

## VII. CONCLUSION

It has been shown that the observed hfs of  $\text{Lu}^{175}$  can be understood in terms of current hfs theory provided one assumes that the  $5d6s^2$  ground configuration contains an admixture of higher configurations. The magnetic dipole and electric quadrupole moments of the Lu nucleus have been computed. Lack of knowledge of the exact wave functions of the ground state introduces uncertainties, however. More theoretical work seems necessary for a complete understanding of the experimental observations.

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## Nuclear Spin, Hyperfine Structure, and Nuclear Moments of 6.8-Day Lutetium-177†

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The atomic-beam magnetic-resonance method has been used to measure the nuclear spin and hyperfine structure of 6.8-day  $\text{Lu}^{177}$  in the ground  $^2D_{3/2}$  state and in the  $^2D_{5/2}$  electronic state. The results are:  $I = \frac{7}{2}$ ;  $^2D_{3/2}$ :  $a = 194.84(2)$  Mc/sec,  $b = 1466.71(12)$  Mc/sec;  $^2D_{5/2}$ :  $a = 147.17(1)$  Mc/sec,  $b = 1805.93(14)$  Mc/sec. The uncorrected nuclear moments for  $\text{Lu}^{177}$  calculated from these measurements and from known constants of  $\text{Lu}^{175}$  are:  $\mu_I = +2.217(10)$  nm,  $Q = +5.51(6)$  b.

## I. INTRODUCTION

AN atomic-beam magnetic-resonance study of the ground-state nuclear properties of radioactive lutetium isotopes has started with reactor-produced  $\text{Lu}^{177}$ .<sup>1</sup> This isotope was a reasonable choice since it could be produced easily in metallic form from stable lutetium metal by the  $(n, \gamma)$  reaction and would likely possess properties similar to those of stable  $\text{Lu}^{175}$  described in the preceding paper by Ritter.<sup>2</sup> A systematic knowledge of the spins and static moments in this highly deformed region of nuclides should furnish valuable test information for nuclear theories of the ground state as well as provide a basis for nuclear spectroscopic studies.

## II. THEORY OF THE EXPERIMENT

The atomic beam technique provides a sensitive method for observing radio-frequency transitions between two energy states of a free atom whose

Hamiltonian is

$$\begin{aligned} \mathcal{H}(\text{Mc/sec}) = & a\mathbf{I} \cdot \mathbf{J} + b[3(\mathbf{I} \cdot \mathbf{J})^2 + \frac{3}{2}(\mathbf{I} \cdot \mathbf{J}) \\ & - I(I+1)J(J+1)]/2I(2I-1)J(2J-1) \\ & - g_I(\mu_0/h)\mathbf{I} \cdot \mathbf{H} - g_J(\mu_0/h)\mathbf{J} \cdot \mathbf{H}, \quad (1) \end{aligned}$$

where  $\mathbf{I}$  and  $\mathbf{J}$  are the nuclear and electronic angular momenta in units of  $\hbar$ ,  $a$  and  $b$  are the dipole and quadrupole hyperfine-structure coupling constants,  $\mathbf{H}$  is the applied external magnetic field, and  $g_I$  and  $g_J$  are the nuclear and electric  $g$  factors defined by  $\mu_I/I$  and  $\mu_J/J$ , respectively, where the magnetic moments  $\mu_I$  and  $\mu_J$  are in units of the Bohr magneton  $\mu_0$ . The terms in this Hamiltonian are, from left to right: the magnetic dipole interaction between the nuclear magnetic moment and the electronic magnetic field; the electric quadrupole interaction between the nuclear electric quadrupole moment and the gradient of the electric field produced by the electrons; the interaction between the nuclear magnetic moment and the applied external field; and the interaction between the electronic magnetic moment and the applied external field.

The eigenvalues of this Hamiltonian may be found by using digital computing techniques, and hence the energy levels may be obtained as a function of the various parameters in Eq. (1). Figures 1 and 2 show some of the levels in the  $^2D_{3/2}$  and  $^2D_{5/2}$  states of  $\text{Lu}^{177}$  as a function of the external magnetic field. Primarily those

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<sup>1</sup> F. R. Petersen and H. A. Shugart, *Bull. Am. Phys. Soc.* **5**, 273 (1960); **6**, 224 (1961).

<sup>2</sup> George J. Ritter, preceding paper [*Phys. Rev.* **125**, 240 (1962)].

