Hyperfine-Structure Anomalies of Stable Ytterbium Isotopes†

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Hyperfine-structure anomalies of the stable ytterbium isotopes Yb^{171} ($I=\frac{1}{2}$) and Yb^{173} ($I=\frac{5}{2}$) have been measured in the two lowest-lying $^3P_1$ states of the Yb atom. For the $(4f)^{14}6s6p\,^3P_1$ level $\Delta=-0.367(9)\%$, while for the $(4f)^{13}5d(6s)^2\,^3P_1$ level $\Delta=+0.084(22)\%$. The former result is the first conclusive evidence that the Nilsson model can account for the distribution of nuclear magnetism in highly deformed nuclei. The second result, in conjunction with the first, can be used to establish the amount of unpaired s-electron spin density in a state explicitly lacking in unpaired s electrons. If we neglect other forms of configuration interaction, we calculate that the core-polarization magnetic field produced by the $5d$ electron at the nuclear site is -1.7×10^5 G. Byproducts of our work have been the lifetimes of the two excited electronic states. We find $\tau(6s6p\,^3P_1)=7.6(8)\times10^{-7}$ sec and $\tau(f^{-1}ds^2\,^3P_1)=1.7(2)\times10^{-8}$ sec.

INTRODUCTION

The influence of nuclear structure on the hyperfine structure (hfs) of heavy elements was early recognized in the work of Bohr and Weisskopf.[1] These authors showed that anomalies in the hfs of isotopes of certain elements which failed to obey the Fermi-Segre relation[2]

$$A^1/A^2=g_I^{\,1}/g_I^{\,2} \qquad (1)$$

could be explained if one assumed "essentially different distributions of magnetism in the two nuclei." In the above equation, A is the magnetic hfs interaction constant, and g_I is the nuclear g factor. The superscripts refer to the two nuclei.

Since 1950, quite a number of hfs anomalies of this type have been measured. For those nuclei, which can be adequately treated in a configuration mixing model (small deformations), the anomalies have been successfully interpreted.[3] However, no measurements existed in the region of highly deformed nuclei whose description requires the Nilsson model. In particular, the sensitivity of the anomaly to the nuclear deformation was of considerable interest.

In the concluding paragraph of their article, Bohr and Weisskopf suggest that the stable isotopes of ytterbium, $Yb^{171}(I=\frac{1}{2})$ and $Yb^{173}(I=\frac{5}{2})$ should show a large anomaly. Once accurate values for the nuclear g factors of these isotopes became available,[4] a measurement of the anomaly became feasible. It was simply necessary to measure the A constants for the two isotopes in the same electronic configuration.

It has recently been pointed out[5] that detection of hfs anomalies may serve another useful purpose, that of probing the nature of the electron distribution. The presence of an anomaly unambiguously implies an s electron ($p_{1/2}$ electron) content in the electronic wave function. For configurations which do not explicitly contain s electrons, the measurement of an anomaly is a sensitive gauge of the degree of configuration interaction. To exploit this circumstance, the anomaly produced by a configuration explicitly containing an s electron must first be measured for the two isotopes. The ytterbium atom, like the europium atom,[6] possesses at least two configurations in which a hfs anomaly can be measured. The detection of an anomaly in the $(4f)^{13}5d(6s)^2$ configuration, which does not contain an unpaired s electron, may be interpreted in terms of polarization of the core of paired electron spins, primarily by the $5d$ electron.

THEORY OF EXPERIMENT

The two $^3P_1$ levels which have been studied by the level-crossing technique in our work belong to the configurations $(4f)^{14}6s6p$ and $(4f)^{13}5d(6s)^2$. The fine structure levels relevant to our work are shown in Fig. 1. Both $^3P_1$ levels decay to the $(4f)^{14}(6s)^2\,^1S_0$ ground state, emitting intercombination lines of wavelength 5556 and 3464 Å, respectively. Preliminary results of work on the $6s6p$ configuration have been reported.[7]

