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Alan T. Ramsey and Sanford Stein

July 17, 1967

THE GROUND-STATE HYPERFINE STRUCTURE OF  $^{165}\text{Dy}^*$

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University of California  
Berkeley, California

July 17, 1967

ABSTRACT

The magnetic-dipole and electric-quadrupole hyperfine-interaction constants of the ground state of  $^{165}_{66}\text{Dy}$  have been measured to be  $a = \pm 90.1 \pm 0.7$  MHz and  $b = \mp 1530 \pm 30$  MHz, respectively. From these data we calculate  $\mu = -0.50$  nm and  $Q = 2.8$  b, uncorrected.

## INTRODUCTION

The rare earths have been subject to considerable study, both because of interest in the atomic properties of the  $f^n$  and  $f^{n-1}d$  configurations, and because the region around  $A = 150$  is characterized by large nuclear deformations which offer a good test for the Nilsson model of strongly deformed nuclei. In dysprosium, work has been done on  $^{155}\text{Dy}$  and  $^{157}\text{Dy}$  (Ref. 1),  $^{159}\text{Dy}$  (Ref. 2),  $^{161}\text{Dy}$  and  $^{163}\text{Dy}$  (Ref. 3), and  $^{166}\text{Dy}$  (Ref. 4). Dysprosium-166 is even-even and has no nuclear spin, and has been used to determine  $g_J$  to high accuracy. Also, the spin of  $^{165}\text{Dy}$  previously has been measured to be  $I = 7/2$  by Cabezas.<sup>5</sup> In this paper we report on a measurement of the hyperfine structure of the ground state of  $^{165}\text{Dy}$  by atomic-beam magnetic resonance.

## EXPERIMENTAL METHOD

Dysprosium-165 has a half life of 2.3 h, decaying by  $\beta^-$  emission to stable  $^{165}\text{Ho}$ . It was produced by thermal-neutron capture by  $^{164}\text{Dy}$ . Natural dysprosium (28% of  $^{164}\text{Dy}$ ) was irradiated for 5 min in a nuclear reactor with a neutron flux of about  $1 \times 10^{13} \text{ sec}^{-1} \text{ cm}^{-2}$ . The sample was placed in a Ta oven and heated by electron bombardment until a satisfactory beam was obtained. Beams were stable and lasted about 4 h, by which time all of the approximately 1/2 g sample was evaporated out of the oven. The machine employed conventional two-pole magnets in a flop-in configuration. The beam was collected on freshly flamed Pt foils and counted in a methane-filled  $\beta$  counter. Counter background and machine background (a 5-min resonance button with the rf off) were both 1 to 2 counts per minute (cpm), and resonances were from 10 to 30 cpm for a full beam (magnets off) of about 500 cpm for a 1-min exposure. Dysprosium has a  $^5I_8$  ground state arising from a  $4f^{10}6s^2$

configuration. With a spin of  $7/2$ , there are 136 Zeeman sublevels in the beam, giving rise to eight Zeeman flop-in resonances (see Fig. 1). We observed seven of these resonances but could not see a resonance in the  $F = 9/2$  level, probably because of the low relative transition probability and the limited power of the rf supplies used. In the three highest  $F$  states the resonances were observed at fields up to 220 G. The linewidth of the machine is rather large, as may be seen in a typical resonance pictured in Fig. 2.

#### ANALYSIS OF THE DATA

The resonance data were analyzed by using the Berkeley Atomic Beam Group's computer program, HYPERFINE-4. Smith and Spaulding's<sup>4</sup> value of  $g_J = -1.24166 \pm 0.00007$  was used, and the program adjusted  $a$  and  $b$  to minimize the  $\chi^2$  of the fit. The results are  $a = \pm 90.1 \pm 0.7$  MHz, and  $b = \mp 1530 \pm 30$  MHz.