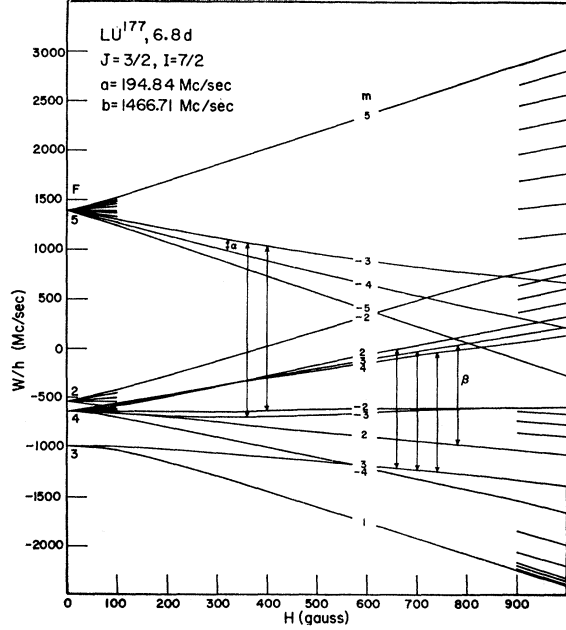


FIG. 1. Energy-level diagram of the hyperfine structure in the  $^2D_{3/2}$  state of  $\text{Lu}^{177}$  ( $a=194.84$  Mc/sec,  $b=1466.71$  Mc/sec).

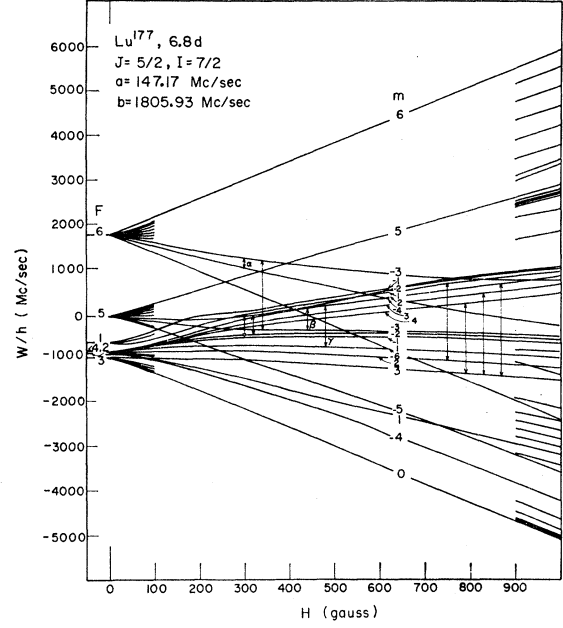


FIG. 2. Energy-level diagram of the hyperfine structure in the  $^2D_{3/2}$  state of  $\text{Lu}^{177}$  ( $a=147.17$  Mc/sec,  $b=1805.93$  Mc/sec).

levels involved in observed transitions are shown. The transitions labeled  $\alpha$ ,  $\beta$ , and  $\gamma$  are of the type  $\Delta F=0$ ,  $\Delta m=\pm 1$ , and at high fields involve a reversal of the sign of the effective atomic magnetic moment. Whereas the two conditions on  $\Delta F$  and  $\Delta m$  obey transition probability selection rules, the third condition ( $m_J=\pm\frac{1}{2} \leftrightarrow \mp\frac{1}{2}$ ) is imposed by the apparatus arrangement. At sufficiently low fields these transitions depend linearly on the field with a constant of proportionality which unambiguously fixes the nuclear spin. For example, the  $\alpha$  transition (the focusable transition among the levels of maximum  $F$  of the type  $\Delta F=0$ ,  $\Delta m=\pm 1$ ) in the  $^2D_{3/2}$  state has a frequency dependence given by

$$\nu = -g_J[3\mu_0/(2I+3)h]H + \text{higher-order terms in } H. \quad (2)$$

When this transition is observed at several field values to insure dominance of the first term of Eq. (2), the nuclear spin is established, since all quantities are known except  $I$ .

All transitions other than  $\alpha$ ,  $\beta$ , and  $\gamma$  in Figs. 1 and 2 are of the type  $\Delta F=\pm 1$ ,  $\Delta m=0, \pm 1$ , and also involve

a reversal of the sign of the effective atomic magnetic moment at high fields. These transitions approach the hyperfine-structure intervals near zero field and provide the best measure of these separations and hence of the constants  $a$  and  $b$ . Owing to the presence of field inhomogeneities in the transition region, it is frequently advisable to investigate these direct ( $\Delta F=\pm 1$ ) transitions at fields where their frequency dependence ( $\partial\nu/\partial H$ ) is a minimum. Table I gives a summary of the regions in the  $^2D_{3/2}$  state where several lines show minimum field dependence and hence can be expected to be narrow. These narrow lines observed at moderate fields frequently give information concerning  $g_I$  and  $g_J$  as well as precise values of the constants  $a$  and  $b$ .

