Nuclear Spin and Magnetic Moment of 3.1 hr Cs^{134m}

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THE atomic beam magnetic resonance method has been used to measure the spin, hyperfine structure constant, and magnetic moment of the radioactive nucleus 3.1-hr Cs^{134m}. The apparatus constructed for this purpose incorporated the magnet design of Nagle,[1] but contained a movable compartment for rapid insertion and pumpdown of sources, and a detector compartment, removable through vacuum locks, making possible the collection of the radioactive atoms on disks at liquid nitrogen temperatures. The beam intensity of the active species was determined by counting, in a windowless flow counter, the 100-kev conversion electrons of Cs^{134m} from the deposit formed during constant exposure time.

The "flop-in" method of Zacharias[2] was employed to detect the low-field $[F=I+\frac{1}{2},\ m_F=-F\leftrightarrow F=I+\frac{1}{2},\ m_F=-(F-1)]$ transitions in both the active nuclide and inactive Cs^{133} in the beam. Collected in Table I are

TABLE I. Observed low-field resonance frequencies in Cs^{134m} and Cs^{133}.

ν_{133} (Mc/sec)	ν_{134m} (Mc/sec)
9.365	4.480
17.220	8.295
43.940	21.934
90.937	48.403
164.105	97.140

the resonances in Cs^{134m} found in magnetic fields determined by observing resonances of the same transition in Cs^{133} ($I=7/2$, $\Delta\nu=9193$ Mc/sec). In general, each frequency value is an average of the results of two experiments. A typical curve of a resonance in Cs^{134m} appears in Fig. 1.

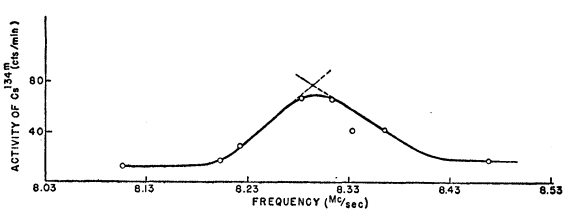

FIG. 1. A typical curve of a resonance in Cs^{134m}.

In sufficiently low magnetic fields the frequency at which the $F=I+\frac{1}{2}$, $m_F=-F\leftarrow m_F=-(F-1)$ transition is observed is given to a high degree of approximation by[3]

$$\nu=1.400\frac{H}{I+\frac{1}{2}}+\left(1.400\frac{H}{I+\frac{1}{2}}\right)^2\frac{2I}{\Delta\nu},$$

where ν is the low-field transition defined above (in Mc/sec), H is the magnetic field (in gauss), I is the nuclear spin (in units of $\hbar$), and $\Delta\nu$ is the hyperfine structure constant (in Mc/sec). Solution of this equation using the first two pairs of data of Table I gives unambiguously a spin of 8 and $\Delta\nu\approx3600$ Mc/sec. From the Fermi relation,[4]

$$\Delta\nu_{134m}/\Delta\nu_{133}=\frac{(2I_{134m}+1)\mu_{134m}}{I_{134m}}\cdot\frac{I_{133}}{(2I_{133}+1)\mu_{133}},$$

the magnetic moment, μ_{134m}, was then calculated to be 1.1 nm ($\mu_{133}=+2.58$ nm). At higher magnetic fields the approximate low-field equation is no longer valid, and the complete Breit-Rabi relation[5] is used to arrive at a more precise value of the hfs constant. Our best estimate at present is $\Delta\nu_{134m}=3662$ Mc/sec, based on the highest pair of frequencies listed in Table I and assuming that μ_I is positive in sign. The magnetic moment is then more precisely calculated to be 1.10 nm. Further experiments at higher frequencies are being conducted to establish the algebraic sign of the moment.

We wish to thank J. A. Dalman, whose numerous contributions of ingenious design have made possible the surmounting of the difficult technique problems inherent in this experiment and for his great assistance in the performance of the experiments. Acknowledgment is also gratefully made of the extensive design work of H. W. Ostrander and of the advice of and consultation with D. E. Nagle, which gave great impetus to the project in its initial stages.

