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CURRENT STATUS OF MEASUREMENTS OF
GROUND STATE MOMENTS OF NUCLEI*

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Victor W. Cohen

Brookhaven National Laboratory

Upton, New York 11973 U.S.A.

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ABSTRACT

While the spins of all stable nuclei have been determined measurements of magnetic dipole and higher moments are being made with increasing precision with accuracy adequate to determine hyperfine anomalies. The methods of nuclear resonance in many variants, atomic beam resonance, and optical pumping are being actively pursued to determine spins and moments of short-lived nuclei. A number of recent results are given which indicate directions of current progress.

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In this paper I would like, to review a number of features of the measurements of nuclear moments. I shall not discuss experimental details of the various techniques. These have been adequately covered in numerous reviews.⁽¹⁾ I shall attempt to point out:

- A. The interactions which involve the various moments.
- B. The actual physical quantities measured.
- C. Some of the limitations in precision attainable in current measurements.
- D. Some of the limitations in evaluating the moments from experimentally measured quantities.
- E. A number of specific results of nuclear moment measurements, principally to illustrate the scope and nature of some of the very interesting contemporary programs.

There is no attempt here to present a complete table of recent measurements. The Table of Nuclear Spins and Moments by Fuller and Cohen published in 1969 contains data published up to August 1968.⁽²⁾ A Table of Magnetic Hyperfine Anomalies, also by Fuller and Cohen, published in 1970⁽³⁾ contains data in that area up to 1969. Some work has been done to bring these tables up-to-date, and it is hoped that a revised edition of these tables will appear in due time. Several papers at this conference will discuss recent developments in specific areas.

The interactions of an electric monopole are quite different from the multipole moment, and I will not discuss them.

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The existence of a static electric dipole moment for particles with spin can be excluded only upon aesthetic arguments. If such a moment were to exist, it would violate the principle of parity and time symmetry. Since violations of these symmetries have been observed in β decay, the existence or non-existence of an electric dipole moment must rest upon experimental evidence.

The existence of an electric dipole moment of the electron would be exhibited as an amplified moment of the neutral Cs atom. A search for this has so far yielded a null result with an upper limit placed at $3 \times 10^{-24} e \text{ cm.}$ ⁽⁴⁾ Similar searches for an electric dipole moment of the neutron have yielded a null result with an upper limit of the order of $10^{-23} e \text{ cm.}$ ⁽⁵⁾

A search for an electric dipole moment for the neutral atom which can be ascribed to the odd proton, is being sought for by P.G.H. Sandars at Oxford. ⁽²⁴⁾ Preliminary results yield $|d| = 7 \pm 9 \times 10^{-21} e \text{ cm.}$ This work is being extended but results are not yet available.

A nucleus composed of protons and neutrons, subject to the usual known and unknown nuclear forces, can be approximated, for external interactions, in terms of monopole, dipole, and multipole electric and magnetic moments. For a more complete description, in particular for interactions within the nuclear volume, the multipole approximation is not adequate. For a consideration of any interaction between the nucleus and a penetrating particle, such as an electron or muon, the nucleus must be described in terms of a spatial distribution of its basic properties, mass, charge, and magnetization.

A theoretical description of the HFS of the deuteron implies a consideration of the fact that the spatial distribution of the

mass and charge are such that respective monopoles do not coincide in space. (6,7)

An evaluation of the hyperfine structure interaction must take into consideration that an S-state valence electron cloud penetrates the nucleus and within the nuclear volume the distribution of magnetization is not uniform. One must, therefore, evaluate an integral of the form

$$W = \int \vec{M}(\vec{R}) \cdot \vec{B}(\vec{R}) dv, \quad (1)$$

over the nuclear volume, where $\vec{M}$, the nuclear magnetization and $\vec{B}$, the magnetic field of the electrons or muon, are both functions of $\vec{R}$, the nuclear coordinates. This lack of linearity between the HFS energy and the magnetic moment gives rise to the hyperfine anomaly, defined for isotopes 1 and 2 of the same element for heavy nuclei ($m > 20$)

$${}_1A_2 \equiv \frac{A_1}{A_2} \cdot \frac{g_2}{g_1} - 1, \quad (2)$$

where A 's are the HFS interaction constants and g 's are the nuclear g -factors. More generally for lighter masses

$${}_1A_2 = \frac{A_1}{A_2} \cdot \frac{g_2}{g_1} \left(\frac{M_{r2}}{M_{r1}} \right)^3 - 1, \quad (3)$$

where M_r 's refer to the reduced masses of the respective nuclei,

$$M_r = \frac{Mm}{M + m}, \quad (4)$$

where M is the nuclear mass and m is the electron mass.

