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Authors
Ramsey, Alan T.
Stein, Sanford.

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University of California

Ernest O. Lawrence Radiation Laboratory

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ABSTRACT

The magnetic-dipole and electric-quadrupole hyperfine-interaction constants of the ground state of 2.3-h $^{165}_{66}$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}Dy and ^{157}Dy (Ref. 1), ^{159}Dy (Ref. 2), ^{161}Dy and ^{163}Dy (Ref. 3), and ^{166}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}Dy previously has been measured to be $I = 7/2$ by Cabezas.[5] In this paper we report on a measurement of the hyperfine structure of the ground state of ^{165}Dy by atomic-beam magnetic resonance.

EXPERIMENTAL METHOD

Dysprosium-165 has a half life of 2.3 h, decaying by β^- emission to stable ^{165}Ho. It was produced by thermal-neutron capture by ^{164}Dy. Natural dysprosium (28% of ^{164}Dy) was irradiated for 5 min in a nuclear reactor with a neutron flux of about 1×10^{13} sec^{-1} 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 β 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[4] value of $g_J = -1.24166 \pm 0.00007$ was used, and the program adjusted a and b to minimize the χ^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 μ 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

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

where

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

and

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

Here μ_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[6]

$$a = g_I \mu_N 2\mu_o \langle \frac{1}{r^3} \rangle \Bigg\{ \frac{J(J+1) + L(L+1) - S(S+1)}{2J(J+1)}$$

$$+ \frac{2(2L-n^2)}{n^2(2L-1)(2\ell-1)(2\ell+3)} \Bigg[\frac{L(L+1)\{J(J+1) + S(S+1) - L(L+1)\}}{2J(J+1)}$$

$$- \frac{3}{4} \frac{J(J+1) - L(L+1) - S(S+1)[J(J+1) + L(L+1) - S(S+1)]}{J(J+1)} \Bigg] \Bigg\} \tag{4}$$

and

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

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[7] 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 $\langle 1/r^3 \rangle = 8.7$ a.u.[8] Using these equations and Bleaney's value for $\langle 1/r^3 \rangle$, we find $\mu = -0.50$ nm and $Q = 2.8$ barns, where the sign of Q has been chosen positive, thus fixing the sign of μ. 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[9]

$$Q_o = \frac{4}{5} ZR^2\delta(1 + \frac{2}{3} \delta) , \tag{6}$$

where $R = 1.2 \times 10^{-13} A^{1/3}$ cm. The ground state of ^{165}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 δ is a slowly varying parameter, and is approximately equal to 0.26.[10] The observed quadrupole moment is related to the intrinsic quadrupole moment by a projection factor such that[11]

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

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[9] as

$$\mu = \frac{I}{I+1} [(g_s - g_\ell)\frac{1}{2} \sum_\ell(a^2_{\ell,\Omega-1/2} - a^2_{\ell,\Omega+1/2}) + g_\ell I + g_R] , \tag{8}$$

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 δ, and the appropriate values were found by interpolation to $\delta = 0.26$. For neutrons, we have $g_\ell = 0$, and from Chiao[10] we take $g_s = -2.4$ and $g_R = 0.2$. Using these values we find $\mu_{calc} = -0.51$, compared with $\mu_{meas} = -0.50$.

The agreement between the calculated values of μ (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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†Present address: Department of Physics, Brandeis University, Waltham, Massachusetts.

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FIGURE LEGENDS

Fig. 1. Schematic Breit-Rabi diagram for the ground state of ^{165}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.

