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Precise Measurements of Hyperfine Structure in the $2\,^3P$ State of ^{3}He

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Transitions within the $2\,^3P$ state of ^{3}He were measured to determine the parameters C, D, and E which represent respectively the contact, dipole, and tensor terms in the hyperfine Hamiltonian. For the first time, the effect of core polarization on the hyperfine structure has been detected. The present results are $C=-4283.84(1)$ MHz, $D=-28.02(6)$ MHz, and $E=+7.08(2)$ MHz and are consistent with the theoretical values after the combined fine and hyperfine interactions with the $2\,^1P$ state are taken into account in the analysis of the data.

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The spectra of excited states ($1snl$) of ^{3}He have been the subject of several recent experimental investigations. The techniques employed are level crossings and anticrossings,[1] various forms of Doppler-free laser spectroscopy,[2,3] and quantum beats in beam-foil spectra.[4] States of ^{3}He which have been studied include $n\,^3S$, $n\,^3D$, and $n\,^1D$ up to $n=6$, and $n\,^3P$ up to $n=8$. The measured intervals within these states are now known with accuracies ranging from 0.1 to 20 MHz. As the principal quantum number n increases, the ^{3}He$^+$ core dominates first the fine structure, then the exchange interaction, and ultimately (above $n\sim100$) the gross level structure, leading to two ionization limits. We hope to explore these effects to a precision of about 0.03 MHz using an extension of the optical microwave technique reported here.

In this Letter we report a measurement of the $1s2p\,^3P$ hyperfine structure which is 2 to 3 orders of magnitude more precise than earlier data. In particular we have measured with high precision the contribution of the p electron to the hyperfine structure, a phenomenon which was previously barely resolved from the noise,[3] and we have measured previously undetected core-polarization effects.

The hyperfine Hamiltonian is given by[5]

$$\mathcal{H}_{\rm hfs}=-2\mu_0\sum_{i=1}^{2}\left\{-\frac{8\pi}{3}(\vec{s}_i\cdot\vec{\mu})\delta(\vec{r}_i)-\frac{1}{r_i^{\,3}}\vec{l}_i\cdot\vec{\mu}+\frac{1}{r_i^{\,3}}\left[\vec{s}_i\cdot\vec{\mu}-\frac{3(\vec{s}_i\cdot\vec{r}_i)(\vec{\mu}\cdot\vec{r}_i)}{r_i^{\,2}}\right]\right\}. \quad (1)$$

The sum is taken over the two electrons, $\vec{\mu}$ is the nuclear magnetic moment, and $\vec{s}_i$, $\vec{l}_i$, and $\vec{r}_i$ have the usual meanings for an individual electron.

Within a pure ^3P state, Eq. (1) may be written

$$\mathcal{H}_{\rm hfs}=C\vec{I}\cdot\vec{S}+D\vec{I}\cdot\vec{L}+(2\sqrt{10})E\vec{I}\cdot(\vec{S}C^{(2)})^1, \quad (2)$$

where $C^{(2)}$ is a second rank tensor in coordinate space. To order $\alpha^2(m_e/M_{^3\mathrm{He}})$, the hyperfine constants are given by

$$C=\frac{8\pi}{3}\mu\mu_0\langle\sum_{i=1}^{2}\delta(r_i)\rangle, \tag{3a}$$

$$D=2\mu\mu_0\langle\sum_{i=1}^{2}(\vec{r}_i\times\vec{p}_i)_z/r_i^3\rangle, \tag{3b}$$

$$E=-\tfrac{5}{4}\mu\mu_0\langle\sum_{i=1}^{2}(r_i^2-3z_i^2)/r_i^5\rangle, \tag{3c}$$

where μ_0 is the Bohr magneton and expectation values are taken over the state $|^3P, M_L=+1\rangle$. The terms in Eq. (2) represent respectively interactions of the nuclear magnetic moment with the s-electron spin, the p-electron orbit, and the p-electron spin. In our data analysis it was necessary to extend Eq. (2) to include the hyperfine interaction between $2\,^3P$ and $2\,^1P$.

The ^{3}He nucleus has a spin of $\frac{1}{2}$ and the $2\,^3P$ energy levels are shown in Fig. 1 compared with those of ^{4}He which has zero nuclear spin. It can be seen that for $J=1, 2$ the ^{3}He hyperfine splittings are comparable to the fine structure and J is not a good quantum number. The energy levels as a function of magnetic field are shown in Fig. 2. The experiment was performed in a magnetic field to provide a convenient means of sweeping through a microwave transition resonance.