In the calculation of nuclear moments from hyperfine-structure data, several alternatives are possible, depending upon prior knowledge concerning the element and upon the precision of the investigation. With high resolution, the effect of the nuclear magnetic moment ( $\mu_I$ ) in the Hamiltonian may be observed directly. Second, the nuclear dipole and quadrupole

TABLE I. Regions of minimum field dependence of the observable  $\Delta F=\pm 1$  transitions in the  $^2D_{3/2}$  electronic state of  $\text{Lu}^{177}$ . The calculations were performed for  $a=147.167$  and  $b=1805.928$ .

Transition ( $F_1, m_1 \leftrightarrow F_2, m_2$ )	$(\partial\nu/\partial H)_{\min}$ (Mc/sec-gauss)	$H$ (gauss)	$\nu(g_I+)$ (Mc/sec)	$\nu(g_I-)$ (Mc/sec)
6, $-3 \leftrightarrow 5, -3$	0	805.2	1230.572	1230.572
5, $-2 \leftrightarrow 4, -2$	0	243.9	358.595	358.595
5, $-2 \leftrightarrow 4, -1$	0	226.5	410.476	410.279
4, $2 \leftrightarrow 3, 3$	0.042	0	175.885	175.885
4, $4 \leftrightarrow 3, 3$	1.134	0	175.885	175.885
4, $3 \leftrightarrow 3, 3$	0.588	0	175.885	175.885
1, $1 \leftrightarrow 2, 2$	0	37.2	172.868	172.835

moments are calculable from the coupling constants  $a$  and  $b$  through theoretical formulas describing the interaction of the electrons and nucleus. Third, when the moments for one isotope of an element are known, moments of another isotope can be obtained by using relatively simple proportions between hyperfine-structure constants and respective moments. In this work, the first method is employed to determine the sign of the nuclear magnetic moment, while the third method yields the most precise value for both the magnetic dipole and electric quadrupole moments.

For a single  $d$  electron (lutetium ground-state configuration is  $5d^1 6s^2$ ), the dipole and quadrupole hyperfine-structure coupling constants are related to the nuclear moments in the following way<sup>3</sup>:

$$a(\text{Mc/sec}) = \frac{2\mu_0^2 g_I L(L+1)}{10^6 h(J+1)} \left\langle \frac{1}{r^3} \right\rangle_{\text{av}} F_r(J, Z_i), \quad (3)$$

$$b(\text{Mc/sec}) = \frac{e^2 Q(2J-1)}{10^6 h(2J+2)} \left\langle \frac{1}{r^3} \right\rangle_{\text{av}} R_r(L, J, Z_i), \quad (4)$$

where  $\langle 1/r^3 \rangle$  is frequently evaluated through the fine-structure formula

$$\left\langle \frac{1}{r^3} \right\rangle_{\text{av}} = \frac{hc\Delta}{2\mu_0^2(L+\frac{1}{2})Z_i H_r(L, Z_i)}. \quad (5)$$

In these equations  $F_r$ ,  $R_r$ , and  $H_r$  are relativistic correction factors given by Casimir<sup>4</sup> and tabulated by Kopfermann<sup>5</sup>;  $c(\text{cm/sec})$  is the velocity of light;  $\Delta(\text{cm}^{-1})$  is the fine-structure splitting between the  $(L+\frac{1}{2})$  and  $(L-\frac{1}{2})$  electronic states ( $\Delta=1993.92 \text{ cm}^{-1}$ )<sup>5</sup>;  $Z_i$  is the effective atomic charge seen by the electron ( $Z_i=57.8$ ).<sup>2</sup> Here hyperfine-structure-anomaly effects have been neglected.

If configurations are mixed, as is actually the case in lutetium, the values of  $a$  obtained experimentally must be corrected before use in Eq. (3). Schwartz has considered the case in which one of the  $s$  electrons is raised to another  $s$  state, such as to the  $5d6s7s$  configuration.<sup>6</sup> The resulting effect is expected to change the magnetic-dipole interaction constant considerably but to have very little effect on the fine-structure separation and the quadrupole interaction constants. A procedure is outlined for correcting the dipole interaction constants, if experimental measurements in both electronic states of the doublet are available. If  $a_0$  is

the corrected constant, then we have

$$\begin{aligned} a(\tfrac{3}{2}) &= a_0(\tfrac{3}{2}) + \delta, \\ a(\tfrac{5}{2}) &= a_0(\tfrac{5}{2}) - \delta, \\ \frac{a_0(\tfrac{3}{2})}{a_0(\tfrac{5}{2})} &= \left( \frac{7}{3} \right) \frac{F_r(\tfrac{3}{2}, Z_i) |C(\tfrac{3}{2})|^2}{F_r(\tfrac{5}{2}, Z_i) |C(\tfrac{5}{2})|^2}, \end{aligned} \quad (6)$$

where  $|C(\tfrac{3}{2})/C(\tfrac{5}{2})|$  is approximately equal to 1 and  $\delta$ , the correction factor, is evaluated from Eq. (6).