To extract values for  $\mu$  and  $Q$  from  $a$  and  $b$  one needs to know the magnetic and electric fields at the nucleus due to the electrons. The hyperfine Hamiltonian for dipole and quadrupole interactions is

$$H = a \bar{I} \cdot \bar{J} + \frac{b}{2I(2I-1)J(2J-1)} [3(\bar{I} \cdot \bar{J})^2 + \frac{3}{2}(\bar{I} \cdot \bar{J}) - I(I+1)J(J+1)] , \quad (1)$$

where

$$a = - \mu_N H_N / JI \quad (2)$$

and

$$b = - e^2 q_J Q . \quad (3)$$

Here  $\mu_N$  is the nuclear magnetic moment,  $H_N$  is the magnetic field in the  $z$  direction at the nucleus due to the electrons, evaluated in the state

$I + J = F = M_F$ ,  $Q$  is the nuclear quadrupole moment, and  $q_J$  is the  $z$  component of the gradient of the field of the electrons evaluated at the nucleus. For  $n$  equivalent electrons (or holes) coupling to the Hund's rule ground state, these fields have been calculated to be<sup>6</sup>

$$a = g_I \mu_N 2\mu_o \left\langle \frac{1}{r^3} \right\rangle \left\{ \frac{J(J+1) + L(L+1) - S(S+1)}{2J(J+1)} + \frac{2(2L-n^2)}{n^2(2L-1)(2l-1)(2l+3)} \left[ \frac{L(L+1)\{J(J+1) + S(S+1) - L(L+1)\}}{2J(J+1)} - \frac{3}{4} \frac{J(J+1) - L(L+1) - S(S+1)[J(J+1) + L(L+1) - S(S+1)]}{J(J+1)} \right] \right\} \quad (4)$$

and

$$q_J = \mp \left\langle \frac{1}{r^3} \right\rangle \left[ \frac{3K(K-1) - 4L(L+1)J(J+1)}{(2L-1)(J+1)(2J+3)} \right] \left[ \frac{2L-n^2}{n(2l-1)(2l+3)} \right], \quad (5)$$

where  $K = J(J+1) + L(L+1) - S(S+1)$ ,  $n$  is the number of equivalent electrons (or holes), the upper sign is taken for electrons, and the lower sign for holes. An analysis of the low-lying levels of Dy by Conway and Wybourne<sup>7</sup> indicates that breakdown of L-S coupling in the  $^5I$  state mixes in only about 4% of the  $^3K$  levels, which is a smaller uncertainty than that introduced by the value for  $\langle 1/r^3 \rangle$  and relativistic corrections, which are probably about 10%. The value for  $\langle 1/r^3 \rangle$ , taken from Bleaney, is  $\langle 1/r^3 \rangle = 8.7 \text{ a.u.}^8$  Using these equations and Bleaney's value for  $\langle 1/r^3 \rangle$ , we find  $\mu = -0.50 \text{ nm}$  and  $Q = 2.8 \text{ barns}$ , where the sign of  $Q$  has been chosen positive, thus fixing the sign of  $\mu$ . No diamagnetic or Sternheimer corrections have been applied.

#### COMPARISON WITH THEORY

In the strongly deformed region of nuclear structure, the intrinsic quadrupole moment is very simply predicted to be<sup>9</sup>



$$Q_0 = \frac{4}{5} ZR^2 \delta \left(1 + \frac{2}{3} \delta\right), \quad (6)$$

where  $R = 1.2 \times 10^{-13} A^{1/3}$  cm. The ground state of  $^{165}\text{Dy}$  is characterized by an asymptotic Nilsson orbital for the 99th neutron of  $7/2+[633]$ . A systematic study by Chiao of the magnetic properties of deformed nuclei indicates that in the region of  $A = 165$ , the deformation  $\delta$  is a slowly varying parameter, and is approximately equal to 0.26.<sup>10</sup> The observed quadrupole moment is related to the intrinsic quadrupole moment by a projection factor such that<sup>11</sup>

$$Q = Q_0 \frac{3K^2 - I(I+1)}{(I+1)(2I+3)}. \quad (7)$$

Using these relations we calculate  $Q = 3.2$  barns, about 14% above the value calculated from the measured interaction constant  $b$ .

The magnetic moment is given by Nilsson<sup>9</sup> as

$$\mu = \frac{I}{I+1} \left[ (g_s - g_\ell) \frac{1}{2} \sum_\ell (a_{\ell, \Omega-1/2}^2 - a_{\ell, \Omega+1/2}^2) + g_\ell I + g_R \right], \quad (8)$$

where the  $a_{\ell, \Omega+1/2}$ 's are mixing coefficients found by diagonalizing the deformation Hamiltonian in a shell-model representation. Nilsson tabulates these (in an unnormalized form) for various values of  $\delta$ , and the appropriate values were found by interpolation to  $\delta = 0.26$ . For neutrons, we have  $g_\ell = 0$ , and from Chiao<sup>10</sup> we take  $g_s = -2.4$  and  $g_R = 0.2$ . Using these values we find  $\mu_{\text{calc}} = -0.51$ , compared with  $\mu_{\text{meas}} = -0.50$ .