The hyperfine anomaly is discussed elsewhere in this conference by Dr. H. Stroke.

The combined hyperfine and Zeeman interactions of an atom in a magnetic field can be described, using the multipole approximation, by the Hamiltonian

$$\begin{aligned}
 \mathcal{H} = & \mu_B H \cdot (g_J \vec{J} + g_I \vec{I}) && \text{(Zeeman effect)} \\
 & + h A \vec{I} \cdot \vec{J} && \text{(mag. dipole)} \\
 & + h B [\text{terms in } (\vec{I} \cdot \vec{J})^2, (\vec{I} \cdot \vec{J}), I \text{ and } J] && \text{(elec. quadrupole)} \\
 & + h C [\text{terms in } (\vec{I} \cdot \vec{J})^3, (\vec{I} \cdot \vec{J})^2, (\vec{I} \cdot \vec{J}), I \text{ and } J] && \text{(mag. octupole)}
 \end{aligned} \tag{5}$$

where A, B, and C are the magnetic dipole, electric quadrupole, and magnetic octupole constants, H is an externally applied magnetic field, and the other symbols have their usual connotations. We have omitted consideration of quantum electrodynamic effects.

Of particular importance is the special case of an atom in a state in which $J = 1/2$ for which the solution is expressed by the well-known Breit-Rabi equation:

$$W = \frac{\Delta W}{2(2I+1)} + m_F g_I \mu_B H \pm \frac{\Delta W}{2} \left(1 + \frac{4m_F^2 X}{2I+1} + X^2 \right)^{1/2} \tag{6}$$

where $X = (g_J - g_I) \mu_B H / \Delta W$. The behavior of the magnetic levels as a function of H for the case of $I = 3/2$ are shown in Figure 1.

II. MEASURED QUANTITIES

1. Nuclear Spin

The nuclear spin is the basic property to which static magnetic and electric moments are all referred. The simplest property of angular momentum that submits to measurement is the multiplicity of

orientations along an axis external to the nucleus, such as an applied magnetic field. This field may be due to motion of atomic electrons or other moving charges to which the nucleus is coupled.

If there is no appreciable coupling to atomic electrons, the nuclear orientation in an externally applied magnetic field will be specified by the quantum number m_I with $2I + 1$ multiplicity, $-I \leq m_I \leq I$. If there is appreciable coupling to the electron system, then in a weak field we can specify the quantum number F where $|I - J| \leq F \leq I + J$ so that F will have multiplicity $2I + 1$ if $I < J$ or $2J + 1$ if $J < I$. The effect of the weak magnetic field is to split each F state into $2F + 1$ magnetic states each specified by m_F with the relation $-F \leq m_F \leq F$.

In a field in which the coupling between H and I or J is strong, F is no longer a good quantum number, and the system may be specified by m_I and m_J with $2I + 1$ and $2J + 1$ multiplicity respectively.

In order to determine the spin of a stable nucleus one must observe the multiplicity in energy levels as mentioned above.

The principal methods for determining nuclear spin are optical spectroscopy, atomic beam magnetic resonance, and electron spin resonance. It must be pointed out that although the study of the alternating intensities of rotational bands of homopolar molecules is of historic interest, it is the only method which can establish definitely a nuclear spin of zero. Other methods can establish only some upper limit for an undetectable magnetic or electric spin interaction.

The atomic beam magnetic resonance and optical pumping methods are particularly well adapted to spin determinations for atoms with a

total atomic $J > 0$ in the ground state. In some cases a metastable state can be populated in adequate numbers for study.