For two isotopes of the same element, Eq. (3) yields a relation between the respective  $a$ 's and  $g_I$ 's, since all other quantities presumably remain constant. The resulting equation is uncertain to within  $\pm 0.5\%$  due to hyperfine-structure-anomaly effects:

$$a_1/a_2 \approx (g_I)_1/(g_I)_2. \quad (7)$$

Similarly Eq. (4) gives, for the quadrupole moments,

$$b_1/b_2 \approx Q_1/Q_2, \quad (8)$$

where the subscripts refer to different isotopes of the same element.

### III. APPARATUS

Since the atomic-beam apparatus and general technique have been described previously,<sup>7</sup> only a summary is included here. The inhomogeneous  $A$  and  $B$  deflecting fields are arranged so that only transitions for which the effective atomic magnetic moment changes sign are focused on the detector collector and consequently observed. In the absence of a transition both magnets deflect atoms in the same direction transverse to the beam and thus cause those atoms to miss the collector. However, when a transition is induced in the homogeneous  $C$  field located between the deflecting magnets, the deflection caused by the  $A$  field is compensated by the  $B$  field. That portion of the beam undergoing a transition is then focused on the detector. Consequently, resonance signals are observed as increases in the rate of deposition of radioactive atoms on the detector collecting surface. After a suitable collection time, the collector is removed from the apparatus and counted in continuous-flow-methane beta counters. Sulfur-coated "buttons" served as collectors. Resonance signals appeared typically as 15-to-30-counts/min decay rates above a 15-counts/min apparatus background and a 2-counts/min counter background. A resonance example is shown in Fig. 3.

The lutetium beam was produced from a tantalum oven of cubic shape measuring  $\frac{3}{8}$  in. on a side. Radioactive material was introduced through the oven top into a well containing a sharp-edged tantalum crucible for preventing the molten lutetium from flowing around the oven interior. The well was closed by a press-fitting

<sup>3</sup> H. Kopfermann, *Nuclear Moments*, English version by E. E. Schneider (Academic Press Inc., New York, 1958), 2nd ed.

<sup>4</sup> H. B. G. Casimir, *On the Interaction Between Atomic Nuclei and Electrons* (Teyler's Tweede Genootschap, Haarlem, 1936).

<sup>5</sup> P. F. A. Klinkenberg, *Physica* **21**, 53 (1955).

<sup>6</sup> Charles Schwartz, *Phys. Rev.* **97**, 380 (1955).

<sup>7</sup> J. P. Hobson, J. C. Hubbs, W. A. Nierenberg, H. B. Silsbee, and R. J. Sunderland, *Phys. Rev.* **104**, 101 (1956); also W. B. Ewbank, L. L. Marino, W. A. Nierenberg, H. A. Shugart, and H. B. Silsbee, *Phys. Rev.* **120**, 1406 (1960).

plug, but communicated via a channel to 4-mil-wide slits on the oven front. The entire assembly was heated by electron bombardment. Calibrating beams of rubidium isotopes were produced from a second oven located behind the radioactive oven. By moving the radioactive oven to one side, a calibrating beam could be observed.

The rf transition "hairpin" consisted of a vertical, flattened coaxial transmission line shorted directly below the beam. Slots were cut in the outer coaxial conductor to allow passage of the beam on one side of the central conductor. This hairpin worked very well for  $\pi$  transitions ( $\Delta m = \pm 1$ ), but tended to give double-peaked resonances for  $\sigma$  transitions ( $\Delta m = 0$ ). The double peak probably results because the rf field component (parallel to the static field) that is effective in  $\sigma$  transitions occurs at two successive locations along the beam path, and these components are 180 deg out of phase. This simulates a two-loop situation which predicts a local minimum in the transition probability at resonance.<sup>8</sup>

Radio frequencies from 1 to 2000 Mc/sec were produced by four signal generators in conjunction with suitable wide-band or traveling-wave tube amplifiers. The oscillators and their ranges were as follows: Tektronix, type 190, 0.35 to 50 Mc/sec; Hewlett-Packard, model 608C, 10 to 480 Mc/sec; Airborne Instruments, type 124C, 200 to 2500 Mc/sec; and Gertsch, model FM-4, 500 to 1000 Mc/sec. Frequencies were measured by using a Hewlett-Packard Transfer Oscillator, model 540A, in conjunction with a model 524B electronic counter. The 100-kc/sec internal reference crystal in the counter was checked against a separate laboratory standard which was monitored weekly against WWV time signals and against a