The agreement between the calculated values of  $\mu$  (using a quenched  $g_s$ ) and  $Q$  and the values deduced from  $a$  and  $b$  is very good, considering the uncertainties in the atomic calculations. The results again confirm the applicability of the Nilsson individual-nucleon, strong-deformation approach in this region of the periodic table.

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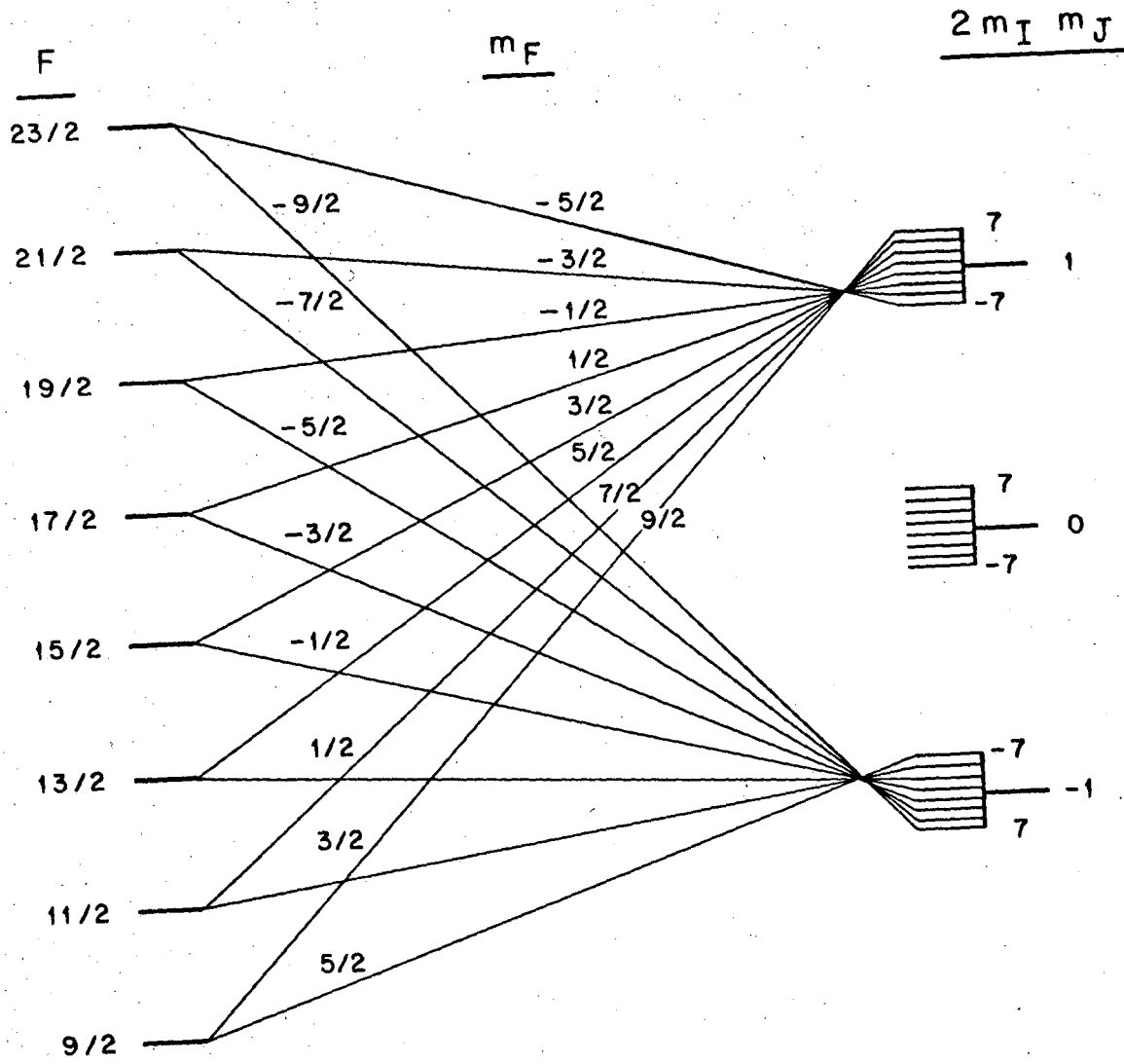
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FIGURE LEGENDS

Fig. 1. Schematic Breit-Rabi diagram for the ground state of  $^{165}\text{Dy}$ , abbreviated to show only the 16 levels involved in low-field flop-in Zeeman transitions. There are 120 other Zeeman levels not shown here.

