TABLE II. Ratio of 54-min to 13-sec activities of In^{116} after irradiation by neutrons at various energies.

Neutron energy (ev)	26.8-mg/cm² foil Ratio of activities[1]	26.8-mg/cm² foil Corrected ratio of activities	96-mg/cm² foil Ratio of activities[1]	96-mg/cm² foil Corrected ratio of activities
3.86			0.85±0.05	1.20
2.66			1.57±0.15	2.23
1.45	2.99±0.15	2.45	1.98	
0.10	2.5 ±0.3	2.05		
Pile beam	3.02±0.18	2.48	1.705	2.40

various energies listed in Table II (excepting that at 3.86 ev) have a mean value of 2.32 with a standard deviation of 0.18 or 7.8%. The most different value from the mean, 2.05, differs from the mean by 12% or 1.5 standard deviations. However there is an uncertainty in the original data at this point of ±12%. On this basis there is no evidence that the ratio of activities is a function of the energy in the interval from pile neutrons to 2.66 ev.

The front-back counting ratio was also close to unity for the case of the thick foil at the 3.86-ev resonance energy. The ratio of activities for this case was 0.85; even after applying the correction factor, the resulting ratio of activities of 1.20 is approximately one-half of the other corrected values. This may indicate that the ratio of activities does depend on energy at 3.86 ev.

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Hyperfine Structure of the $(5p)^5(6s)\ ^3P_2$ State of $_{54}Xe^{129}$ and $_{54}Xe^{131}$†

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The hyperfine structures of the metastable $(5p)^5(6s)\ ^3P_2$ state of $_{54}Xe^{129}$ and $_{54}Xe^{131}$ have been measured by the atomic beam magnetic resonance method. The zero magnetic field intervals $f(F\leftrightarrow F')$ are: for Xe^{129}, $f(\frac{3}{2}\leftrightarrow\frac{5}{2})=5961.2577(9)$ Mc/sec; and for Xe^{131}, $f(\frac{5}{2}\leftrightarrow\frac{7}{2})=2693.6234(7)$ Mc/sec, $f(\frac{3}{2}\leftrightarrow\frac{5}{2})=1608.3475(8)$ Mc/sec, and $f(\frac{1}{2}\leftrightarrow\frac{3}{2})=838.7636(4)$ Mc/sec. The values of the quadrupole and octupole moments of Xe^{131}, without polarization corrections and without corrections for any effects of configuration mixing, are $Q=-0.120(12)$ b and $\Omega=+0.048(12)$ nmb. The hyperfine-structure anomaly for the two isotopes due to the $s_{\frac{1}{2}}$ electron alone is $\Delta(s_{\frac{1}{2}})=+0.0440(44)\%$, in disagreement with the prediction of the single-particle model.

I. INTRODUCTION

THE experiment to be described is one in a sequence to measure the hyperfine structure (hfs) of the metastable $^3P_2$ states of elements from Groups II and VIII of the periodic table by the atomic beam magnetic resonance method. The purpose is to measure hfs to a sufficiently high precision to determine the higher nuclear moments, and, where more than a single isotope of odd mass number exists in sufficient abundance, the hyperfine anomalies. For an electronic state of angular momentum J, there is no interaction higher than the 2^{2J} pole, and the ground states of elements from Groups II and VIII, which are $^1S_0$, have no hfs. However, all these atoms (excluding He) have excited states with $J\geq 2$ which can be expected to have lifetimes much greater than the transit time over the 30-cm length of a typical beam-resonance apparatus, so that they are stable for all observational purposes. The experiments performed to date have yielded data on the hfs of the metastable $^3P_2$ states of Group VIII atoms $_{10}Ne^{21}$, $_{54}Xe^{129,131}$ and Group II atoms $_{80}Hg^{199,201}$, $_{48}Cd^{111,113}$, $_{30}Zn^{67}$, $_{12}Mg^{25}$, and $_4Be^9$.[1–5] For the former set, the $^3P_2$ state belongs to a p^5s configuration, and for the latter to an sp, in each case the lowest excited configuration. Other atoms having metastable $^3P_2$ states are A, Kr (p^5s configurations), Ca and Sr (sp configurations). Ba and Ra have $^3P_2$ states which belong to similar sp configurations, but there are lower-lying sd levels to which decay is allowed. The lifetimes of the metastable $^3P_2$ states of xenon and the other inert gases (excluding He) may be expected to be quite long, probably greater than one second. For these atoms, the $^3P_2$ state is the first excited state. The lowest first order mode of decay from a pure $^3P_2$ state to a pure $^1S_0$ state, such as is the

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* Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Faculty of Pure Science, Columbia University.

[1] G. M. Grosof, P. Buck, W. Lichten, and I. I. Rabi, Phys. Rev. Letters **1**, 214 (1958).
[2] M. N. McDermott and W. Lichten, Phys. Rev. **119**, 134 (1960).
[3] W. L. Faust, M. N. McDermott, W. Lichten, Phys. Rev. **120**, 469 (1960).
[4] A. Lurio, Bull. Am. Phys. Soc. **4**, 7 (1959).
[5] A. Lurio and A. G. Blachman, Bull. Am. Phys. Soc. **5**, 5 (1960).

ground state of these atoms, is the magnetic quadrupole mode.