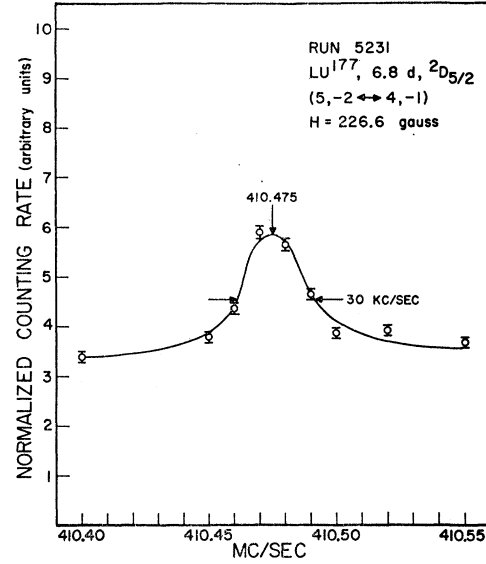


FIG. 3. A sample resonance corresponding to the transition  $F, m=5, -2 \leftrightarrow 4, -1$  in the  $^2D_{5/2}$  state of  $\text{Lu}^{177}$  at  $H = 226.6$  gauss.

National Company Atomichron. All frequencies were recorded to the nearest kc/sec.

#### IV. ISOTOPE PRODUCTION AND IDENTIFICATION

The  $\text{Lu}^{177}$  used in these experiments was produced by the  $(n, \gamma)$  reaction on  $\text{Lu}^{176}$ , whose natural abundance is 2.6%. Each sample consisted of approximately 200 mg of stable lutetium metal (99.9% purity) contained in an evacuated quartz capsule which in turn was enclosed in a special 99.999% pure aluminum container.

TABLE II. Summary of  $\text{Lu}^{177}$  resonances in the  $^2D_{5/2}$  state.

Calibrating isotope	$\nu_c$ (Mc/sec)	$\delta\nu_c$ (Mc/sec)	$H$ (gauss)	$\delta H$ (gauss)	$F_1$	$m_1$	$F_2$	$m_2$	$\nu_{\text{obs}}$ (Mc/sec)	$\delta\nu_{\text{obs}}$ (Mc/sec)	Residual (Mc/sec)	Weight factor
Rb <sup>85</sup>	3.460	0.040	7.371	0.085	5	-3	5	-4	2.470	0.050	-0.006	301.5
Rb <sup>85</sup>	28.660	0.070	58.653	0.137	5	-3	5	-4	20.000	0.050	-0.008	209.8
Rb <sup>85</sup>	106.545	0.110	195.126	0.173	5	-3	5	-4	69.308	0.075	-0.027	101.2
Rb <sup>85</sup>	3.463	0.040	7.377	0.085	4	3	4	2	1.600	0.050	+0.005	355.1
Rb <sup>85</sup>	28.652	0.070	58.637	0.137	4	3	4	2	13.400	0.200	+0.026	21.1
Rb <sup>85</sup>	50.618	0.030	100.211	0.055	4	3	4	2	74.600	0.200	-0.252	20.7
Rb <sup>85</sup>	4.667	0.030	9.922	0.063	5	-3	4	-3	2018.450	0.200	+0.014	24.7
Rb <sup>85</sup>	4.668	0.030	9.924	0.063	5	-3	4	-2	2016.150	0.120	+0.025	63.1
Rb <sup>85</sup>	4.688	0.030	9.966	0.063	5	-3	4	-2	2016.050	0.150	-0.050	41.8
Rb <sup>85</sup>	28.340	0.035	58.027	0.069	4	3	3	3	407.125	0.350	-0.122	7.9
Rb <sup>87</sup>	20.234	0.100	28.666	0.140	4	4	3	3	387.200	0.300	+0.201	9.2
Rb <sup>85</sup>	13.713	0.030	28.731	0.062	4	4	3	3	387.250	0.200	+0.189	23.0
Rb <sup>85</sup>	28.364	0.030	58.074	0.059	4	4	3	3	416.200	0.300	-0.026	10.7
Rb <sup>85</sup>	1.403	0.040	2.999	0.085	2	2	3	3	459.000	0.750	-0.773	1.8
Rb <sup>85</sup>	28.364	0.030	58.074	0.059	2	2	3	3	411.030	0.120	-0.010	67.7
Rb <sup>85</sup>	29.314	0.040	59.931	0.078	2	2	3	3	410.525	0.100	-0.052	98.2
Rb <sup>85</sup>	29.356	0.040	60.013	0.078	2	2	3	3	410.550	0.080	-0.014	152.4
Rb <sup>85</sup>	29.371	0.030	60.042	0.059	2	2	3	3	410.566	0.080	+0.007	154.1
Rb <sup>85</sup>	30.883	0.030	62.986	0.058	2	2	3	3	410.510	0.100	+0.017	99.5
Rb <sup>85</sup>	30.931	0.030	63.079	0.058	2	2	3	3	410.525	0.100	+0.021	99.5