In general the g-factor for an atom in a weak magnetic field will be approximated by:

$$g_F = g_J \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)} . \quad (7)$$

Referring to Fig. 1 the transition α may be observed at a known magnetic field which permits the determination of g_F very readily. It is possible to resolve this line clearly in a field of a few tenths of a gauss so that the assumption of a "weak" field is valid. Clearly g_F is a function of I so that I can be determined quite definitely. If $J > 1/2$ the level diagrams are more complex, and there will be more than one transition available to establish I .

The great virtue of the ABMR technique is that the hyperfine or Zeeman transitions are observed directly and not, as in optical spectroscopy, as a small difference between two nearly equal optical transitions.

The ABMR has been applied to many elements, both stable and radioactive and with vaporization temperatures ranging from room temperature to 3300°C .

To determine nuclear spin by optical spectroscopy one must analyze the spectrum of a hyperfine multiplet completely. Depending upon whether $I < J$ or $I > J$ determines whether the spin can be determined from (a) the number of components, (b) the interval rule, which can be perturbed by a quadrupole interaction, or (c) relative

intensities of components which can be severely distorted in excitation or measurement. Figure 2 illustrates schematically the energy level diagram and spectral line pattern of the hyperfine structure of an optical transition $P_{3/2} \rightarrow S_{1/2}$ for an atom with a nuclear spin $3/2$.

Modern techniques in optical spectroscopy permit hyperfine measurements to be made with samples as small as 10^{14} and 10^{16} atoms. An atomic beam spin determination can be made with as few as $10^6 - 10^{10}$ atoms of a radioactive species with lifetimes of a few hours. Tables I and II list a number of spins and moments of rare earth nuclei measured by atomic beam methods by the groups at Uppsala and Göteborg.

2. Magnetic Dipole Moments

The magnetic dipole moment interacts with both the applied field H and the magnetic field associated with J . This permits the two interactions to be measured independently.

From a measurement of the A-factor one can calculate μ_I from an interaction of the nature of $I \cdot J A = \vec{\mu}_I \cdot H(o)$, where $H(o)$ represents the magnetic field of the electrons at the nucleus. The limitation on accuracy here is due to the imperfection of the atomic wave function for evaluating $H(o)$.

In principle the interaction $\vec{\mu}_I \cdot H$ or $g_I \cdot H$, where H is an applied field, provides a simple interaction for evaluating g_I . The essential limitation lies in the difficulty in getting an accurate measurement of H .

There are two essential difficulties in measuring H accurately.

In principle one rarely measures H in absolute terms but compares measurements of $g_I H$ for one nucleus with either $g_I H$ for another one or $g_J H$ in the same or different atom. In the first case if the two nuclei are isotopes of the same element, the ratio $g_{I,1}/g_{I,2}$ may be accurately measured. If the two elements are different then, as discussed below, the fields at the nuclei may not be equal. If $\nu_I = g_I H/h$ is compared to $\nu_2 = g_J H/h$ the two frequencies are so widely different for the same field that systematic experimental errors may be significant (10^{-4} to 10^{-6}).

In a free atom we may express the field as:

$$H = H_0 + \Delta H_I = H_0(1 + \sigma_I) \quad (8)$$

where σ_I , essentially negative, represents the diamagnetic shielding due to atomic electrons.

The factor $|\sigma_I|$ ranges in value from about 10^{-6} for $Z = 1$ to over 10^{-2} for $Z = 92$. It would be extremely difficult to measure. It can be computed precisely for $Z = 1$ and with adequate precision for the light elements. For some time the values generally adopted were calculated by Dickinson⁽⁸⁾ and carried appreciable uncertainty. Recent calculations including relativistic effects show that the earlier ones are reasonably correct for the lighter elements but are too low for the heavier ones by as much as a factor of 2.⁽⁹⁾ A basic limitation in evaluating g_I or μ_I is therefore in the uncertainty in σ_I .

By optical pumping and atomic beam techniques g_I of several nuclei have been measured in terms of g_e to a precision of the order of 1 part in 10^6 . For example,

$R_b^{87}, g_I/g_J = 4.969\ 914\ 7(50) \times 10^{-4}(10)$ and for $Rb^{85} g_I/g_J = 1.466\ 490\ 8(30) \times 10^{-4}$. By ABMR, $Na^{23}, \mu_I = 2.216\ 010(36)\text{mm}$ uncorrected for diamagnetism. (11) (See also Table XI.B.)