In the present work are reported the results of a study of the hfs of the $^3P_2$ states of the two odd isotopes of xenon, Xe^{129} and Xe^{131}. The experimental arrangement is as follows (Fig. 1): A beam of atoms in the ground state issues from a slit and passes through an exciter, in which it is bombarded by a transverse beam of electrons. A fraction of the atoms emerge in the metastable $^3P_2$ state. The atoms pass through a conventional Rabi arrangement of one inhomogeneous-field region before, and one after, a homogeneous-field region in which an rf field may induce transitions. Unless the frequency and amplitude of the rf field are such as to cause transitions, the atoms are refocussed on the stop wire, the center of which lies on a straight line through the centers of the exciter and collimator slits. The atoms are intercepted by the stop wire and have no further effect. An rf-induced change of state within the C field alters the magnetic moment of the atom and thus its trajectory, so that the atoms that have made transitions miss the stop wire and strike a detector surface beyond it. The detector is an alkali-surface cathode from which metastables eject electrons by the surface Auger effect. They are collected on an anode, and the current is measured by an electrometer.

II. XENON: THE ISOTOPES AND THE $^3P_2$ STATE

The present experiment was performed with xenon with the natural abundances 26% for Xe^{129} and 21% for Xe^{131}. There are no other known stable isotopes of nonzero nuclear spin.

The $^3P_2$ state of xenon belongs to the configuration $(5p)^5(6s)$, if we neglect configuration interaction. For Xe^{131}, $I=\frac{3}{2}$. The $p_{\frac{3}{2}}$ hole gives dipole, quadrupole, and octupole interactions. The $s_{\frac{1}{2}}$ electron gives a dipole interaction about three times larger than that of the $p_{\frac{3}{2}}$ hole. For Xe^{129}, $I=\frac{1}{2}$, and there exist only the $p_{\frac{3}{2}}$ and $s_{\frac{1}{2}}$ dipole interactions. Since the nuclear dipole moments have been measured by a nuclear magnetic resonance technique,[6] the $s_{\frac{1}{2}}$ electron hfs anomaly between the two isotopes can be determined. The $p_{\frac{3}{2}}$ hole contributes no appreciable anomaly because it has a vanishing density at the nucleus.

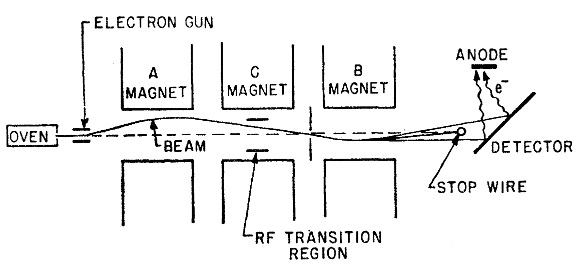

FIG. 1. Schematic diagram of apparatus.

[6] E. Brun, J. Oeser, H. H. Staub, C. G. Telschow, Phys. Rev. **93**, 904 (1954).

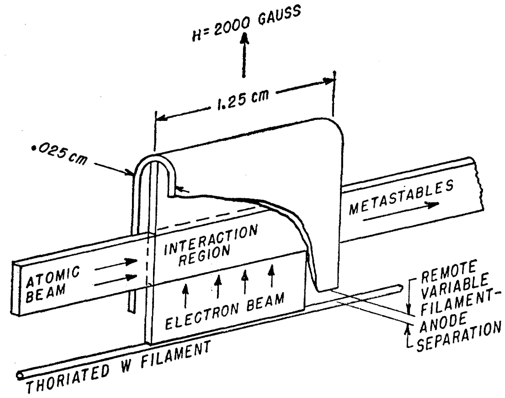

FIG. 2. Schematic diagram of electron gun.

Previous measurements by optical methods of the hfs of the metastable $^3P_2$ state of Xe^{129} and Xe^{131} are given in Table I.

III. DETAILS OF THE EXPERIMENTAL ARRANGEMENT

A. The Electron Gun

A schematic diagram of the electron gun is shown in Fig. 2. A U-shaped copper-sheet anode is located above a tungsten filament, within a strong collimating magnetic field to confine the electrons to the interaction region between the copper faces. It is essentially the same as that described in reference 1, except that: (a) a thoriated tungsten filament was used, (b) provision was made for manual adjustment from outside the vacuum envelope of the filament-anode separation, and (c) the heater current was supplied by a 200-kc/sec oscillator. Thoriation of the tungsten filament makes possible a lower operating temperature, which gives improved mechanical stability and much longer life. The mechanical adjustment allows one to operate the device with the minimal separation between filament and anode consistent with freedom from shorting so as to obtain the largest possible bombarding electron current. The rf heating was introduced to avoid lateral deflection of the filament by the collimating magnetic

TABLE I. Optical hfs measurements (in units of 10^{-3} cm^{-1}) on the $^3P_2$ state of Xe. Intervals given in parentheses were not directly observed. The present work is given for comparison.