The method employed may best be understood by referring to Fig. 2. Here are depicted the energy levels of the $6s6p\,^3P_1$ state as functions of an external magnetic field. If a beam of resonance radiation is incident on a vapor of ytterbium atoms in a magnetic field, each of the excited-state Zeeman sublevels will be populated and will subsequently decay independently. However, at a field of 1554 G the levels $(F, M_F)=(\frac{7}{2}, \frac{7}{2})$ and $(\frac{5}{2}, \frac{3}{2})$ become degenerate. The light absorbed and scattered by these levels will exhibit an interference effect which can be observed if the fluorescence is monitored by a fixed photomultiplier as a function

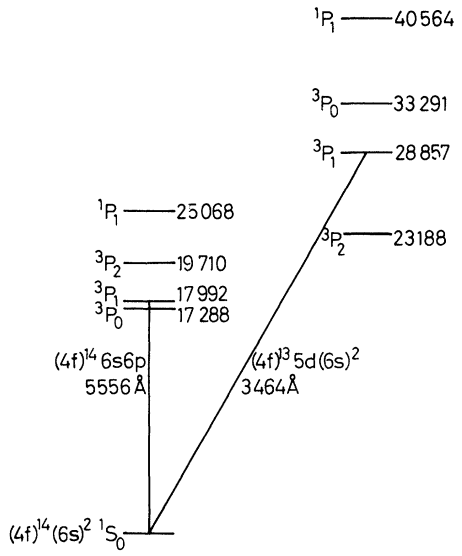

FIG. 1. ^3P and ^1P levels of the configurations $6s6p$ and $(4f)^{13}5d(6s)^2$. All levels have been observed except for $^3P_0$ of $f^{13}d$, which is a calculated value (Ref. 19).

of the magnetic field.

Detailed analyses of the hfs of an (sl) configuration have appeared in the literature. In particular, the relationship between the crossing field and the hfs constants for an $(sp)\,^3P_1$ state has been given for nuclear spins of $\frac{1}{2}$, $\frac{3}{2}$,[8] and $\frac{5}{2}$.[9] Most of the nuclei of Zn, Cd, and Hg, as well as the two stable Yb isotopes, have spins with these values. For any spin, only the ratio (A/g_J) can be determined in a level-crossing experiment. However, for the evaluation of hfs anomalies this presents no handicap, since g_J is identical for the two isotopes. Thus, to first order in the magnetic field, the field H_c at which the levels $(\frac{3}{2}, -\frac{3}{2})$ and $(\frac{1}{2}, \frac{1}{2})$ intersect in Yb^{171} is related to $A(171)$ by the equation

$$A(171)/g_J = \mu_0 H_c(171)\,(1 + \tfrac{1}{2} g_I/g_J). \qquad (2)$$

Similarly, for the $(\frac{7}{2},\frac{7}{2})$ and $(\frac{5}{2}, \frac{3}{2})$ intersection shown in Fig. 2, we have

$$3A(173)/g_J[(1+3b/10)(1-3b/40)] = \mu_0 H_c(173) \times \left\{1 + \frac{9b}{40} + \frac{1}{2}\left[\left(1 - \frac{3b}{20} + \frac{81b^2}{1600}\right)\Big/\left(1 + \frac{9b}{40}\right)\right]\right\}\frac{g_I}{g_J}, \qquad (3)$$

where $b = B/A$, the ratio of quadrupole to dipole hfs interaction constants. In these expressions g_I is negative for a positive nuclear moment and g_J is positive.

References 8 and 9 also provide formulas for evaluating second-order hyperfine-Zeeman and cross hyperfine-Zeeman corrections which arise from interactions with other fine structure levels. These are required for $(sp)\,^3P_1$ states, where the experimental precision is generally very high, owing to the narrow signals associated with intercombination lines and the high magnetic field at which the level crossings occur. For Yb, for example, typical linewidths for the crossing signal at 1554 G are 0.14 G.

An important factor in the success of the present work is the favorable combination of hfs and isotope shift in the line at 5556 Å. The spacing between the levels is such that at the positions of the level crossings of the odd-A isotopes there is an abundance of pumping radiation from the even isotopes in our light source. This is readily apparent from a spectrogram of the 5556 line in Yb shown in Ref. 2, p. 175, or from a more detailed drawing presented in Fig. 3.[10] The position of the main crossing for each isotope is marked by an X on the horizontal axis.