Fig. 2. Typical resonance at 220 G in the highest F state. The error bars indicate one standard deviation.



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Fig. 1.

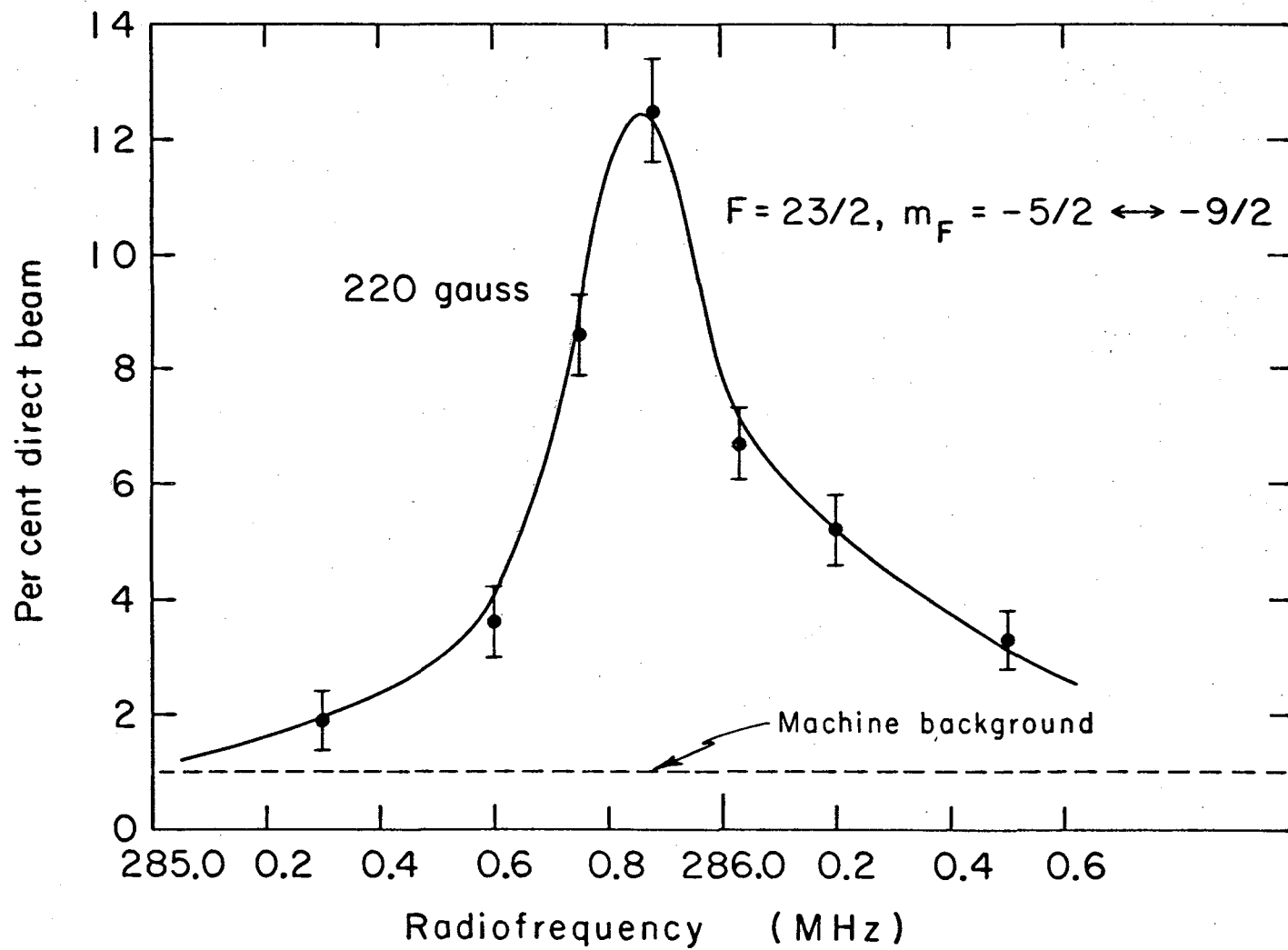


Fig. 2.

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