Investigators	Xe^{129} $\frac{3}{2}\leftrightarrow\frac{5}{2}$	$\frac{1}{2}\leftrightarrow\frac{3}{2}$	Xe^{131} $\frac{3}{2}\leftrightarrow\frac{5}{2}$	$\frac{5}{2}\leftrightarrow\frac{7}{2}$
Jones[a]	−198			
Kopfermann and Rindall[b]	−196	(36)	(59)	(83)
Bohr, Koch, and Rasmussen[c]	−198.4	(27.3)	(52.9)	89.7
Present work	−198.845[d]	27.9781[d]	53.6486[d]	89.8494[d]

[a] E. Jones, Proc. Roy. Soc. (London) **144**, 587 (1933).
[b] H. Kopfermann and E. Rindall, Z. Physik **87**, 460 (1933).
[c] A. Bohr, J. Koch, and E. Rasmussen, Arkiv Fysik **4**, 455 (1952).
[d] $c=2.998930\times10^{10}$ cm/sec.

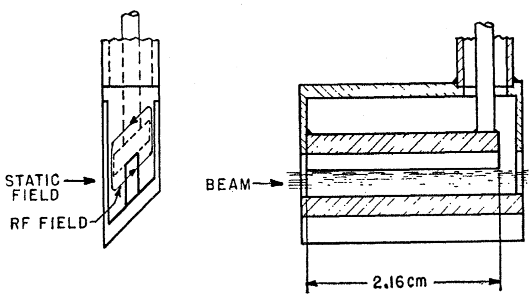

FIG. 3. Schematic diagram of $\pi-\sigma$ hairpin.

field. These three modifications made the device much more reliable and less critical of adjustment in assembly than the exciter described in reference 1.

B. The Detector Surface

The detector surface used in this experiment was a coat of cesium sprayed on a nickel-plated copper sheet. The cesium was sprayed onto the surface by an oven containing CsCl powder and metallic calcium filings. An adequate amount of cesium is produced when the oven is heated to 450°C.

Rough estimates from the observed beam magnitude indicate that, if f is the fraction of the atoms which leave the electron gun in the $^3P_2$ state and η is the fraction of metastables which produce electrons upon striking the detector, then $f\eta=1.4\times10^{-4}$. If the cross section for metastabilization is taken to be $0.5\pi a_0^2$, f is estimated to be 0.4% so that η is 4%, very approximately.

C. rf Equipment

A Raytheon X26F klystron was used as the exciting oscillator for the zero-field interval $f(\frac{3}{2}\leftrightarrow\frac{5}{2})$ of Xe^{129} at 5961 Mc/sec. A Sylvania 6BL6 klystron tube in an Amerac Model 198A external cavity was used in measurement of the intervals $f(\frac{5}{2}\leftrightarrow\frac{7}{2})$ and $f(\frac{3}{2}\leftrightarrow\frac{5}{2})$ of Xe^{131} at 2694 Mc/sec and 1608 Mc/sec, respectively. A modified war-surplus radar jammer T-85/APT-5 was used in measurement of the $f(\frac{1}{2}\leftrightarrow\frac{3}{2})$ interval of Xe^{131} at 839 Mc/sec.

For precise frequency measurements, a number of discrete frequencies were made available by the use of a Gertsch FM-4 frequency multiplier driven by a quartz-crystal controlled frequency standard. A beat frequency (typically 30 Mc/sec), produced between the transition-inducing oscillator and some harmonic of one of these discrete frequencies, was measured with a Gertsch FM-3 frequency meter.

For the single interval of Xe^{129}, $f(\frac{3}{2}\leftrightarrow\frac{5}{2})$, a shielded parallel-plate hairpin with a length of 1.5 cm along the beam was used to generate the rf field. Such a hairpin produces an rf field perpendicular to the static field, and induces π transitions only, for moderate rf field amplitude.

Except for a portion of the data on the $f(\frac{1}{2}\leftrightarrow\frac{3}{2})$ interval, the measurements on Xe^{131} were made with the shorted coaxial hairpin shown in Fig. 3. Since the rf magnetic-field vector has both a component parallel to and one perpendicular to the static field, it excites both π and σ lines. The use of this hairpin made it feasible to take all measurements entering into the final results for the intervals $f(\frac{3}{2}\leftrightarrow\frac{5}{2})$ and $f(\frac{5}{2}\leftrightarrow\frac{7}{2})$ of Xe^{131} on σ lines only, particularly on certain σ lines of very low field dependence. It is preferable to use σ lines rather than π lines because σ lines are not subject to a Millman shift.[7] Lines for which the frequency has a low field dependence show little broadening from static-field inhomogeniety, and their use for determining zero-field intervals minimizes errors due to fluctuations in the static field.

For the $f(\frac{1}{2}\leftrightarrow\frac{3}{2})$ interval of Xe^{131} about one half of the data were taken with each of the hairpins. This served two purposes: first, to place a limit on any Millman shift associated with the π hairpin, since the σ lines (observed with the π-σ hairpin) have no such shift; and second, to place a limit upon any errors in the determinations of the intervals arising from the use of a particular rf magnetic-field configuration. To observe and cancel out the effects of Doppler shifts, data were taken with the hairpin axis aligned first parallel and then anti-parallel to the beam. No effects attributable to a Millman shift, a Doppler shift, or other such mechanism appeared under the tests made.