<sup>8</sup> N. F. Ramsey, *Molecular Beams* (Oxford University Press, New York, 1956).

TABLE III. Summary of  $\text{Lu}^{177}$  resonances in the  $^2D_{3/2}$  state.

Calibrating isotope	$\nu_e$ (Mc/sec)	$\delta\nu_e$ (Mc/sec)	$H$ (gauss)	$\delta H$ (gauss)	$F_1$	$m_1$	$F_2$	$m_2$	$\nu_{\text{obs}}$ (Mc/sec)	$\delta\nu_{\text{obs}}$ (Mc/sec)	Residual (Mc/sec)	Weight factor
Rb <sup>85</sup>	11.506	0.025	24.193	0.052	6	-3	6	-4	17.150	0.075	+0.078	143.4
Rb <sup>85</sup>	22.070	0.025	45.633	0.050	6	-3	6	-4	32.445	0.050	+0.008	263.2
Rb <sup>85</sup>	50.625	0.030	100.224	0.055	6	-3	6	-4	72.560	0.200	-0.011	24.0
Rb <sup>87</sup>	173.599	0.070	230.907	0.087	6	-3	6	-4	174.480	0.250	-0.256	14.8
Rb <sup>85</sup>	11.520	0.025	24.222	0.052	5	-2	5	-3	16.240	0.075	+0.145	145.4
Rb <sup>85</sup>	22.082	0.020	45.657	0.040	5	-2	5	-3	31.400	0.100	+0.218	92.3
Rb <sup>87</sup>	94.650	0.070	129.941	0.092	5	-2	5	-3	99.250	0.300	-0.268	10.3
Rb <sup>87</sup>	129.137	0.030	174.817	0.039	5	-2	5	-3	144.750	0.300	-0.021	10.9
Rb <sup>87</sup>	156.861	0.030	210.017	0.038	5	-2	5	-3	187.500	0.600	-0.288	2.8
Rb <sup>85</sup>	2.327	0.040	4.966	0.085	4	2	4	1	2.700	0.100	+0.129	85.4
Rb <sup>85</sup>	5.045	0.030	10.719	0.063	4	2	4	1	5.230	0.100	+0.128	94.3
Rb <sup>85</sup>	7.077	0.030	14.987	0.063	4	2	4	1	6.640	0.100	+0.058	96.4
Rb <sup>85</sup>	7.111	0.040	15.058	0.084	4	2	4	1	6.690	0.075	+0.086	159.2
Rb <sup>85</sup>	7.588	0.040	16.056	0.084	4	2	4	1	7.000	0.075	+0.099	161.0
Rb <sup>85</sup>	8.718	0.040	18.413	0.083	4	2	4	1	7.630	0.100	+0.086	95.6
Rb <sup>85</sup>	2.282	0.040	4.871	0.085	6	-3	5	-3	1810.730	0.150	-0.183	44.0
Rb <sup>85</sup>	138.837	0.070	244.001	0.102	5	-2	4	-2	358.610	0.050	+0.015	400.0
Rb <sup>85</sup>	138.869	0.070	244.048	0.102	5	-2	4	-2	358.600	0.050	+0.005	400.0
Rb <sup>85</sup>	138.877	0.070	244.059	0.102	5	-2	4	-2	358.600	0.050	+0.004	400.0
Rb <sup>85</sup>	138.924	0.090	244.128	0.131	5	-2	4	-2	358.610	0.040	+0.014	624.9
Rb <sup>85</sup>	139.052	0.310	244.314	0.451	5	-2	4	-2	358.625	0.075	+0.028	177.4
Rb <sup>85</sup>	1.654	0.030	3.534	0.064	5	-2	4	-1	797.150	0.400	-0.289	6.1
Rb <sup>85</sup>	127.008	0.050	226.540	0.075	5	-2	4	-1	410.473	0.010	-0.001	9999.8
Rb <sup>85</sup>	127.024	0.060	226.564	0.090	5	-2	4	-1	410.475	0.015	+0.001	4444.4
Rb <sup>85</sup>	127.496	0.180	227.270	0.269	5	-2	4	-1	410.480	0.010	+0.001	8815.8
Rb <sup>85</sup>	1.592	0.030	3.402	0.064	4	4	3	3	180.050	0.300	+0.171	10.4
Rb <sup>85</sup>	2.274	0.040	4.854	0.085	4	2	3	3	176.950	0.100	+0.085	91.4
Rb <sup>85</sup>	16.420	0.050	34.255	0.102	1	1	2	2	173.100	0.150	-0.218	42.7
Rb <sup>85</sup>	17.763	0.030	36.978	0.061	1	1	2	2	172.875	0.050	+0.005	399.6
Rb <sup>85</sup>	17.873	0.050	37.200	0.101	1	1	2	2	172.890	0.040	+0.023	625.0
Rb <sup>85</sup>	17.911	0.060	37.277	0.121	1	1	2	2	172.975	0.100	+0.108	100.0
Rb <sup>85</sup>	18.045	0.030	37.548	0.061	1	1	2	2	172.960	0.090	+0.088	123.4
Rb <sup>85</sup>	18.053	0.040	37.564	0.081	1	1	2	2	172.880	0.025	+0.007	1579.7