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Decay of Cs^{134m} (3.1 hr)

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THE discovery reported in the two preceding letters,[1,2] that Cs^{134m} (3.1 hr), has a spin of 8 units ($\hbar$), reopens the question of its correct decay scheme. It was previously shown that this isomer decays by a 128-kev transition, identified as an $E3$ transition from its K conversion coefficient.[3] As the ground state of Cs^{134} has a measured spin of 4 units,[4] and as no β rays are observed from Cs^{134m}, it was considered likely that the metastable state has a spin of 7 units.[5] Because of the discrepancy between this value and the now directly measured value of 8 units for the

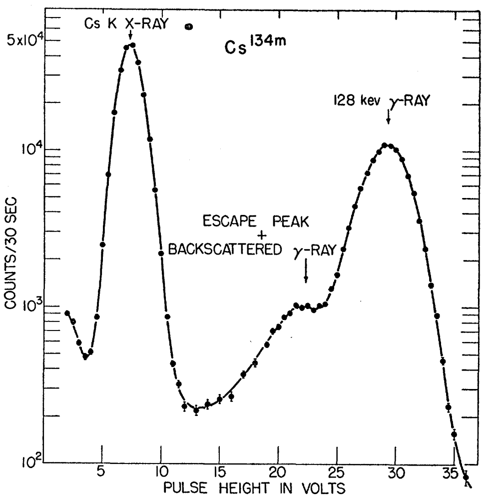

FIG. 1. Scintillation counter spectrum of Cs^{134m}, showing 128-kev γ ray and K x-rays accompanying K internal conversion.

spin, we have redetermined the K conversion coefficient of the 128-kev transition. The method was the same as previously described: x_K/γ ratio,[3] but an improved scintillation spectrometer was used (see Fig. 1). The $E3$ character of the 128-kev transition was confirmed. We find $\epsilon_K = 2.6 \pm 0.3$, whereas the theoretical values are $\alpha_2 \approx 0.61$, $\alpha_3 \approx 2.8$, $\alpha_4 \approx 14$.

It thus appears probable that the previously made tacit assumption of a single step (γ_1) from the metastable state to the ground state is incorrect, and that γ_1 is followed by a "hidden" low-energy transition (γ_2). We therefore searched for low-energy γ rays with a proportional counter and found indeed a 10.5 ± 0.7 kev γ ray (γ_2) of low intensity (see Fig. 2); $\gamma_2/x_K \approx 2 \times 10^{-2}$, $\epsilon_{tot} \approx 200$. From the recently calcluated absolute L_{I} and L_{II} conversion coefficients,[6] and the approximate empirical[7] and theoretical[8] L-subshell ratios (Table I)

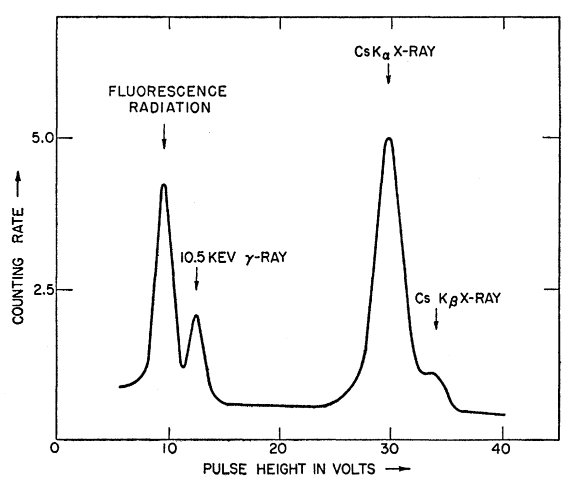

FIG. 2. Proportional counter spectrum showing 10.5-kev γ ray. An average of a counting rate meter trace is shown. Fluorescence radiations from the brass walls of the counter are also present.

TABLE I. Theoretical L conversion coefficients for γ_2.