D. Deflecting Fields

The deflecting fields were set at approximately 2000 gauss, corresponding to $x=1.8$ for Xe^{129} and $x=6.1$ for Xe^{131}, where $x=g_J\mu_0H/A$.

Values for the magnetic moment of an atom in each state and for the change in moment associated with each allowed transition, as a function of x, were obtained by exact diagonalization of an approximate Hamiltonian including first order, magnetic dipole and electric quadrupole effects; the energy levels were differentiated numerically to obtain the moments. The moments and moment changes, calculated on an IBM 650, were used for qualitative prediction of the trajectories and, thus, of the relative observable signal intensities for the transitions. These predictions agree with experiment to within a factor of about 2, although no allowance was made for possible unequal population of the states F, M_F by the electron bombardment mechanism.

E. Homogeneous Field C

The homogeneous field C was between $\frac{1}{4}$ and $\frac{1}{2}$ gauss. One gauss corresponds to an x value of 0.003 for Xe^{131} and 0.0009 for Xe^{129}, so that the Zeeman displacements are nearly linear. Corrections for the quadratic terms in the dependence of the levels upon the homogeneous

[7] S. Millman, Phys. Rev. 55, 522 (1938).

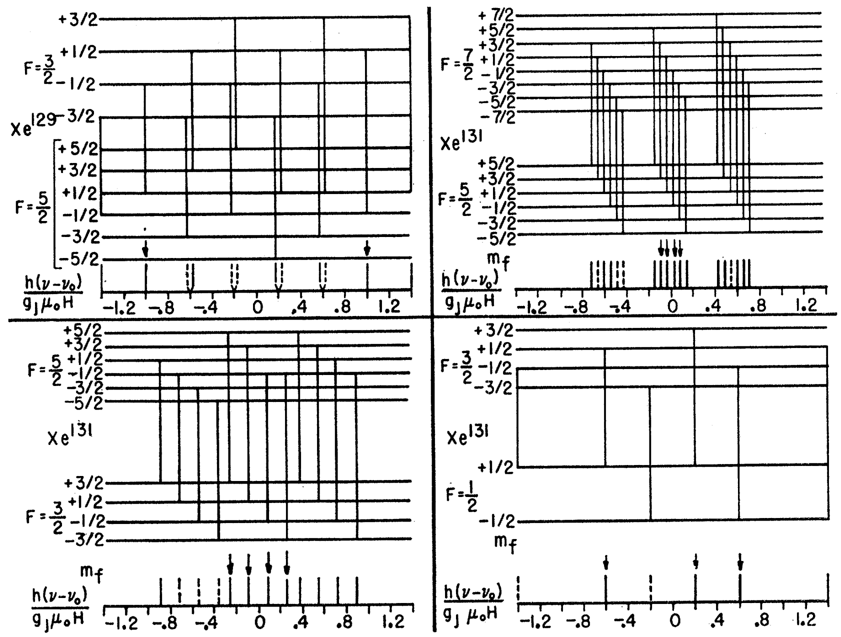

FIG. 4. The spectrum of Xe^{129} and Xe^{131} in the $^3P_2$ state. Unobserved transitions are represented by dashed lines, observed ones by solid lines. Lines used for accurate determination of zero-field intervals are indicated by arrows.

field[8] were nevertheless made. The magnitude of these corrections ranges up to 2 kc/sec.

IV. MEASUREMENT OF RESONANCE FREQUENCIES

A. General Considerations

In preliminary measurements on a particular hfs interval, a search was made for all transitions of the type $\Delta F=\pm1, \Delta M_F=0, \pm1$. The predicted spectrum is shown in Fig. 4. Some transitions were not observed because of unfavorable trajectories of the atoms through the apparatus.

For the precise determination of a resonance frequency, the oscillator was set at a series of closely spaced frequencies and the difference between metastable signal with rf power on and rf power off was noted. Typically, 13 points were taken on a resonance curve, 6 between the half-signal points. The points were taken first at the approximate center and then further away alternately on the higher and lower sides. The resonance frequency was obtained graphically from a smooth fit of a resonance curve to the points.

Except for a portion of the data on the $f(\frac{1}{2}\leftrightarrow\frac{3}{2})$ interval of Xe^{131}, all final determinations of zero-field intervals were made on the basis of pairs of lines of equal but opposite linear field dependence. The average of the two members of the pair (plus the small correction quadratic in the static field) gives the hyperfine interval. This method should minimize the effect of possible distortions in the line shapes due to field inhomogeneity, since the two members of the pair tend to be distorted symmetrically about the zero-field interval.

[8] A. K. Mann and P. Kusch, Phys. Rev. **77**, 427 (1949).

For each of the zero-field intervals, correct identification of the component lines was insured not only by observing most of the lines, but also by checking that the precisely measured lines had the proper magnetic-field dependence.

The signal-to-noise ratio for transitions for which the resonance curves were observed ranged from about 30 to 1, under the worst conditions, for the 2694-Mc/sec interval of Xe^{131} to 500 to 1, under favorable conditions, for the 5691-Mc/sec interval of Xe^{129}.