The search for the level crossings was mitigated by the more recent optical work dealing with the $6s6p$ configuration in Yb.[11,12] The optical values for the hfs constants and for the Landé g factor[13] were sufficiently accurate that the positions of the main and foldover crossings could be first predicted, and then located, within one or two narrow sweep ranges. The main level crossings could be observed with difficulty directly on an oscilloscope screen. The foldover crossings are considerably broader, due to the wide range of the magnetic field for which the levels remain within

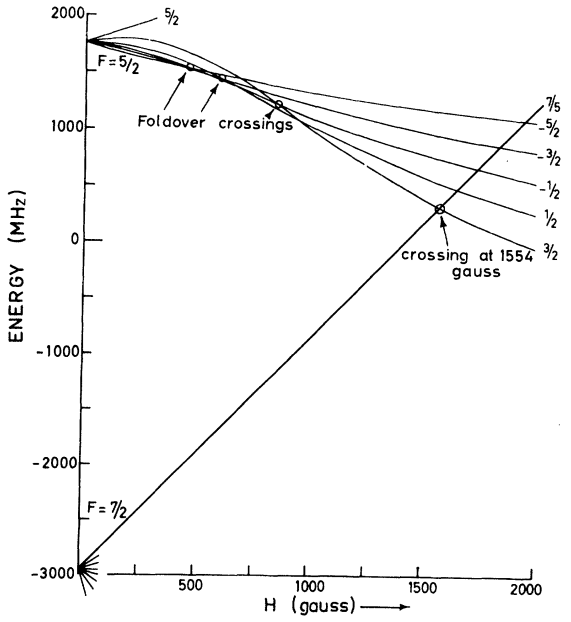

FIG. 2. Energy levels of Yb^{173} in a magnetic field. Observed level crossings are circled.

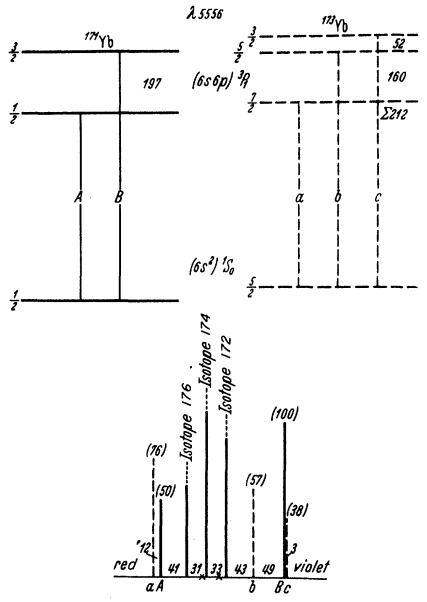

FIG. 3. Isotope shift and hfs of the 5556 line in YbI (Ref. 10).

a natural linewidth of one another. In practice, all data were taken with lock-in detection techniques. The magnetic field was modulated at 28 cps and measured by observation of proton NMR in a mineral oil sample.

When natural Yb metal (Yb^{173} is 16% abundant, Yb^{171} only 14%) is used to scatter the resonance radiation, the foldover crossings in the $f^{13}ds^2$ configuration were barely observable. However, when a sample enriched to 85% in Yb^{173} was substituted as scatterer, strong signals were observed. The main crossings for both isotopes in this configuration were easily located in a slow handsweep of the magnetic field. They were readily identified since the ratio of the crossing fields was almost identical to that for the $6s6p$ configuration. Conclusive evidence was provided by the presence of only one main crossing when the enriched isotopic sample was used.

EXPERIMENTAL APPARATUS AND PROCEDURE

A dense atomic beam of ytterbium served as scatterer. The apparatus for producing the beam has been described earlier.[14] However, it was not necessary to heat the oven containing the Yb metal by electron bombardment. Approximately 40 W of power supplied by a 0.065-in. tungsten filament surrounding the oven caused the Yb to sublime. A copper heat shield confined the heating radiation and prevented the filament glow from reaching the photomultiplier (EMI 6256B) detector. Ovens of tantalum and molybdenum were used successfully.

The hollow cathode light source was also of a design that has already been described.[15] The Yb was machined from two small ingots of natural metal. Proper operation of the lamp was signalled by the appearance of an intense green discharge, characteristic of the 5556 line. The transfer of energy from the neon discharge to the Yb atoms is especially efficient.