Bombardments ranged from 1 to 2 weeks at neutron flux densities from  $0.8$  to  $9 \times 10^{13}$   $n/\text{cm}^2\text{-sec}$ . The characteristic  $\gamma$  rays and the half-life of  $\text{Lu}^{177}$  served to establish the identity and purity of the radioactive samples. Since several days usually elapsed between the end of bombardment and the use of a sample, the 3.7-hr isomer of  $\text{Lu}^{176}$  produced from the  $\text{Lu}^{175}(n, \gamma)$  reaction had usually decayed below detectability.

### RESULTS

A total of 33 resonances in the  $^2D_{3/2}$  state and 20 resonances in the  $^2D_{5/2}$  state were observed at field values ranging from 3 to 250 gauss. Among these, the

lower-field resonances corresponding to the  $\alpha$ ,  $\beta$ , and  $\gamma$  transitions initially established the nuclear spin of  $\text{Lu}^{177}$  to be  $\frac{7}{2}$ , while the higher-field resonances of these transitions gave preliminary values of  $a$  and  $b$ . When these constants were sufficiently well established, direct  $\Delta F = \pm 1$  transitions were observed at field-independent points in order to obtain the highest precision. In the final analysis, digital computer techniques were used to obtain values for  $a$  and  $b$  by the method of least squares (e.g., see references 9 and 10). Summaries of these results appear in Tables II and III. Various physical constants used in these calculations are listed here. Uncertainties enclosed in parentheses refer to the least significant figures of the preceding value.<sup>2,3,8,11</sup>

$M_p/M_e = 1836.12$ ; $\mu_0/h = 1.399677$ Mc/gauss Lutetium-175 (reference 2)			$^2D_{3/2}$	$^2D_{5/2}$
$I = \frac{7}{2}$ $\mu_{I\text{uncorr}} = +2.211(10)$ nm (reference 11) $Q_{\text{uncorr}} = +5.68(6)$ b			$g_J = -0.79921(8)$ $a = 194.3316(4)$ Mc/sec $b = 1511.401(30)$ Mc/sec	$g_J = -1.20040(16)$ $a = 146.7790(8)$ Mc/sec $b = 1860.6480(80)$ Mc/sec
Rubidium-85 (references 3 and 8)			$^2S_{1/2}$	
$I = \frac{5}{2}$ $\mu_{I\text{uncorr}} = +1.348190(5)$ nm			$g_J = -2.00238(4)$ $\Delta\nu = 3035.735(2)$ Mc/sec	
Rubidium-87 (references 3 and 8)			$^2S_{1/2}$	
$I = \frac{3}{2}$ $\mu_{I\text{uncorr}} = +2.7413970(47)$ nm			$g_J = -2.00238(4)$ $\Delta\nu = 6834.685(2)$ Mc/sec	

<sup>9</sup> H. L. Garvin, T. M. Green, E. Lipworth, and W. A. Nierenberg, Phys. Rev. **116**, 393 (1959).

<sup>10</sup> F. R. Petersen and H. A. Shugart, Phys. Rev. **125**, 284 (1962).

<sup>11</sup> A. H. Reddock and G. J. Ritter, National Research Council, Ottawa (private communication, 1961).

The residual quoted in these tables represents the difference between the measured resonance frequency and the value of the frequency predicted by the final computed atomic and nuclear constants. The weight factor is the reciprocal of the sum of the squares of the frequency uncertainties due to resonance linewidth and magnetic field uncertainty.