B. Measurements of the Individual Intervals

Transitions will be specified here by the notation $(F,M_F;F',M_F')$, and by the linear field dependence factor $(g_FM_F-g_{F'}M_F')/g_J$. A run is defined as a set of measurements in which there was no deliberate change of significant experimental parameters. The results of individual runs are shown in Table II.

(1) Xe^{129} $f(\frac{3}{2}\leftrightarrow\frac{5}{2})$ at 5961 Mc/sec

All determinations entering into the final data were made with the symmetric π pair $(\frac{3}{2},+\frac{1}{2}\leftrightarrow\frac{5}{2},-\frac{1}{2})$, $+5/5$ and $(\frac{3}{2},-\frac{1}{2}\leftrightarrow\frac{5}{2},+\frac{1}{2})$, $-5/5$. Use of the lines of lower field dependence was deemed unwise because of effects of unfortunate coincidences of π's and σ's among these lines, at low field. Two runs were made, involving a total of fifteen measurements of this symmetric pair. The linewidths were about 25 kc/sec.

(2) Xe^{131} $f(\frac{5}{2}\leftrightarrow\frac{7}{2})$ at 2694 Mc/sec

Determinations were made with two symmetric σ pairs of very low field dependence: first $(\frac{5}{2},-\frac{1}{2}\leftrightarrow\frac{7}{2},-\frac{1}{2})$, $+1/35$ and $(\frac{5}{2},+\frac{1}{2}\leftrightarrow\frac{7}{2},+\frac{1}{2})$, $-1/35$ and second

TABLE II. Results for the hfs intervals from individual runs.

Lines used	Hairpin π or π-σ	Direction of hairpin	Static field $g_J\mu_0H/h$ (kc)	Frequency observed (Mc/sec)	Standard deviation of Mean (kc)	Number meas. of pairs
Xe^{129} $F=\frac{3}{2}\leftrightarrow F=\frac{5}{2}$						
$(\frac{3}{2}, \pm\frac{1}{2}\leftrightarrow\frac{5}{2}, \mp\frac{1}{2})$, $+5/5$	π	forward	388	5961.2576	0.5	6
	π	reversed	304	5961.2577	0.4	9
Xe^{131} $F=\frac{5}{2}\leftrightarrow F=\frac{7}{2}$						
$(\frac{5}{2}, \mp\frac{1}{2}\leftrightarrow\frac{7}{2}, \mp\frac{1}{2})$, $\pm1/35$	π-σ	forward	3504	2693.6230	0.5	4
$(\frac{5}{2}, \mp\frac{3}{2}\leftrightarrow\frac{7}{2}, \mp\frac{3}{2})$, $\pm3/35$	π-σ	forward	2818	2693.6240	0.3	2
$(\frac{5}{2}, \mp\frac{1}{2}\leftrightarrow\frac{7}{2}, \mp\frac{1}{2})$, $\pm1/35$	π-σ	forward	2828	2693.6239	0.3	3
$(\frac{5}{2}, -\frac{1}{2}\leftrightarrow\frac{7}{2}, -\frac{1}{2})$, $+3/35$						
Xe^{131} $F=\frac{3}{2}\leftrightarrow F=\frac{5}{2}$						
$(\frac{3}{2}, +\frac{1}{2}\leftrightarrow\frac{5}{2}, +\frac{1}{2})$, $\pm3/35$	π-σ	forward	2518	1608.3477		1
	π-σ	forward	2439	1608.3478		1
$(\frac{3}{2}, \mp\frac{1}{2}\leftrightarrow\frac{5}{2}, \mp\frac{1}{2})$, $\pm3/35$	π-σ	forward	1990	1608.3480	1.3	2
$(\frac{3}{2}, \mp\frac{3}{2}\leftrightarrow\frac{5}{2}, \mp\frac{3}{2})$, $\pm9/35$						
$(\frac{3}{2}, \mp\frac{1}{2}\leftrightarrow\frac{5}{2}, \mp\frac{1}{2})$, $\pm3/35$	π-σ	reversed	1865	1608.3474	0.2	4
Xe^{131} $F=\frac{1}{2}\leftrightarrow F=\frac{3}{2}$						
$(\frac{1}{2}, +\frac{1}{2}\leftrightarrow\frac{3}{2}, +\frac{3}{2})$, $+1/5$	π-σ	reversed	1718	838.7638	0.2	4
$\Delta M_J=\pm1$	π	forward	701	838.7638	0.2	4
$(\frac{1}{2}, \mp\frac{1}{2}\leftrightarrow\frac{3}{2}, \mp\frac{1}{2})$, $\pm3/5$	π-σ	reversed	415	838.7636	0.2	12

$(\frac{5}{2}, -\frac{3}{2}\leftrightarrow\frac{7}{2}, -\frac{3}{2})$, $+3/35$ and $(\frac{5}{2}, +\frac{3}{2}\leftrightarrow\frac{7}{2}, +\frac{3}{2})$, $-3/35$. Two runs were made, involving a total of nine measurements of symmetric pairs. The line widths were about 12 kc/sec.