	α_1	β_1	α_2	β_2
L_{I}[a]	~ 5.3	~ 76	~ 10	$\sim 1.7 \times 10^4$
L_{II}[a]	~ 5	~ 6.5	$\sim 10^4$	$\sim 10^3$
L_{III}[b]	[~ 10]	[~ 0.3]	[$\sim 1.8 \times 10^4$]	—
L_{total}	~ 20	~ 83	$\sim 2.8 \times 10^4$	$\sim 1.8 \times 10^4$

[a] Extrapolated values from tables of Rose, Goertzel, and Swift (reference 6).
[b] Estimated from L_{II} conversion using L_{II}/L_{III} values of Gellman, Griffith, and Stanley (reference 8) at 14.5 kev and $Z = 49$.

the best agreement is obtained for an $M1$ transition (with a probable admixture of $\lesssim 0.5$ percent $E2$, depending on the amount of M conversion). These conversion data alone cannot rule out the alternative assignment (99 percent) $E1+1$ (percent $M2$), which would, however, lead to unlikely parity assignments. The 10.5-kev γ ray and L radiations presumed to come from the internal conversion of the 10.5-kev transition, were found to be in coincidence with the 128-kev unconverted γ ray ($T_{1/2} \lesssim 10^{-7}$ sec). Thus, the following sequence of spins and parities: 4+, 5+, 8− (see Fig. 3),

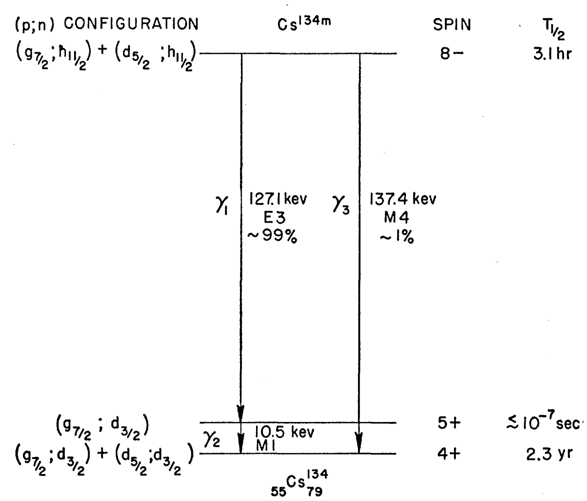

FIG. 3. Proposed decay scheme of Cs^{134m}. The most plausible configurations for the odd proton and odd neutron leading to the observed spins and compatible with the measured magnetic moments are shown.

is compatible with the experimental evidence. From these assignments and from the empirical formula for $M4$ lifetimes[9] a crossover transition (γ_3), $8- \xrightarrow{M4} 4+$, with an energy $\gamma_1 + \gamma_2 = 138.5$ kev and an intensity of ~ 0.5 percent should be expected. A search for the crossover transition with a 180° permanent magnet spectrograph was indeed successful, showing K, L, and M conversion electrons and yielding an energy $E_3 = 137.4 \pm 0.5$ kev. An improved value for the energy of γ_1 was obtained, $E_1 = 127.1 \pm 0.5$ kev. The energy difference between these two transitions could be estimated more accurately as $E_2 = E_3 - E_1 = 10.3 \pm 0.4$ kev, in good agreement with the value found directly for γ_2.

The crossover transition was too weak to permit an accurate estimate of its electron intensities. Comparing its K and L electrons to the M electrons of the "stop over" 127-kev transition, we find for the intensity of the crossover transition 0.8 ± 0.5 percent, in good agreement with the expectations for a one-particle transition $h_{11/2}\rightarrow d_{3/2}$. The K/L ratio was found to be 2 ± 1.3, which is more consistent with the empirical K/L ratio[9] for an $M4$ than for an $E4$ transition.