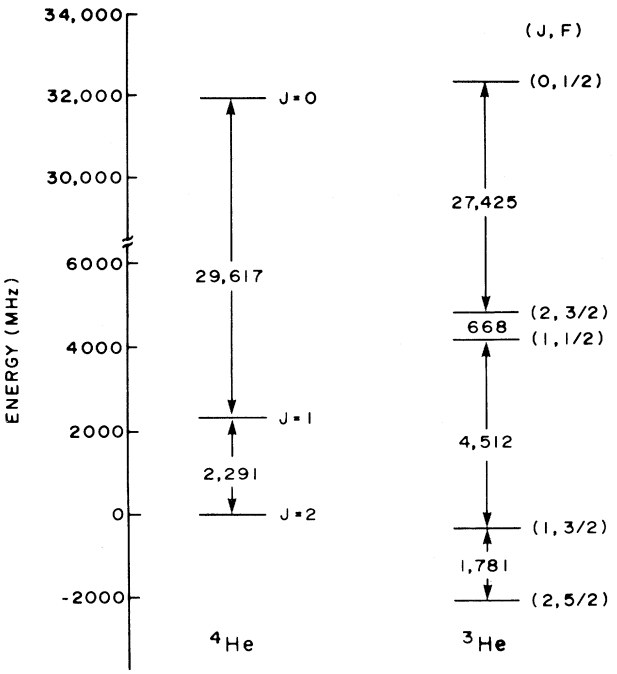

FIG. 1. $2\,^3P$ energy levels of ^{4}He and ^{3}He in zero magnetic field.

The basic experimental technique has been described in our earlier work on the ^{4}He fine-structure and Zeeman parameters.[6] A beam is formed in the metastable $2\,^3S$ state by electron bombardment of atoms in the $1\,^1S$ ground state effusing from a multichannel array. The $2\,^3S$ atoms are state selected according to their magnetic sublevels M_s (=1, 0, or −1) by means of a standard "two-wire" deflecting magnet. The state-selected beam is then optically excited to the $2\,^3P$ state, resulting in a redistribution of the populations among the $2\,^3S(M_s)$ sublevels after radiative decay. An atom which has transferred from one sublevel to another is observed by means of its trajectory after passing through a second deflecting magnet, and we call the resulting signal the "light flop." When a microwave magnetic-dipole resonance transition is induced between a pair of $2\,^3P(F, M_F)$ sublevels, there is a further $2\,^3S(M_S)$ redistribution, and the microwave resonance is observable as a change in the light flop.

The apparatus was essentially that described in Ref. 6 with a significant improvement in the metastable $2\,^3S$ beam intensity. In addition, a Rb magnetometer was used to stabilize the field, new microwave systems were developed to ac-

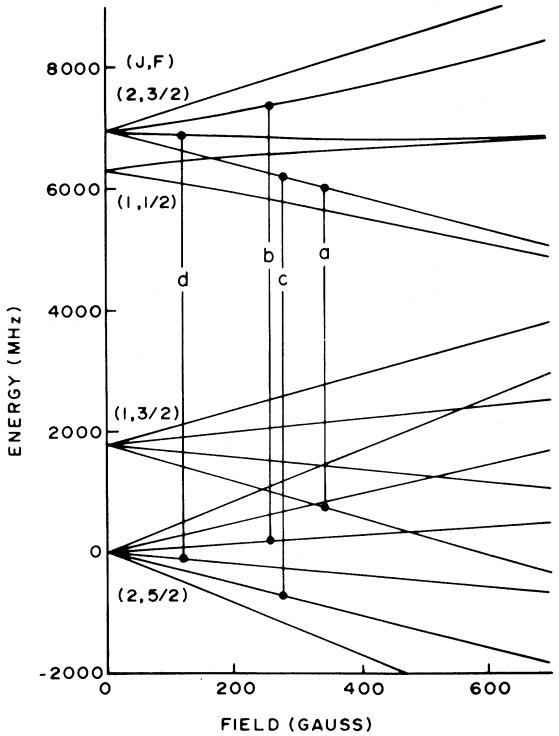

FIG. 2. $2\,^3P$ ($J=1$ and 2) energy levels of ^{3}He as a function of magnetic field. The transitions and the fields at which they were measured are indicated.

commodate the frequencies required for ^{3}He, and a gas-recirculation system was built to conserve ^{3}He. The transitions observed are labeled *a* and *b* in Fig. 2, and these were analyzed in conjunction with *c* and *d* (see Fig. 2), which were measured earlier on a different apparatus.[7] All the transitions have $\Delta M_F = 0$ and are therefore field independent to first order. The frequencies and magnetic fields used for the four transitions are listed in Table I. Between fifteen and twenty experimental resonances were measured for each transition. The signal was recorded as a fractional change in the light flop due to the microwave resonance.