(3) Xe^{131} $f(\frac{3}{2}\leftrightarrow\frac{5}{2})$ at 1608 Mc/sec

Nine determinations were made with the symmetric σ pair $(\frac{3}{2}, -\frac{1}{2}\leftrightarrow\frac{5}{2}, -\frac{1}{2})$, $+3/35$ and $(\frac{3}{2}, +\frac{1}{2}\leftrightarrow\frac{5}{2}, +\frac{1}{2})$, $-3/35$, with line widths about 12 kc/sec. A single determination was made with the symmetric σ pair $(\frac{3}{2}, -\frac{3}{2}\leftrightarrow\frac{5}{2}, -\frac{3}{2})$, $+9/35$ and $(\frac{3}{2}, +\frac{3}{2}\leftrightarrow\frac{5}{2}, +\frac{3}{2})$, $-9/35$, with line widths about 15 kc/sec. These ten determinations were made in the course of four runs.

(4) Xe^{131} $f(\frac{1}{2}\leftrightarrow\frac{3}{2})$ at 839 Mc/sec

In two runs, eight determinations were made by measuring the π line $(\frac{1}{2}, +\frac{1}{2}\leftrightarrow\frac{3}{2}, +\frac{3}{2})$, $+1/5$ and the transition of the even isotopes $\Delta M_J=\pm1$, also a π line. Note that these are the only precise measurements in this experiment which were not made upon symmetric pairs. Of these two runs, one was made with the π hairpin and the other with the π-σ hairpin; the results agree to 0.1 kc/sec. A single additional run was made on the symmetric σ pair $(\frac{1}{2}, -\frac{1}{2}\leftrightarrow\frac{3}{2}, -\frac{1}{2})$ $+3/5$ and $(\frac{1}{2}, +\frac{1}{2}\leftrightarrow\frac{3}{2}, +\frac{1}{2})$, $-3/5$, four resonance curves on the former and five on the latter. Typical line widths were 12 kc/sec for the $+1/5$ π line, 38 kc/sec for the $\Delta M_J=\pm1$ π line, and 28 kc/sec for the $\pm3/5$ π lines.

V. DISCUSSION OF ERRORS

The greatest source of spread among the different determinations of a hyperfine interval was drift in the static field in which transitions were induced, between measurements of the two lines of a symmetric pair.

Possible hairpin-dependent shifts were mentioned in the discussion of rf equipment. These include Millman shift, Doppler shift, and effects of the rf power magnitude and distribution. It is believed that there are no such effects exceeding 400 cps for the measurements on Xe^{129} and 200 cps for those on Xe^{131}. The Bloch-Siegert effect[9] is negligible for hyperfine intervals as large as those measured.

The frequency standard was estimated to be accurate to 3 parts in 10^8, so that its uncertainty is not considered to contribute significantly to the over-all error.

To allow for possible systematic effects associated with the imperfectly homogeneous C field, as well as possible unfavorable accumulation of errors in the fairly small body of data taken, the limits of error for a given hfs interval have arbitrarily been taken as three times the standard deviation of the mean of all runs on that interval. In arriving at the standard deviation, a consecutive measurement of two lines to determine a hyperfine interval was considered as a single observation.

VI. RESULTS AND DISCUSSION

The final experimental values for the zero-field intervals are

$$Xe^{129},\ f(\tfrac{3}{2}\leftrightarrow\tfrac{5}{2})=5961.2577(9)\text{ Mc/sec},$$
$$Xe^{131},\ f(\tfrac{5}{2}\leftrightarrow\tfrac{7}{2})=2693.6234(7)\text{ Mc/sec},$$
$$f(\tfrac{3}{2}\leftrightarrow\tfrac{5}{2})=1608.3475(8)\text{ Mc/sec},$$
$$f(\tfrac{1}{2}\leftrightarrow\tfrac{3}{2})=\ 838.7636(4)\text{ Mc/sec}.$$

[9] F. Block and A. Siegert, Phys. Rev. **57**, 522 (1940).

Although first-order perturbation theory is generally adequate for obtaining the magnetic dipole and electric quadrupole interaction constants from the energy intervals, earlier work[2,10,11] has shown that, in all cases thus far investigated, a second order treatment results in sizable corrections to the magnetic octupole interaction as derived from the first order theory. For a state $|^3P_2,F\rangle$, belonging to an sp configuration, an expression[12] for the part of the second-order hyperfine energy $W_F^{(2)}$ associated with the states $|^3P_1,F\rangle$, $|^3P_0,F\rangle$, and $|^1P_1,F\rangle$ of that same configuration was given in reference 2. The expression for $W_F^{(2)}$ and the definitions of quantities involved given in reference 2 are valid for the general case intermediate between L-S and j-j coupling and for arbitrary I; they apply directly to the $|^3P_2,F\rangle$ states of Xe^{129} and Xe^{131}. The expression does not allow for any effect of configuration interaction upon the second order corrections. The constants necessary for the evaluation of $W_F^{(2)}$ are c_1, c_2, a_s, $a_{\frac{3}{2}}$, $b_{\frac{3}{2}}$, ξ, and η. Note that $c_1'=c_2$ and $c_2'=-c_1$.

For xenon, c_1 and c_2 values were obtained by a method due to Breit and Wills[13] from the measured $g_J|^3P_1\rangle=1.204(2)$.[14] They are $c_1=+0.9970(4)$ and $c_2=+0.0773(40)$. As a check values also were obtained from the term values of the electronic states $|^3P_2\rangle$, $|^3P_1\rangle$, and $|^3P_0\rangle$. (For the nearly perfect j-j coupling of xenon, the states corresponding to $|^3P_1\rangle$ and $|^1P_1\rangle$ are better described as $|s_{\frac{1}{2}}, p_{\frac{3}{2}}, J=1\rangle$ and $|s_{\frac{1}{2}}, p_{\frac{1}{2}}, J=1\rangle$.) They are $c_1=+0.996$ and $c_2=+0.085$. Calculation by the method of Wolfe[15] gives $c_1=+0.994$ and $c_2=+0.111$ from the multiplet separations; this method involves the term value of the state $|^1P_1\rangle$, which state is discussed later in this paper. The octupole moment derived from the third pair of c values is only 3% greater than that derived from the first pair, and Ω is not, therefore, critically dependent on the choice of c values.

The values of $a_{\frac{3}{2}}$ and a_s were derived from the experimental values of $A|^3P_2\rangle$ and $A|^3P_1\rangle$ (footnote c, Table I) by the theory given in reference 2. They are

$$a_s(129)=-4491(225)\ \text{Mc/sec},$$
$$a_s(131)=+1336(66)\ \text{Mc/sec},$$
$$a_{\frac{3}{2}}(129)=-1682(84)\ \text{Mc/sec},$$
$$a_{\frac{3}{2}}(131)=+\ 498(25)\ \text{Mc/sec}.$$

The errors were chosen large enough to include a value of $a_{\frac{3}{2}}$ calculated from the fine structure. This is the principal source of the stated error in the interaction constants corrected to second order. The error in $a_{\frac{3}{2}}$ due to stated errors in the quantities entering the calculation from $A|^3P_2\rangle$ and $A|^3P_1\rangle$ is only 2%.

[10] C. Schwartz, Phys. Rev. **97**, 380 (1955).
[11] C. Schwartz, Phys. Rev. **105**, 173 (1957).
[12] The right-hand side of the expression for $W_F^{(2)}$ given in reference 2 should be multiplied by the factor $\frac{1}{16}$.
[13] G. Breit and L. A. Wills, Phys. Rev. **44**, 470 (1933).
[14] J. B. Green, E. H. Hurlburt, D. W. Bowman, Phys. Rev. **59**, 72 (1941).
[15] H. C. Wolfe, Phys. Rev. **41**, 443 (1933).

Comparison of various calculations of c_1 and c_2 (from $g_J|^3P_1\rangle$, from $g_J|^1P_1\rangle$, and from term values) shows that those involving the $|^1P_1\rangle$ state give a relatively large spread of results among themselves. On the assumption that the $|^1P_1\rangle$ state was perturbed, the use of properties of that state was avoided; but in any case, Ω is not very sensitive to c_1 and c_2. It is to be noted that the configuration is not described by simple theory as may be inferred from the following: The same considerations which give a_s and $a_{\frac{3}{2}}$ from $A|^3P_2\rangle$ and $A|^3P_1\rangle$ can be used to infer a theoretical value of $A|^1P_1\rangle$; and the considerations which gave c_1 and c_2 values from the term values (excluding $|^1P_1\rangle$) can be used to infer a theoretical term value for $|^1P_1\rangle$. The experimentally determined A value for this state is 28% smaller than the theoretical value, and the observed difference of term values between the $|^1P_1\rangle$ and $|^3P_0\rangle$ states is 66% greater than the theoretical difference.

The uncertainties in the values of the constants that appear in reference 2 that have not been discussed in the previous paragraphs have no significant effect on the interpretation of the present data. The values taken are: $b_{\frac{3}{2}}=B_{131}=+252.514$ Mc/sec (Xe^{131}), $\eta=1.139$ (Xe^{131}), $\xi=1.056, \theta=1.419$, $(1-\delta)_{\frac{1}{2}}=0.997$, $(1-\epsilon)_{\frac{1}{2}}=1.000$ (Xe^{129} and Xe^{131}). θ, ξ, and η are proportional to the value assumed for C''/C', which we took to be $-1.044(15)$.

If the second-order energy is calculated with these constants and subtracted from the measured hyperfine structure intervals, the usual first order theory can be used to obtain the corrected interaction constants

$$A_{129}'=-2384.5271(144)\ \text{Mc/sec},$$
$$A_{131}'=+706.4714(7)\ \text{Mc/sec},$$
$$B_{131}'=+252.5145(64)\ \text{Mc/sec},$$
$$C_{131}'=+0.000728(105)\ \text{Mc/sec}.$$

The ordering of the levels of different F, which determines the signs of A_{129}' and A_{131}', was determined from the optical measurements. The values for the interaction constants without the second-order corrections are

$$A_{129}=-2384.5031(4)\ \text{Mc/sec},$$
$$A_{131}=+706.47422(18)\ \text{Mc/sec},$$
$$B_{131}=+252.5263(6)\ \text{Mc/sec},$$
$$C_{131}=+0.000456(18)\ \text{Mc/sec}.$$

The corrections are significant only in the case of C_{131}.

The nuclear octupole moment, given by the relation

$$\Omega_{131}=(7g_I/Z^2)(F_{\frac{3}{2}}/T)(c_{\frac{3}{2}}/a_{\frac{3}{2}})a_0^2\times 10^{24}\ \text{nmb}$$
(nuclear magneton barn),

is $\Omega_{131}=+0.048(12)$ nmb. The value $T/F_{\frac{3}{2}}=0.9476$ has been obtained from Schwartz.[11] $c_{\frac{3}{2}}=C_{131}'$. In the derivation of the value of C_{131}', the correction due to configuration mixing of the $|^3P_2\rangle$ state has been ignored. The extreme single-particle model gives for a single $d_{\frac{3}{2}}$

neutron, with $g_s=-3.83$, $\Omega_{131}=+0.0463$ nmb. Hg^{201} and Xe^{131} are the first odd-neutron nuclei for which an octupole moment has been measured. In Fig. 5 is given a Schmidt-limit type diagram for the octupole moments of odd-neutron nuclei, plotted according to the theory of Schwartz,[10] who gives the corresponding diagram for odd-proton nuclei.

The quadrupole moment, obtained from the relation

$$Q_{131}=(8/3)(b_{\frac{3}{2}}/a_{\frac{3}{2}})(F_{\frac{3}{2}}/R)(g_I m/M_p)(\mu_0{}^2/e^2)\times 10^{24}\text{ barn},$$

is $Q_{131}=-0.120(12)$ b, in good agreement with the result of Bohr, Koch, and Rasmussen.[14] The value $R/F_{\frac{3}{2}}=1.0506$ has been obtained from Schwartz. $b_{\frac{3}{2}}=B_{131}'$. There is included no correction for the effect of polarization of the electron core, as discussed by Sternheimer.[16]

The quantity of interest in the consideration of the hyperfine structure anomaly is the anomaly of the $s_{\frac{1}{2}}$ electron alone, $\Delta(s_{\frac{1}{2}})$, given by

$$\Delta(s_{\frac{1}{2}})=\left\{\frac{A'(129)g_I(131)}{A'(131)g_I(129)}-1\right\}\left\{1+3\frac{a_{\frac{3}{2}}(131)}{a_s(131)}\right\}.$$

With the value of the nuclear dipole moment ratio $g_I(129)/g_I(131)=-3.37456(8)$ given by Brun *et al.*,[6] it follows that $\Delta(s_{\frac{1}{2}})=+0.0440(44)\%$. The theoretical anomaly due to the distributed nuclear magnetic moment is $\Delta_{BW}(s_{\frac{1}{2}})=+0.24\%$, according to the single-particle model as discussed by Bohr and Weisskopf[17] and as developed by Eisinger and Jaccarino[18] and by Stroke.[19] The anomaly due to the distributed nuclear charge, Δ_{BR}, discussed by Breit and Rosenthal,[20] is about $\frac{1}{10}$ as great. Thus, for $Xe^{129,131}$, as for $Hg^{199,201}$, the experimentally observed anomaly is several times smaller than the value predicted by the single-particle model. The anomalies for these nuclei are the first determined for odd-neutron even-proton nuclei.

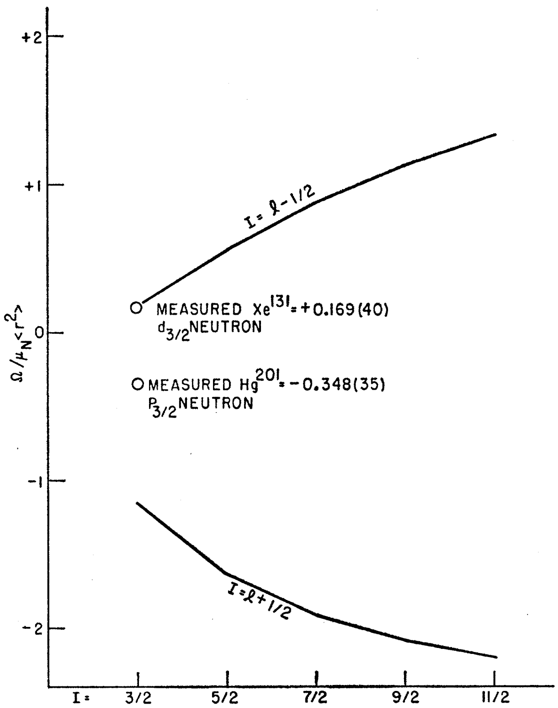

FIG. 5. Octupole moments in the single-particle model for odd-neutron nuclei. $g_s=-3.83$.

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[16] R. M. Sternheimer, Phys. Rev. **95**, 736 (1954); **105**, 158 (1957).

[17] A. Bohr and V. F. Weisskopf, Phys. Rev. **77**, 94 (1950); A. Bohr, Phys. Rev. **81**, 134 (1951); **81**, 331 (1951).

[18] J. Eisinger and V. Jaccarino, Revs. Modern Phys. **30**, 528 (1958).

[19] H. H. Stroke, Quarterly Progress Report, Research Laboratory of Electronics, Massachusetts Institute of Technology, July 15, 1959 (unpublished), p. 63.

[20] J. E. Rosenthal and G. Breit, Phys. Rev. **41**, 459 (1932).