We consider the problem of a measurement by any form of nuclear resonance in which the atom is in a molecule, crystal, or in solution. We have in addition to the σ_1 term additional effects which we may designate as H_2 and H_3 being approximately proportional to σ_2 and σ_3 as in Eq. 8, in which σ_2 refers to the effect of other atoms in a molecule or crystal and σ_3 refers to the effect of the solvent in a solution.

For hydrogen precise experimental intercomparisons have been made for H_2O , H_2 , mineral oil, and the H atom.

For heavier atoms there are no good calculations of σ_2 . However Lutz and co-workers⁽¹²⁾ have investigated a number of nuclear resonances in dilute solutions of different concentrations. By extrapolating to zero concentration the effect of σ_2 is removed and only the solvent effect, σ_3 , is present. One can then evaluate σ_2 by comparison with concentrated solutions and σ_3 by comparison with the free atom values. It is expected that σ_1 for the ion and for the neutral atom would be nearly equal. Only a few of the latter comparisons have been measured. For the alkali atoms Na, Rb, and Cs there appears to be a solvent effect linear in Z as shown in Fig. 3. To date there appears to be no theoretical explanation of this.

Many of the published measurements of nuclear moments by nuclear resonance methods make no allowance for σ_2 or σ_3 . In fact, many of the experimenters do not specify in their publications the concentrations of aqueous solutions used either in their main sample or in a

secondary reference nucleus. As a result care must be used in accepting nuclear resonance measurements of magnetic moments to accuracies greater than one part in 10^3 . In some cases differences in chemical effects may approach 10^{-2} .

The above considerations do not apply generally to ratios of g_I for two isotopes measured under similar conditions.

Advances in technique of nuclear resonance have permitted some more accurate determinations of magnetic moment ratios. In determining hyperfine anomalies the limitations in precision are usually due to the uncertainties in the moment ratios. Recent measurements⁽¹³⁾ by nuclear resonance yield hyperfine anomalies as shown in Tables IIIA and IIIB.

A number of nuclear moment ratios of Hg isotopes as measured by optical pumping are listed in Table IV. Some recent measurements of dipole and quadrupole moments as measured by optical methods are listed in Table V.

3. Hyperfine Structure A-Factor Measurements

The precision with which hyperfine structure can be measured depends, to a great extent, on the lifetimes of the states involved in the measurement. The uncertainty relation,

$$\Delta W \Delta t = h = h \Delta \nu \Delta t,$$

clearly shows that the longer the lifetime (Δt) the more precisely can ν be measured. By conventional optical spectroscopy the lifetimes of the levels involved in transitions are typically 10^{-8} to 10^{-9} sec so that natural line widths are of the order of 100-1000 MHz, and hyperfine intervals can be measured to precisions of the order of one percent.

With the introduction of the tunable LASER it appears that ultra-high resolution in optical spectroscopy is about to be realized.

LASER light source line widths are extremely narrow. Just in what direction this new tool will be used remains to be seen, but the accurate measurement of isotope shifts seems to be very likely. As a strong tunable light source it may greatly extend the scope of optical pumping experiments.

In an atomic beam the effective Δt is usually the transit time of the atom in the r.f. resonance space, typically 10^{-3} to 10^{-4} sec. The natural lifetimes of the Zeeman levels of the ground state are virtually infinite. The detection methods are such that line centers can be determined with a precision of 10^{-2} to 10^{-5} of one line width. In an atomic beam the atoms are far removed from neighbors so that there is no perturbing influence of collisions with other atoms or vessel walls.

For precise measurements of HFS intervals some weak magnetic field ~ 0.001 to 0.1 G is necessary in order to preserve alignment and establish m_F as a good quantum number.