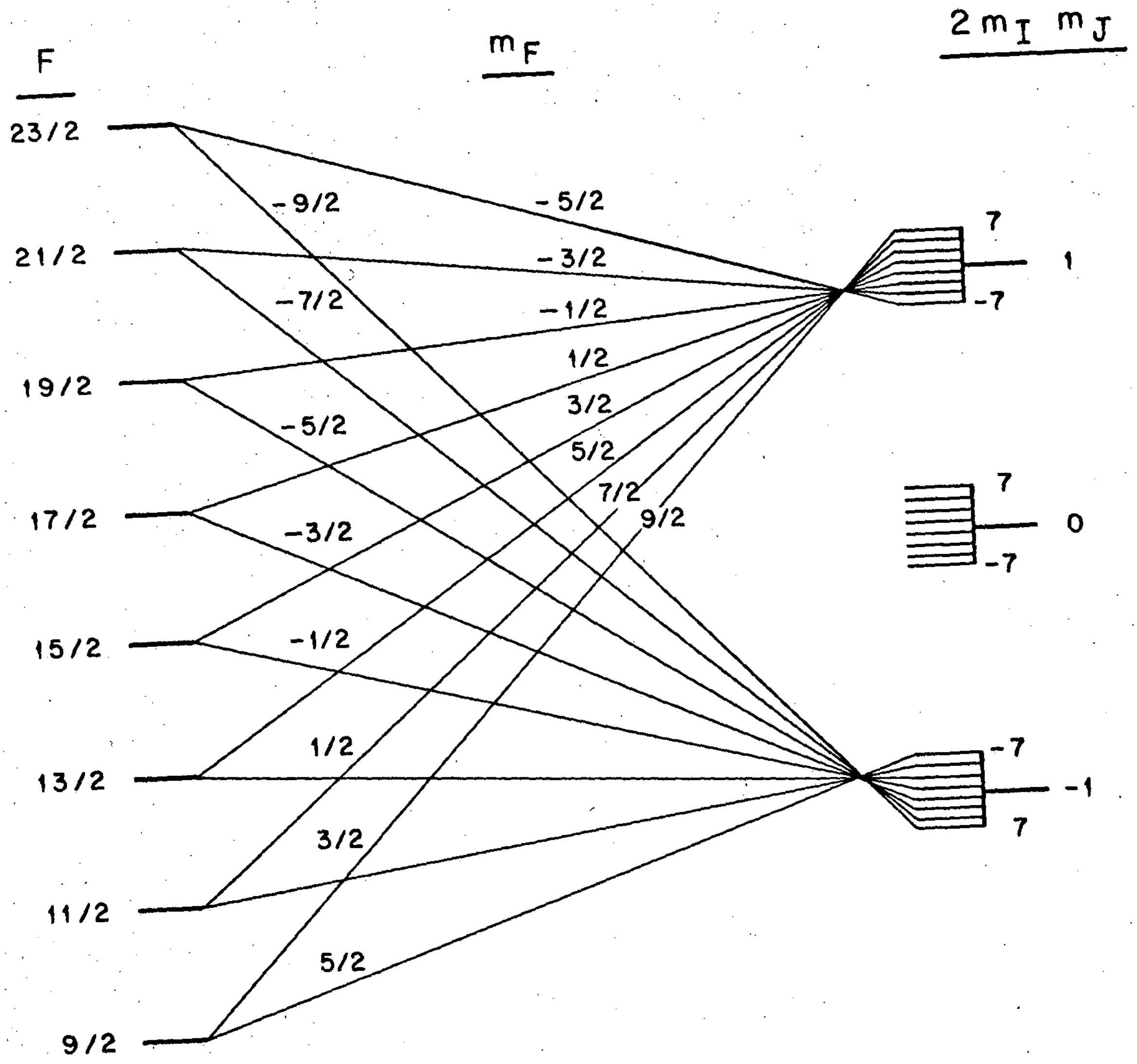

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Fig. 1.

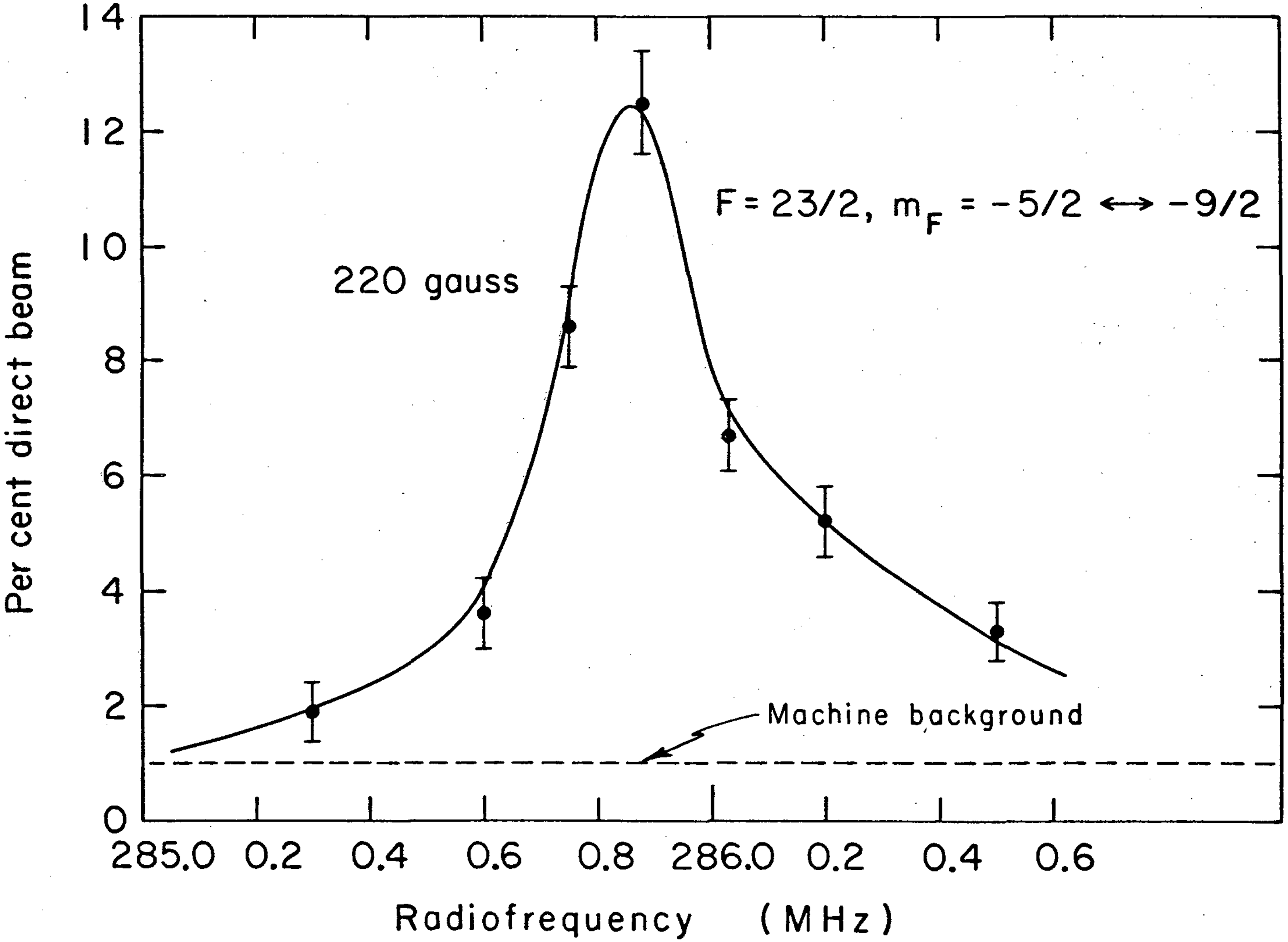

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Fig. 2.