A broad band filter constructed by placing two Corning glass filters (4-76 and 3-69) in series, facilitated observations on the green line. Experiments involving the 3464 Å radiation were performed with the aid of a Corning 7–37 filter, or in the later work, with a narrow-band interference filter peaked at 3450 Å. One phase of our work required polarized light. This dealt with measuring the g factors of both $^3P_1$ levels with the double-resonance technique. A nonglare polarized plastic film GS-10 manufactured by Polacoat, Inc. proved adequate for the green line, while a sample of PL 40 MR polarizer by the same manufacturer has a peak efficiency in the neighborhood of 3500 Å.

The resonance and fluorescence radiations were perpendicular to each other and to the magnetic field. The latter was established in the 3-in. gap of a 12-in. Harvey-Wells electromagnet. A simple shimming procedure makes a homogeneity of about 1 part in 10^5 over a 1-in.^{3} attainable. However, the proton resonance magnetometer was approximately $1\frac{1}{4}$ in. from the center of the magnet. The offset correction was determined in two ways. In the first method, a second probe was slipped into the exact center via a double O-ring seal and the two probes compared. This had the advantage of directly measuring any stray fields, e.g., from the filament heater. In the second method, the apparatus was slipped out from between the magnet pole faces, and a number of readings were taken with a single probe at the center and at the fixed probe's position. This was repeated before and after each run. We hasten to add that for purposes of measuring the hfs anomaly, the second procedure is more than adequate. The offset correction was found to vary almost linearly with the magnetic-field magnitude. Since both main crossings were measured in succession (in the same hysteresis loop), and since only the ratio of the crossing fields is important, the offset correction, as well as any other stray fields, makes an insignificant contribution to the ratio of the A values.

Our laboratory does not yet possess a frequency standard, and this proved to be the limiting factor in our precision. The proton NMR frequency was measured with each of two Hewlett-Packard model 524D electronic counters. The readings agreed to a few parts in 10^6 in the frequency range of interest.

In the runs on the $6s6p$ configuration, we worked with an asymmetric signal due to a misalignment of our optics. For work on the $f^{13}ds^2$ configuration,

an analysis of the overlapping foldover crossing signals demanded symmetric signals. The optics were aligned very carefully and symmetric signals were obtained. We could interpret the asymmetric signals using an analysis due to Shaltiel,[16] based on the amplitudes of the major and minor peaks. However, a more satisfactory procedure was arrived at. If the magnetic field direction is reversed, the asymmetry does likewise. When positions of the major peak for the two field directions are averaged, the result is in excellent agreement with the center of a symmetric curve. Of course, the two averaged curves must have equal and opposite asymmetry.

In addition to reversing the dc magnetic field direction after each run, we also studied the effects of the modulating field's direction and amplitude. Our method for measuring the offset correction automatically resulted in a repositioning of the apparatus after each run. Runs taken in rapid succession were therefore essentially independent.

EXPERIMENTAL RESULTS

The position of all observed level crossings in units of the proton NMR frequency (in kilocycles) is given in Table I. The uncertainties given for the main crossings for the $6s6p$ configuration represent twice the standard deviation for 16 runs made on five separate occasions. Each run consisted of a minimum of two pairs of curves in opposite sweep directions so that shifts due to integration time effects associated with lock-in detection could be averaged out. Four runs were made on the foldover crossings on three distinct dates. The experimental results were subjected to a least-squares fit on an IBM 7040 computer. Only A and B, the magnetic and quadrupole hfs interaction constants, were varied. g_J was held fixed at the value determined from our double-resonance work, 1.49280(4).[17] Auxiliary constants used in our work are 1.3996 Mc/G for the ratio μ_0/h and 4.2577 Mc/sec for the proton NMR frequency in a 1-kG magnetic field. The results are $A = -1094.35(3)$ Mc/sec, $B = -826.59(20)$ Mc/sec, $B/A = 0.7553(2)$. As is apparent from Eq. (3), only the ratio $b = B/A$ is important in arriving at a precise value of A/g_J. When second-order Zeeman and cross hyperfine-Zeeman corrections are included, the ratios

$$\frac{A(173)}{g_J} = -0.33705\ \frac{\mu_0}{h}\ H_c(173),$$

and

$$\frac{A(171)}{g_J} = 0.99987\ \frac{\mu_0}{h}\ H_c(171)$$

are obtained. Further inclusion of second-order hyperfine corrections modifies the ratio of these two ratios, $A(171)/A(173) = 3.61650(5)$. This ratio is extremely insensitive to the precise values chosen for the auxiliary constants given above.