The $(F_2, 0) \leftrightarrow (F_1, 0)$ transition, such as β in Fig. 1, in a weak field, $\ll 1$ G, is very weakly quadratically field dependent so that small imperfections in the value of H do not broaden the resonance line and the line-width is determined essentially by $\ell/\bar{v}$, where ℓ is the length of the interaction region and $\bar{v}$ the mean atom velocity. Such a transition in ^{133}Cs is so stable and reproducible that it has been used to define the second of time. The international definition of the second of Atomic Time, (AT) is the period for 9, 192, 631, 770 oscillations of the ^{133}Cs HFS transition in zero field. Comparisons between Cs atomic clocks can be made to precision of the order of 10^{-12} to 10^{-13} .

If $J > 1/2$ the level structure corresponding to the Hamiltonian⁽⁵⁾ will be more complex but fairly accurate values of A and B can be determined, but not with as high precision as in the case for $J = 1/2$.

The hydrogen MASER can give an interaction time of one second but is still subject to very small perturbation, of the order of 10^{-12} to 10^{-13} , due to the dimensions of the cavity and its surface nature. Optical pumping and related methods achieve an interaction time of the order of 0.1 second by confining the gas under study in a vessel with either an "inert" buffer gas or an "inert" wall coating. Actually the buffer gas is not perfectly inert and does produce a perturbing effect as does also the wall coating. The result is that for absolute measurements these methods are slightly lower in precision than the best atomic beam values. For measuring magnetic moments, however, the difference $\delta\nu = \nu_0 - \nu_Y = 2g_I\mu_B H$ (see Fig. 1) is not appreciably affected by the pressure or wall shifts and the optical pumping technique can give more precise values than can an atomic beam. Some recent measurements of short-lived nuclei by optical pumping methods by Otten and co-workers at Heidelberg and CERN are given in Table VI.

4. Electric Quadrupole Moment

The electric quadrupole interaction as shown in Eq. 5 involves the electric field gradient $\partial E/\partial z$ at the nucleus. The order of magnitude of the quadrupole moment is such that no macroscopic electric field realizable in the laboratory will produce an appreciable interaction. A significant gradient is realized in a free atom or ion with $J > 1$, in a nonsymmetric molecule or in a noncubic crystal.

The $P_{3/2}$ level scheme of Fig. 2 is shown with no electric quadrupole term. If there were one then each of the F levels would be shifted in differing amounts as determined by the Hamiltonian of Eq. 5. The determination of the B-factor would be determined by an analysis of the observed transitions involving this scheme whether by optical, radiofrequency or microwave methods.

The essential difficulty in evaluating the quadrupole moment from the observed B-factor is associated with evaluating the gradient over the region of the nucleus. This gradient may be considered as

$$\frac{\partial E}{\partial z} = \left. \frac{\partial E}{\partial z} \right|_o + \left. \frac{\partial E}{\partial z} \right|_s \quad \text{or using Sternheimer notation}$$

$$B = B_o(1-R)$$

where the subscript o refers to the gradient as computed from the atom unperturbed by the quadrupole, the subscript s refers to the shielding effect induced in the electron core by the quadrupole moment itself (Sternheimer correction) and R is the quadrupole shielding factor.

The initial term may be computed with an accuracy of the order of 5-10%. The shielding (or antishielding), however, may be as high as 30-40%. In order to compute it one must evaluate $\langle r^{-3} \rangle$. In order to obtain some confidence in the reliability of the calculations of the shielding factor, it has been computed for two electronic states in each of several atoms with consistency of a few percent.⁽¹⁴⁾ (See Table VII.) As a further check on the validity of the $\langle r^{-3} \rangle$ calculation the same wave functions have been used to calculate the fine structure splitting for the alkali atoms. The results of the fine

structure calculations are given in Table VIII from ref. 15. With the exception of Li the agreement is 18% or better.

Schaefer, Klemm and Harris have also made extensive calculations of the Sternheimer correction with the results given in Table IX.⁽¹⁶⁾ These authors have checked their wave functions by using them in calculating the hyperfine A-factor using measured values of μ_I . These results agree with experiment to within a few percent. As a result of these various calculations we probably know several electric quadrupole moments to within a few percent.

Childs⁽¹⁷⁾ has computed the shielding factor for ^{159}Tb for several states of the configurations: $4f^9 6s^2$ and $4f^8 5d 6s^2$ and obtains a value $Q = +1.34 \pm 0.11$ b.