From the computer analysis the hyperfine-structure coupling constants for Lu<sup>177</sup> are: for the  $^2D_{3/2}$  state,  $a=194.84(2)$  Mc/sec,  $b=1466.71(12)$  Mc/sec; and, for the  $^2D_{5/2}$  state,  $a=147.17(1)$  Mc/sec,  $b=1805.93(14)$  Mc/sec. From these values of  $a$  and  $b$  the zero-field hyperfine-structure separations (in Mc/sec) are calculated as

$$\begin{aligned} ^2D_{3/2} \quad \Delta\nu_{5-4} &= 2021.850(130), \\ \Delta\nu_{4-3} &= 360.300(85), \\ \Delta\nu_{3-2} &= -463.130(105), \end{aligned}$$

$$\begin{aligned} ^2D_{5/2} \quad \Delta\nu_{6-5} &= 1811.784(95), \\ \Delta\nu_{5-4} &= 800.348(50), \\ \Delta\nu_{4-3} &= 175.896(50), \\ \Delta\nu_{3-2} &= -138.968(55), \\ \Delta\nu_{2-1} &= -221.640(45). \end{aligned}$$

The values of  $a$  corrected for configuration mixing by the procedure outlined in Sec. II are  $a_0(\frac{3}{2})=242.32$  Mc/sec and  $a_0(\frac{5}{2})=99.69$  Mc/sec. In the work presented here no use is made of these corrected values.

The nuclear magnetic moment sign is determined directly from the  $^2D_{3/2}$  resonances in Table III and the Hamiltonian [(Eq. 1).] The value of the uncorrected moment obtained in this manner is  $\mu_I=+1.9(8)$  nm. Similarly the  $^2D_{5/2}$  state yields a nominal positive moment  $+2.9(3.7)$  nm, but the error is considerably larger and does not exclude the possibility that the moment is negative. Although the  $^2D_{3/2}$  results establish the sign of the moment, the magnitude is best obtained by comparison with the NMR value for Lu<sup>175</sup>. With the known constants for Lu<sup>175</sup> listed above and no hyperfine-structure anomaly, Eq. (7) results in an uncorrected magnetic moment of  $\mu_{I\text{uncorr}}=+2.217(10)$  nm for Lu<sup>177</sup>. The diamagnetically corrected moment is then  $\mu_{I\text{corr}}=+2.235(10)$  nm if the correction factor 1.00827 is used.<sup>3</sup> This procedure using Eq. (8) gives  $Q=+5.51(6)$  b for the uncorrected quadrupole moment. In addition to having the same spin, both Lu<sup>176</sup> and Lu<sup>177</sup> have very similar magnetic dipole and electric quadrupole moments.

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## Coulomb Excitation of Second 2+ States in Ge<sup>74</sup>, Ge<sup>76</sup>, Se<sup>76</sup>, Se<sup>78</sup>, and Se<sup>80</sup>

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The location of a second 2+ state has been established for five even-even nuclei by means of Coulomb excitation produced by 6-, 7-, and 8-Mev  $\alpha$  particles. The relatively weak excitation of these states is detected by a coincident measurement of the cascade gamma rays. The  $B(E2)$ 's for decay of the second 2+ state to the ground state by the crossover transition are rather small, being about single-particle value or a little less. For Ge<sup>74</sup>, Se<sup>76</sup>, and Se<sup>78</sup>, the cascade/crossover ratio for the decay of the second 2+ state is known from radioactive decay measurements. The upper cascade  $B(E2, 2' \rightarrow 2)$ 's exhibit enhancements comparable to those for the lower cascade  $B(E2, 2 \rightarrow 0)$ 's. The ratios of the  $B(E2)$ 's for the decay of the first and second 2+ states are compared to the predictions of several collective models. The  $B(M1, 2' \rightarrow 2)$  values for Ge<sup>74</sup> and Se<sup>76</sup> are small, being about  $10^{-3}$  times the single-particle estimate. This result is in qualitative agreement with the collective models for vibrational excitations.

### I. INTRODUCTION

IN a previous report<sup>1</sup> the location of a second 2+ state was observed for 13 even-even medium-weight ( $A=98$  to 122) nuclei by means of Coulomb excitation produced by 8-, 9-, and 10-Mev  $\alpha$  particles. The relatively

weak excitation of these states was detected by a coincident measurement of the cascade gamma rays. The crossover  $B(E2)$ 's, deduced from the observed gamma-ray yields, exhibited some uniformity and were all rather weak, being about single-particle value or a little less. For several of those nuclei the cascade/crossover ratio for the second 2+ state was known from

<sup>1</sup> P. H. Stelson and F. K. McGowan, Phys. Rev. **121**, 209 (1961).