The numerical values for the individual electron hfs constants used in making the second-order correction are listed in Table II. They were deduced from Ref. (12). The hfs anomaly Δ is defined by the equation

$$A(171)/A(173) = g_I(171)/g_I(173)(1+\Delta)\ . \qquad (4)$$

For the ratio $g_I(171)/g_I(173)$, Ref. (4) yields $-3.6298(3)$. Thus, $\Delta(sp\,^3P_1) = -0.367(9)$.

The procedure for treating the $f^{13}ds^3$ configuration involves one additional step. The overlapping foldover crossings were analyzed by calculating the intensities, line shapes, and linewidths of each of the donor signals. A plot of the superposed curve revealed the direction and magnitude of the perturbation undergone by each signal. A study

TABLE I. Summary of all observed level crossings. All entries are in units of kilocycles of the proton NMR frequency. The last row, entitled ratio, is the average value of the ratio of the magnetic fields for the two main level crossings.

Isotope	Configuration	Identification	Crossing field (kc)
Yb^{171}	$6s6p$	$\frac{3}{2}-\frac{3}{2},\ \frac{1}{2}\frac{1}{2}$	8065.85(12)
	$f^{13}ds^2$	$\frac{3}{2}-\frac{3}{2},\ \frac{1}{2}\frac{1}{2}$	3149.4(4)
Yb^{173}	$6s6p$	$\frac{7}{2}\frac{7}{2},\ \frac{5}{2}\frac{3}{2}$	6616.74(7)
		$\frac{5}{2}\frac{3}{2},\ \frac{5}{2}-\frac{1}{2}$	3497.4(2)
		$\frac{5}{2}\frac{1}{2},\ \frac{5}{2}-\frac{3}{2}$	2561.3(2)
		$\frac{5}{2}-\frac{1}{2},\ \frac{5}{2}-\frac{5}{2}$	1919.6(3)
	$f^{13}ds^2$	$\frac{7}{2}\frac{7}{2},\ \frac{5}{2}\frac{3}{2}$	2579.1(3)
		$\frac{5}{2}\frac{3}{2},\ \frac{5}{2}-\frac{1}{2}$	1515(3)
		$\frac{5}{2}\frac{1}{2},\ \frac{5}{2}-\frac{3}{2}$	1146(8)
Ratio	$6s6p$	1.219005(16)	
	$f^{13}ds^2$	1.22109(5)	

TABLE II. Constants and parameters used in making second-order corrections to the hfs constants.

Individual electron interaction constant	Yb^{171} (mk)	Yb^{173} (mk)	Parameters	Value of parameters
a_S	341.3	−94.38	c_1	0.4636
$a_{1/2}$	36.96	−10.22	c_2	0.8859
$a_{3/2}$	4.92	−1.36	ξ	1.02
$b_{3/2}$	•••	43.8	η	1.26

of the nonresonant background scattered light showed that its variation over the region of the two measured crossings was negligible.

No treatment of second-order effects for an fd configuration has been given. However, as is evident from Fig. 1, the fine structure separations for this configuration in Yb I are much larger than for $6s6p$. In addition, the hfs and Zeeman splittings are a good deal smaller. Finally, since the data are considerably less precise than for $6s6p$, due to the shorter lifetime of the excited states, we feel justified in neglecting all second-order corrections. Again, a computer fit was used to obtain the ratio $B/A = 0.6423(56)$, while g_J was held fixed at 1.2635(9).[17] We also find that A(173) = −359.99(9) Mc/sec. The uncertainty in A is due mainly to the uncertainty in g_J and is not of importance in determining the anomaly. The sign of A was not measured but has been chosen to be the same as that of the nuclear dipole moment.