5. Magnetic Octupole Moments

The magnetic octupole moment must be evaluated from a measured C-factor. To evaluate such a term one must observe a departure from the interval rules as determined by A and B, as well as any perturbations from nearby levels. The C-factor may be as small as 10^{-6} times the A. If, after these complications, a value of C is derived with confidence, then the extraction of Ω depends upon electron wave functions of sufficient accuracy to enable evaluation of $\langle r^{-5} \rangle$ as well as the other terms. As in the case of quadrupole evaluation from B-factors the evaluation of octupole moments should be appreciably improved by utilizing C-factors derived from more than one electronic state.

The evaluation of C-factors in this way has been done in the case of ^{197}Au , however, with some disagreement in the calculation of the octupole moment.

$$5d^9 6s^2 {}^2D_{3/2} \quad \Omega = 0.0098(7) \times 10^{-24} \text{ nm cm}^3 \quad (25)$$

$$5d^9 6s {}^2D_{5/2} \quad \Omega < 0.06(6) \times 10^{-24} \quad (25)$$

$$5d^9 6s 6p {}^4F_{9/2} \quad \Omega = 0.13 \quad (26)$$

Clearly it would be desirable to observe C in several different electronic configurations.

6. 16-pole Electric Moment

Very recently Penselin, at Bonn, has reported (personal communication) observing evidence for an electric 16-pole moment interaction in ${}^{165}\text{Ho}$, ${}^{161}\text{Dy}$ and ${}^{163}\text{Dy}$. Using an atomic beam magnetic resonance apparatus his group has observed a number of F-levels of the ground state atoms that cannot fit the interval pattern calculated on the assumption of A-, B-, and C-constants only. A D-constant enables the calculated pattern to fit experiment. In the following table are listed the pertinent constants, subject to change as better calculations are performed, particularly so for the value of the moment.

${}^{165}\text{Ho}$

A	=	800,583,169(36)Hz
B	=	-1,668,078,920(3300)Hz
C	=	-217(140)Hz
D	=	-151(16)
$\pi(16P)$	=	$0.8 \times 10^{-48} \text{ cm}^4$

${}^{161}\text{Dy}$

A	=	-116,232,180(200)Hz
B	=	1,091,574.0(75.6)KHz
C	=	-790(650)Hz
D	=	-95(75)Hz
π	=	$.6 \times 10^{-48} \text{ cm}^4$

^{163}Dy

A	=	162,754,272(20)Hz
B	=	1,152,863,500(1,200)Hz
C	=	-20(13)Hz
D	=	-109(35)Hz
π	=	$0.7 \times 10^{-48} \text{ cm}^4$

III. ESOTERIC ATOMS

1. Positronium

Positronium, $e^+ + e^-$, is a hydrogen-like atom and its hyperfine interaction should be susceptible to rigorous calculations. Comparison between the theoretical and measured value of the hyperfine structure has been of interest as a check on the validity of quantum electro-dynamics. The most recent work by the Yale group⁽¹⁸⁾ yields a value of $\Delta\nu$ which differs from the theoretical value by slightly more than the estimated limits of error. The limitation in measured precision lies in the correction applied for the effect of pressure of N_2 gas in which the positronium is formed.

The following summarizes their results.

	<u>Assuming Linear N_2 Pressure Shift</u>	<u>Assuming Quadratic N_2 Pressure Shift</u>
$\Delta\nu_{\text{ex}}$	$203, 387 \pm 4 \text{ MHz}$	$203, 397 \pm 6 \text{ MHz}$
$\Delta\nu_{\text{th}} - \Delta\nu_{\text{ex}}$	28 ± 4	18 ± 6

The magnitude of the magnetic moment of the positron has been shown to be equal to that of the electron to within 1 PPM.⁽¹⁹⁾

2. Muonium

The muonium atom, analogous to H, has a magnetic field dependence of energy levels similar to that described by the Breit-Rabi equation. The group under Telegdi at the University of Chicago has succeeded in observing two Zeeman transitions, in the (m_e, m_μ) designation $(1/2, 1/2) \leftrightarrow (1/2, -1/2)$ and $(-1/2, 1/2) \leftrightarrow (-1/2, -1/2)$. At a particular value of H both transitions are practically field independent and can be measured very precisely. The measurements are reduced to the ratio $\mu_\mu / \mu_p = 3.183\ 338(13) \sim 4\ \text{PPM}.$ (20)