A typical experimental resonance is shown in the inset of Fig. 3. The individual points were fitted by a theoretical line shape, which takes into account the variation with magnetic field of the resonant frequency and the dipole matrix elements. The fitting parameters were the height and width of the resonance and the hyperfine constant *D*, the other two constants *C* and *E* being fixed. It was not useful to include *C* and *E* as fitting parameters because they are highly correlated with each other and with *D*. Instead we made several fits using a variety of values for *C* and *E* to find the interdependence between *C*, *D*, and *E*. This interdependence was different for each of the four transitions observed. In Fig. 3 we display the interdependence of *C* and *D* at constant *E* for the transitions observed. A second least-squares adjustment yielded values for *C*, *D*, and *E* which were consistent with all four transitions. The value of *E* used in Fig. 3 is that obtained by our second least-squares adjustment (see Table II).

In the data analysis we diagonalized the Hamiltonian matrix of the entire $1s2p$ configuration so that the $2\,^1P$ admixture into $2\,^3P$ would be properly treated. This required an estimate of hyperfine matrix elements involving the $2\,^1P$ state which was done to the requisite accuracy. The

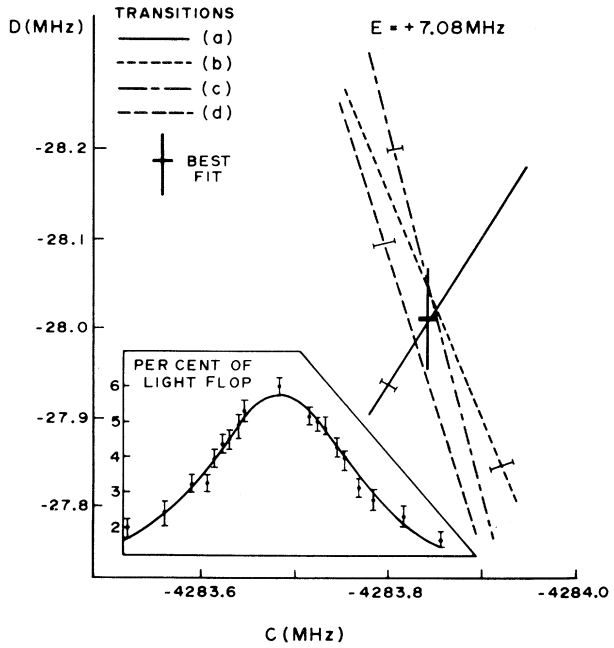

FIG. 3. Inset: typical experimental resonance data together with the fitted theoretical line profile. Main figure: interdependence of hyperfine parameters *C* and *D* for the four measured transitions with *E* at its best-fit value of 7.08 MHz. The fitted values of *C* and *D* and their associated errors are also shown.

^{3}He fine-structure matrix elements were computed from the known ^{4}He fine-structure intervals[6] together with the theoretical fine-structure matrix element[11] coupling $2\,^3P_1$ to $2\,^1P_1$ in ^{4}He. We then scaled from ^{4}He to ^{3}He using the theoretical mass dependence, including nuclear motion[12] and second-order mass-polarization[13] corrections.

The experimental errors were dominated by statistical uncertainty but there were also systematic uncertainties associated with the absolute magnetic field calibration. The only significant uncertainty in the theoretical analysis of the data was associated with the second-order mass-po-

TABLE I. Frequency, field, and field dependence of the various transitions measured.

Transition (JFM_F)	$(J'F'M_F')$	Microwave frequency, f_0 (MHz)	Field, B (G)	$\partial f/\partial B$ (MHz/G)
(*a*) (2,3/2,−3/2)	(1,3/2,−3/2)	5209.700	350	0.253
(*b*) (2,3/2,1/2)	(2,5/2,1/2)	7159.200	264	1.31
(*c*) (2,3/2,−3/2)	(2,5/2,−3/2)	6870.000	283	−0.191
(*d*) (2,3/2,−1/2)	(2,5/2,−1/2)	6990.000	164	0.448

TABLE II. Comparison of experimental results with theory.

Hyperfine parameter	Experimental results Ref. 3.	This work	Theoretical value
C (MHz)	-4285 ± 20	-4283.84 ± 0.01	$-4283.89(2)$ [a]
D (MHz)	-39 ± 15	-28.02 ± 0.06	-28.14 [b]
E (MHz)	$+7.5\pm4.5$	$+7.08\pm0.02$	$+7.13(3)$ [c]
$-D/E$	$+5.2\pm3.7$	$+3.96\pm0.01$	$+3.95(1)$

[a]Derived from Ref. 8 by use of an empirical correction to account for finite nuclear size and radiative and relativistic effects. The quoted uncertainty is our estimate of the reliability of that correction.