For this configuration, the ratio $A(171)/A(173) = -3.6329(5)$. It is immediately apparent from Table III that this ratio is smaller than the ratio of the g factors. Therefore, the anomaly will be of the opposite sign. We find $\Delta(f^{13}ds^2\,{}^3P_1) = +0.084(22)$. Figure 4 exhibits the main crossings in the $f^{13}ds^2$ configuration for both Yb isotopes. The Yb^{173} signal was obtained with our enriched isotopic sample. A natural lump of Yb metal was used in the atomic-beam oven when the trace shown in Fig. 4(b) was observed. A careful study of the linewidth of the Yb signal as a function of the amplitude of the modulating field was performed. Care was also taken to reduce the atomic-beam density to the point where coherence narrowing of the signal was insignificant. The linewidth, extrapolated to zero modulation amplitude, is related to the lifetime of the excited state by the equation

$$\tau = 1/\pi \frac{\partial \nu}{\partial H} \Delta H \quad ,$$

where ΔH is the full width at half-maximum of the signal and is $\sqrt{3}\,\Delta H_{pp}$ (ΔH_{pp} is the peak-to-peak separation). $\partial\nu/\partial H$ is the rate at which the crossing levels approach one another, and may be calculated from a knowledge of the hfs constants and of the g factors. The crossing in the $6s6p$ configuration at 1554 G was subjected to a similar treatment. The results are $\tau(6s6p\,{}^3P_1) = 7.6(8) \times 10^{-7}$ sec and $\tau(f^{13}ds^2\,{}^3P_1) = 1.7(2) \times 10^{-8}$ sec.

DISCUSSION

A prior analysis of the electronic structure of the two configurations reported here is necessary before any conclusions can be drawn regarding hfs anomalies and core polarization. The lifetimes of the $6s6p\ {}^3P_1$ and $6s6p\ {}^1P_1$ levels have recently been measured by the Hanle effect.[18] As shown in Ref. 8, the lifetime measurements offer a means of deducing the extent of breakdown of Russell-Saunders coupling. We find

$$|(sp)^3P_1\rangle = 0.991\,|{}^3P_1{}^0\rangle - 0.133\,|{}^1P_1{}^0\rangle \quad , \qquad (5)$$

where the zero superscript on the wave function on the right-hand side refers to pure Russell-Saunders states. A more complete analysis of configuration interaction between the two configurations studied here has been performed.[19] The conclusion that the $^3P_1$ level is 98% pure is unaltered by the more realistic treatment.

The wave function for the $^3P_1$ level of $f^{13}ds^2$, however, can only be obtained reliably from a configuration interaction approach based on a least-squares fit to the energy levels. Goldschmidt and Nir[19] find that the wave function for this level con-

TABLE III. Ratio of $A(171)/A(173)$ compared to the ratio of the g factors.

Configuration	$\frac{A(171)}{A(173)}$	$\frac{g_I(171)}{g_I(173)}$	Δ
$(4f)^{14}6s6p$	−3.61650(5)	−3.6298(3)	−0.367(9)
$(4f)^{13}5d6s^2$	−3.6329(5)	−3.6298(3)	+0.084(22)

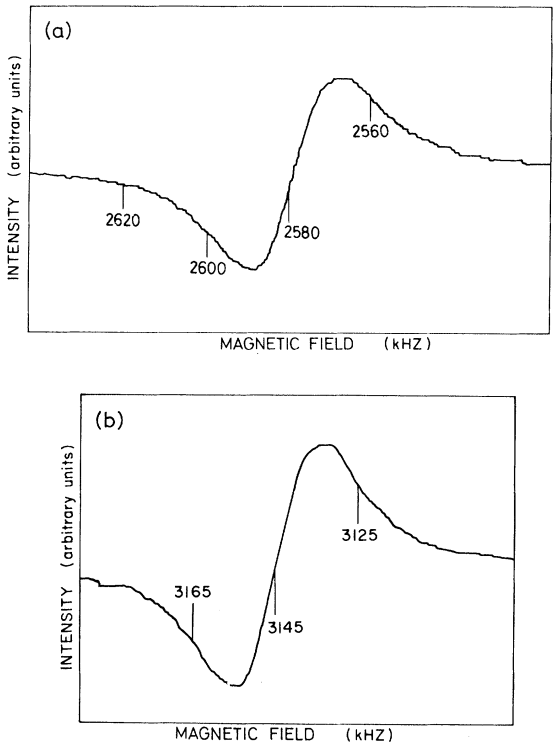

FIG. 4. Curve (a) is a trace of the main crossing obtained with a sample enriched to 85% in Yb^{173}. Curve (b) is the single observable crossing in Yb^{171} taken with a natural Yb sample. Both curves are level crossings in the $f^{13}ds^2$ configuration.