This group has also measured the hyperfine interaction of muonium with the value $\Delta\nu = 4,463,301.17\ (2.30)\ \text{KHz} \pm 0.5\ \text{PPM}.$ (21) Using their measured value of μ_μ / μ_p and the measured value of $\Delta\nu$ they may, in effect, calculate the value of α the fine structure constant. Their result agrees within experimental uncertainties with the value given by Taylor, Parker, and Langenberg. (22) In the near future accuracy will be appreciably improved when meson "factories" will be in operation, increasing flux by 10^4 .

3. Mu-mesic Atoms

The mu-mesic atoms are discussed at length in a paper in this series by C. S. Wu.

A mu-mesic atom is formed when a negative muon is captured by an atom and releases an electron. The muon makes Auger and radiative transitions until it reaches the 1-s state. The muon may then either decay or be captured by the nucleus. Since its mass is approximately 200 times the electron mass its orbit will be 200 times smaller and its motion will be highly influenced by the nuclear structure. The hyperfine energy levels will therefore be sensitive to the distribution of magnetization within the nucleus and will result in a hyperfine anomaly which is much greater than for a normal atom.

While γ -ray and x-ray spectroscopic data from the mu-mesic atoms are not as precise as some of the resonance measurements of normal atoms, it is quite adequate for a comparison with quantities calculated from several different nuclear models.⁽²⁵⁾

Table X summarizes one such comparison.

Acknowledgements

I would like to express my indebtedness to many of my colleagues for assistance in furnishing some of the material in this paper. In particular, I would like to acknowledge helpful discussions with Mrs. Gladys Fuller, Dr. R. M. Sternheimer, and Prof. A. Arima.

TABLE I

Results from spin-measurements in the rare-earth region obtained by the atomic-beam groups at Uppsala and Göteborg.

Element	Mass No.	$T_{1/2}$	Measured spin	Reference
La	131	59 min	3/2	a
	132	4.5 h	2	
	133	4.0 h	5/2	
	135	19.4 h	5/2	
	136	9.9 min	1	
Ce	130	25 min	0	a
	132	4.2 h	0	
	133	5.4 h	1/2	
	134	72 h	0	
	135	17 h	1/2	
	137	9 h	3/2	
	137 ^m	34.4 h	11/2	
	139	140 d	3/2	
Pr	133	7.5 min	5/2	a
	134	18.5 min	2	
	135	24 min	3/2	
	136	13.4 min	2	
	137	76.6 min	5/2	
	138 ^m	2.0 h	7	
	139	4.5 h	5/2	
	140	3.4 min	1	
Nd	134	8 min	0	a
	135	15 min	9/2	
	136	55 min	0	
	137	37 min	1/2	
	138	5.2 h	0	
	139	30 min	3/2	
	139 ^m	5.5 h	11/2	
	140	3.38 d	0	

TABLE I (continued)

Element	Mass No.	$T_{1/2}$	Measured spin I	Reference
Pm	141	20.9 min	5/2	a
Sm	140	14.7 min	0	a
	141	11.3 min	3/2	
	141 ^m	22.1 min	11/2	
	142	72.4 min	0	
	143	8.8 min	3/2	
Eu	145	5.93 d	5/2	a
	146	4.6 d	4	
	147	24 d	5/2	
	148	54 d	5	
	149	93.1 d	5/2	
	150	12.5 h	0	
Gd	145	22.5 min	1/2	a
	147	38.5 h	7/2	
	149	9.4 d	7/2	
	151	120 d	7/2	
Tb	151	18 h	1/2	b
	152	18 h	2	
	153	55 h	5/2	
	154	21 h	0	
	154 ^m	8.5 h	3	
	155	5.6 d	3/2	
	156	5.4 d	3	
Dy	151	18 min	7/2	c
	152	2.4 h	0	
	153	6.4 h	7/2	
	155	10.2 h	3/2	
	157	8.1 h	3/2	