[b]Obtained from a calculation (Ref. 9) of $\langle 1/r^2\rangle$ in which the numerical error is negligible.

[c]Given in Ref. 10. The error is a convergence uncertainty.

larization correction to the fine-structure interaction.[13] Our statistical uncertainty was obtained from the measured fluctuation of the signal and was found to be consistent with Poisson statistics in the beam intensity. In addition, the goodness of fit (χ^2) for all our runs was consistent with statistical expectations indicating that the theoretical line shape was correct within the measured errors. The systematic uncertainties in field calibration and mass-polarization correction were then included, and the final least-squares adjustment was made to determine C, D, and E together with their errors. In this overall fit, χ^2 was 1.3 with one degree of freedom. Our results are summarized in Table II.

Theoretical estimates of the hyperfine parameters are also given in Table II. These values were obtained by use of nonrelativistic, variational wave functions.[8-10] We have estimated C using the value of $\langle\delta(r)\rangle$ given by Accad, Pekeris, and Schiff.[8] In order to account for the finite nuclear size and for radiative and relativistic corrections we have multipled the variational result by a factor $1+5.48\times10^{-4}$. This factor is the ratio in $^3He^+$ of the measured ground-state hyperfine splitting[14] to the hydrogenic nonrelativistic value.[5] The correction is presumably accurate to about 1%, since that is the level at which C for ^3He differs from C for $^3He^+$. Our estimate of D is based on a result given by Schwartz[9] for $\langle 1/r^3\rangle$ which we have corrected for the reduced mass. The numerical error is negligible. The theoretical value of E is taken from Ref. 10.

Our experimental results lead to several conclusions. Aashamar and Hambro[10] have pointed out that D and E are particularly sensitive to correlation; their values are reduced by almost 50% when correlation is neglected. Thus our experiment has demonstrated the ability of the wave functions to reproduce correlation effects at the 1% level. In addition the ratio $-D/E$, which has the value 4 for a pure (s,p) configuration, is expected to differ from 4 because of core polarization.[10] We have achieved sufficient precision to resolve this difference for the first time and at the level of 25% we find the theory to be correct. The consistency between the theoretical and experimental values of C shows that the simple view of the inner shell as a weakly perturbed $^3He^+$ ion is surprisingly accurate. Finally, of course, we have demonstrated the validity of the theory of hyperfine structure in this state of the two-electron atom.

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High-Precision Spectroscopic Studies of Lyman α Lines of Hydrogenlike Iron: A Measurement of the 1s Lamb Shift

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The absolute energies of the Lyman-α lines of hydrogenlike iron have been measured with an accuracy of 90 ppm with use of a high-precision plane-crystal spectrometer calibrated directly with Co $K\alpha$ x rays. A value for the 1s Lamb shift of hydrogenlike iron has been deduced from this measurement.

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In this Letter an experiment is described in which absolute energy measurements of the Lyman-α lines of hydrogenlike iron ($Z=26$) were made. The principle of this experiment is to compare characteristic x-ray references with the energy of the x rays emitted in flight by a foil-excited hydrogenlike iron beam of high energy. In such experiments the main problems to be solved come from the large Doppler shifts associated with the high velocity of the ions, and the low rate of production of hydrogenlike ions. The most accurate way to make an absolute energy measurement with such fast beams is to use a flat-crystal spectrometer. Such a device provides, in contrast with those previously used (curved crystal, Soller slit,...), the two most important properties needed for an absolute energy measurement: (i) a very small angular acceptance (reduction of the Doppler broadening), (ii) a very accurate geometrical definition of the crystal in order to know precisely the relative angle between the line of flight of the ions and the detected x rays. A flat-crystal spectrometer, whose characteristics are described below, has been specially designed with an improved transmission for measuring the x rays emitted by the foil-excited iron beam. With such a spectrometer, the transmission is, however, very poor and one needs a high flux of x rays. In this experiment, the new injector (ABEL) of the SuperHILAC of Berkeley which gave a very intense heavy-ion beam has been used. Moreover, in order to get a very large fraction of excited hydrogenlike ions, in a situation where the lines are free of contamination satellites (influence of outermost captured electrons), the experiment has been carried out at the maximum available energy, 8.5 MeV/u. All these improvements have made possible, for the first time, accurate absolute energy measurements for heavy ions. The precision is now sufficient to observe for the first time the 1s Lamb shift for a hydrogenlike atom heavier than neutral hydrogen. Prior to this measurement the 1s Lamb shift has been measured only in ordinary hydrogen[1] and in deuterium.[2]

The excited hydrogenlike iron ions in the 2p