tains an appreciable admixture from the $f^{14}sp\,{}^1P_1{}^0$ level and smaller contributions from various levels of the $f^{13}d^2s$, $f^{13}d^3$, and $f^{14}dp$ configurations with $J=1$. Not included in their treatment thus far is the interaction with the $(4f)^{13}5d6s7s$ configuration. Levels of all these slightly admixed configurations have not yet been identified.

Using a wave function very similar to Eq. (5), Unna[20] has obtained the relation between the observed hfs anomaly $\Delta(sp^3P_1)$ and the single-electron anomalies, $\Delta(s_{1/2})$ and $\Delta(p_{1/2})$,

$$\Delta({}^3P_1)=0.837\Delta(s_{1/2})+0.157\Delta(p_{1/2}). \tag{6}$$

The overlap of the $p_{3/2}$ electron and nuclear wave function has been neglected.[21] The procedure for using Nilsson wave functions to calculate the single-electron hfs anomalies has also been given by Unna.[20] Two aspects of his calculation are worth emphasizing. The first is that the largest contribution to the anomaly comes from the spin asymmetry terms[3] in the electron-nucleus interaction. The second is that the anomaly is fairly sensitive to the deformation. Only a deformation consistent with that measured by other, more direct, techniques can account for the observed anomaly.

As mentioned in the introduction, the detection of an anomaly in the $f^{13}ds^2$ configuration implies the admixture of configurations with unpaired s spins. Thus, we may write, for the magnetic hfs interaction constant,

$$A({}^3P_1)=A(fd)+A_s, \tag{7}$$

where the experimentally determined $A({}^3P_1)$ is expressed as the sum of two terms. The first is the A value for a pure $f^{13}ds^2$ configuration and is due entirely to the unpaired f and d electrons. The second is a contact term arising from the s-electron content of the wave function.

If Eq. (7) is substituted into Eq. (4) for each isotope, only a small amount of algebra is required to show that

$$\Delta(f^{13}ds^2,\,{}^3P_1)A({}^3P_1\mathrm{Yb}^{173})=\Delta(s_{1/2})A_s(173)\,, \tag{8}$$

$$\text{where}\quad \Delta(s_{1/2})=\frac{A_s(171)}{A_s(173)}\frac{g_I(173)}{g_I(171)}-1 \tag{9}$$

is the hfs anomaly to be expected from a single unpaired s electron. The single-electron anomalies of the f and d electrons are negligible. Now it can be shown on theoretical grounds that the quantity defined in Eq. (9) is independent of the type of s electron chosen (see Ref. 2, p. 130). It can therefore be determined from Eq. (6) for the sp configuration if we allow $\Delta(p_{1/2})=0.20\Delta\times(s_{1/2})$. Then Eq. (8) can be solved for $A_S(173)$. One striking fact is immediately apparent: The reversal of sign for the two measured anomalies is due to the sign of the s-electron contribution to Eq. (7), which is opposite to that of the f and d electrons. This is suggestive of the core-polarization mechanism, which, for the $3d$ and $4d$ ions and atoms, produces a net magnetic field opposite to that of the spin and orbital fields of the d electrons themselves. We find

$$A_s(173)=+72(19)\ \mathrm{Mc/sec}.$$

It is difficult to say with certainty whence this large term arises. Preliminary calculations[19] indicate that the admixture of configurations explicitly containing unpaired s spins is small. The s-electron content stemming from the ${}^1P_1{}^0$ of the sp configuration level cannot lead to an anomaly, since the contact field of the s electron vanishes identically for this level. The admixture of the configuration $(4f)^{13}5d6s7s$, as mentioned above, has not yet been considered in detail. However, it is an example of a more general form of configuration-interaction core polarization in which

s electrons are excited from closed shells. The mechanism responsible for this excitation is the exchange part of the electrostatic interaction between the s electron and the valence electron(s). Only that closed-shell s electron with the same spin direction (the same value for the magnetic spin quantum number m_S) as the valence electron will experience such an exchange interaction. The net effect is that a difference between the probability densities of the two closed-shell s electrons, and hence of their opposing magnetic fields at the nucleus, is produced. The resultant magnetic field, whose origin lies in the polarization of closed shells by the valence electron, is referred to as the core-polarization magnetic field of that particular valence electron. It is convenient to include the contribution from $(4f)^{13}5d6s7s$, however large it may be, as part of the core-polarization magnetic field. This obviates the need for an *a priori* knowledge of its magnitude. However, it is important to bear this extension in mind when comparing with the work of others. Finally, Bleaney has shown[22] that the core polarization of f electrons in atoms possessing paired $6s$ electrons is very small.

We are thus led to the possibility that $A_S(173)$ arises from the core-polarization magnetic field of the $5d$ electron. Denoting this field by $H_C(5d)$, we may write

$$A_S(173)\vec{I}\cdot\vec{S} = -\mu_I \cdot H_C(5d) \ . \tag{10}$$

Substituting $I=\frac{5}{2}$, $S=\frac{1}{2}$, and $\mu_I = 0.678$ mm, we find $H_C(5d) = -1.7\times10^5$ G. This may be compared with the core-polarization magnetic field per unit spin deduced by Jaccarino[23] for the Pt ion, $H_C(5d) = -2.4\times10^6$ G. Experience with the $3d$ and $4d$ ions and atoms has shown that the addition of the two outermost paired s-electron spins to the ion to form the atom has the effect of quenching the core-polarization field by roughly 1 order of magnitude. If this is true for the $5d$ case as well, it follows that $H_C(5d) = -1.7\times10^5$ G per unit spin for the free atom is entirely plausible.

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[1]A. Bohr and V. F. Weisskopf, Phys. Rev. 77, 94 (1950).

[2]H. Kopfermann, Nuclear Moments (Academic Press Inc., New York, 1958), p. 159.

[3]H. H. Stroke, R. J. Blin-Stoyle, and V. Jaccarino, Phys. Rev. 123, 1326 (1961).

[4]L. Olschewski and E. W. Otten, Z. Physik 200, 224 (1967).

[5]A. G. Blachman, D. A. Landman, and A. Lurio, Phys. Rev. 150, 59 (1966).

[6]Y. Bordarier, B. R. Judd, and M. Klapisch, Proc. Roy. Soc. (London) A289, 81 (1965).

[7]B. Budick and J. Snir, Phys. Letters 24B, 276 (1967).

[8]A. Lurio, M. Mandel, and R. Novick, Phys. Rev. 126, 1758 (1962).

[9]A. Landman and R. Novick, Phys. Rev. 134, A56 (1964).

[10]H. Schuler and H. Korsching, Z. Physik 111, 386 (1938).

[11]K. Krebs and H. Nelkowsky, Z. Physik 141, 254 (1955).

[12]J. S. Ross and K. Murakawa, Phys. Rev. 128, 1159 (1962).

[13]W. Meggers (to be published).

[14]B. Budick and L. A. Levin, in La Structure Hyperfine Magnetique des Atomes et des Molecules (Centre Nucléaire Recherche Scientifique, Paris, 1966).

[15]B. Budick, R. Novick, and A. Lurio, Appl. Opt. 4, 229 (1965).

[16]M. Peter *et al.*, Phys. Rev. 126, 1395 (1962).

[17]B. Budick and J. Snir, Phys. Letters 24A, 689 (1967).

[18]M. Baumann and G. Wandel, Phys. Letters 22, 283 (1966).

[19]Z. Goldschmidt and S. Nir (private communication).

[20]I. Unna, Phys. Letters 24B, 499 (1967).

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[22]B. Bleany, in Ref. 14.

[23]A. M. Clogston, V. Jaccarino, and Y. Yafet, Phys. Rev. 134, A650 (1964).