TABLE I (continued)

Element	Mass No.	$T_{1/2}$		Measured spin I	Reference
Ho	154	12	min	1	d
	155	50	min	5/2	
	156	55	min	1	
	157	14	min	7/2	
	158	11	min	5	
	158 ^m	29	min	2	
	159	33	min	7/2	
	160	26	min	5	
	160 ^m	5.0	h	2	
	162	15	min	1	
	162 ^m	68	min	6	
	164	29	min	1	
	164 ^m	38	min	6	
Er	157	20	min	3/2	d
	158	2.3	h	0	d
	159	36	min	3/2	d
	160	29	h	0	e
	161	3.2	h	3/2	d
Tm	159	11	min	5/2	f
	160	9	min	1	f
	161	34	min	7/2	f
	162	21	min	1	f
	164	2	min	1	f
	164 ^m	5	min	6	f
	165	30.1	h	1/2	e
	168	85	d	3	f
Lu	167	54	min	7/2	g
	169	34	h	7/2	e
	170	2.0	d	0	e
	171	8.3	d	7/2	e

TABLE I (continued)

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- g) C. Ekström, S. Ingelman, B. Wannberg and I. L. Lamm, Nuclear ground state spin of ¹⁶⁷Lu, Phys. Letters 39B,199(1972).
- h) H. Nyqvist and A. Rosen, Hyperfine structure investigations of ¹⁵³Dy, ¹⁵⁵Dy and ¹⁵⁷Dy, (in manuscript).

TABLE II

Results from hyperfine structure measurements in the rare-earth region obtained by the atomic-beam groups at Uppsala and Göteborg, 1972.

Isotope	Mass No.	A MHz	B MHz	μI n.m.	Q_0 barn	Ref.
Dy	153	$\bar{+}123.4(8)$	$\bar{+}64(34)$	-0.69(7)	-0.30(11)	a
Dy	155	$\bar{+}136.3(4)$	$\bar{+}422(4)$	-0.33(4)	4.60(60)	
Dy	157	$\bar{+}121.605(4)$	$\bar{+}564.65(7)$	-0.29(3)	6.15(75)	
Er	161	37.1(5)	-2939(40)	0.092(2)	1.87(15)	b
Er	163	167(7)	3275(130)	0.56(2)	2.2(2)	
Tm	166	37.1(5)	-2939(40)	0.092(2)	1.87(15)	
Tm	167	-318.5(5)		-0.197(1)		

a) H. Nyqvist and A. Rosen, Hyperfine structure investigations of ^{153}Dy , ^{155}Dy and ^{157}Dy , (in manuscript).

b) To be submitted to Nuclear Physics.

TABLE IIIA

Hyperfine structure anomalies of gallium and indium isotopes using the A-factors quoted (from Ref. 13).

Isotopic Pair	State	A in %	A_1/A_2	Ref.
^{67}Ga , ^{69}Ga	$^2P_{1/2}$	0.00050(7)	0.91775154(48)	a,b
^{67}Ga , ^{69}Ga	$^2P_{3/2}$	-0.00200(16)	0.9177286(11)	a,c
^{69}Ga , ^{71}Ga	$^2P_{1/2}$	0.00063(6)	0.78701967(44)	a
^{69}Ga , ^{71}Ga	$^2P_{3/2}$	-0.00252(12)	0.78699489(90)	c
^{71}Ga , ^{72}Ga	$^2P_{1/2}$	0.0043(6)	-38.75439(13)	a,b
^{71}Ga , ^{72}Ga	$^2P_{3/2}$	-0.0170(18)	-38.74616(68)	b,c
^{113}In , ^{115}In	$^2P_{1/2}$	0.00074(4)	0.99786841(25)	d
^{113}In , ^{115}In	$^2P_{3/2}$	-0.00239(4)	0.99783714(26)	c
^{115}In , $^{117\text{m}}\text{In}$	$^2P_{1/2}$	-0.0015(12)	-2.445836(31)	d,f
^{115}In , $^{117\text{m}}\text{In}$	$^2P_{3/2}$	0.0048(80)	-2.44599(24)	e,g

^aEhlers, V. J., Kabasakal, Y., