefficients in curly brackets are the statistical tensors describing the excited state which are calculated from the Winther–de Boer Coulomb excitation code,[5] and A_k is the usual γ-ray angular correlation parameter. The factor $G_{kk}{}^\infty(F)$ accounts for the hard-core attenuation in flight, and the factor $G_{kk}(\text{Cu})$ accounts for the loss of 25% of the alignment on implantation into Cu.[6] Q_k is the usual geometrical attenuation coefficient. In our case, the two cosines in Eq. (1) do not differ sufficiently in frequency to allow extraction of f_2 and f_3 separately, so we assumed weights of $2F+1$ and extracted $f = f_2 + f_3$ from the data. Table I shows these fractions along with the other quantities measured. A second detector 45° below the reaction plane gave a very small oscillation amplitude because the two cosines add out of phase.

The measured fractions of atoms with $|g| = \frac{1}{3}$ follows the general trend of the empirically determined[7] charge-state fraction for +8 shown in Fig. 3, but falls about 20% lower than the curve. Since our measurement is an absolute measurement we were very careful to ensure that we were not observing any 197-keV γ rays from other than the Cu catcher, as they would have diluted the apparent anisotropy. As an additional measurement to see if the fraction was indeed less than the expected value, a carbon foil was inserted halfway down the flight path. Assuming that a fluorine atom, in passing through a carbon foil, emerges with the same equilibrium charge-state fractions as for the target foil, but with no correlation between entrance state and exit state, we expect the amplitude of oscillations at $\frac{1}{2}$ of the usual frequency to be proportional to $2f(1-f)$. An independent determination of f with this method agrees with the value arrived at by the absolute measurement and is included in Table I. The lowest-energy datum point is slightly higher than the +8 charge fraction, probably indicating some contribution from three-electron atoms in the $^2S_{1/2}$ ground state, which also have $|g| = \frac{1}{3}$.

Any hydrogenic atoms emitted from the foil with orbital angular momentum $l > 5$ will contribute with random phase to our oscillations because they will spend at least $\frac{1}{2}$ nsec in flight in excited states with weak hyperfine interaction. If we assume that the charge-state fractions of Ref. 7 are exact, then the 20% difference in charge fraction that we observe is an upper limit on the fraction of atoms emitted in higher l states from the foil. This small fraction is con-

TABLE I. Experimental results and parameters.

Beam energy (MeV)	Exit energy (MeV)	Flight time (nsec)	Oscillation frequency (10^{-2} G^{-1})	$b_2(2) + b_2(3)$[a]	$f_2 + f_3$[b] (%)
32.0	20.0	8.8	3.31(6)	0.231	26.6(3.5)
40.0	29.4	7.0	2.59(1)	0.209	34.8(1.6)
43.0	32.6	6.6	2.48(2)	0.196	40.3(2.2)
47.0	36.8	6.3	2.31(1)	0.190	44.8(2.2)
51.0	40.5	6.0	2.19(2)	0.180	46.7(2.7)
54.0	44.0	5.7	2.09(2)	0.171	46.2(2.2)
61.0	51.5	5.3	1.91(3)	0.157	45.3(4.0)
45.0[c]	28.3	7.1	2.63(1)	0.203	32.3(2.2)
45.0[c]	28.3	7.1	1.39(2)[d]	0.203	31.3(1.4)

[a] See text.

[b] An additional 10% error in the absolute normalization has not been included. This error arises from the uncertainty in $G_{22}{}^\infty(\text{Cu})$.

[c] Target thickness of 5.44 mg/cm^2, all others have 3.56 mg/cm^2.

[d] 100-μg/cm^2 carbon foil placed halfway down flight path.

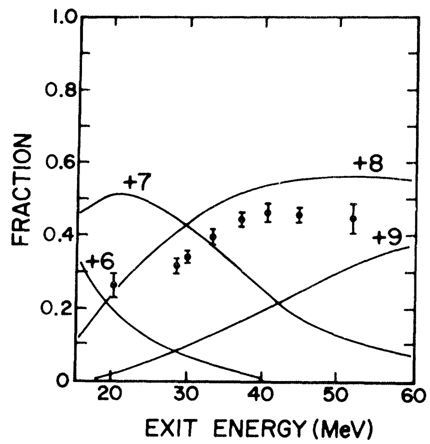

FIG. 3. Data points are fraction of atoms with $|g| = \frac{1}{3}$. Smooth curves are charge-state fractions from Ref. 7.

sistent with our expectations and with the experiments on short-lived states.[1,2]

An indication of the presence of $^3S_1$ heliumlike ions was observed in the 45-MeV data. An improvement to the fit was obtained by including oscillations corresponding to g factors of $\frac{4}{5}$, $\frac{8}{35}$, and $\frac{4}{7}$ for $F = \frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$. The amplitude of the oscillations obtained indicates that about 10% of the heliumlike ions are in the metastable triplet state.

The experiment has illustrated a specialized technique for investigating atomic systems on a nanosecond time scale by utilizing an excited nucleus as a probe. The sensitivity of this new method to atomic alignment and polarization can be used to study oriented atomic systems, and variations on our technique can be used to investigate atomic systems on a picosecond time scale. It has also been shown that it is possible to transfer oriented nuclei from the target to the catcher without the use of holding fields or gas, which makes possible many implantation experiments[8] where the direct beam would either heat up or damage the implantation medium.

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