The most plausible shell model configurations for the odd proton and odd neutron of ${}_{55}Cs^{134}{}_{79}$ are shown in Fig. 3. Mixed states are expected,[10] since $d_{5/2}$ and $g_{7/2}$ proton levels in Cs nearly coincide in energy. These configurations indicate that, in contrast to the $M4$ and $M1$ transitions, the $E3$ transition of Cs^{134m} should be "forbidden" as a one-particle transition, both because the particle making the transition is a neutron, and because in strict j-j coupling the transition is forbidden; it is indeed one of the slowest known $E3$ transitions,[9] with an $|M|^2\approx10^{-6}$.

It is interesting to note that the addition of a proton to Xe^{133} leads to a lowering of the energy difference between metastable and ground state, i.e., the energy of the $M4$ transition is reduced from 232 kev to 137 kev in Cs^{134}, whereas the addition of two protons to Xe^{133} increases the difference between the corresponding states to 275 kev[5] in Ba^{135}.

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Radiative Capture of Orbital Electrons

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The continuous spectra of γ rays accompanying orbital electron capture have recently been measured for a number of elements.[1–3] These have thus far been compared with a theoretical spectrum of the form $x(1-x)^2$ (where $x=E/E_{\max}$), obtained under highly simplified assumptions by Morrison and Schiff.[4] For low-energy γ rays, the observed intensities are far higher than those predicted. In particular, the spectra Fe^{55}, Cs^{131}, and Ge^{71} have been determined down to energies bordering on the characteristic x-ray region; in each, there is an unexplained and precipitous increase of intensity with decreasing photon energy. Deviations from the form $x(1-x)^2$ are, in fact, to be expected. The assumptions of Morrison and Schiff, that Coulomb effects may be neglected and that capture occurs only from the K-shell, are quantitatively valid only for capture processes far more energetic than those mentioned.

We wish to indicate that the above approximations may be avoided; the internal bremsstrahlung spectra may be found almost exactly without difficulty. In particular, the effects of the Coulomb field can be treated precisely. When this is done, the spectrum of magnetic dipole radiation accompanying K capture is found indeed to have the form $x(1-x)^2$, for all energies of interest. Further considerations show the remaining and dominant part of the observed low-energy radiation to be electric dipole in character and to arise from the capture of electrons from P states.

We assume that the electron capture process is an allowed one, with a matrix element of the most general form,

$$H_c=\sum_\lambda c^{(\lambda)}\langle T_\mu{}^{(\lambda)}\rangle(\bar{\chi}(0)T_\mu{}^{(\lambda)}\psi(0)), \qquad (1)$$

in which $\psi(0)$ and $\chi(0)$ are the electron and neutrino wave functions evaluated at the nucleus, the $c^{(\lambda)}$ are linear combination coefficients for the various β-coupling operators $T_\mu{}^{(\lambda)}$, and $\langle T_\mu{}^{(\lambda)}\rangle$ is a nuclear matrix element. The radiative transition of an electron from the state $\psi_i(\mathbf{r})$ to the state $\psi_f(\mathbf{r})$ has the familiar matrix element[5]

$$(H_R)_{fi}=-e(2\pi/k)^{\frac{1}{2}}\int\bar{\psi}_f(\mathbf{r})e_\mu\gamma_\mu e^{-i\mathbf{k}\cdot\mathbf{r}}\psi_i(\mathbf{r})d\tau, \qquad (2)$$

where $\mathbf{k}$ and $\mathbf{e}$ are the propagation and polarization vectors of the emitted photon. The processes of interest combine both radiation and capture; an electron initially in an S or a P state will ordinarily emit a photon during a virtual transition to an S state, from which it is subsequently captured by the nucleus. The virtual transitions to S states already occupied in the atom are, however, forbidden by the exclusion principle. The absence of these terms in the summations over intermediate states, it may be shown, is precisely compensated for by the occurrence of transitions in which the capture of an electron from the occupied state precedes the radiative transition.

For a radiative capture process which leaves vacant an initially occupied state $\psi_n(r)$ (with $E_n<0$), the expressions (1) and (2) may be shown, after some re-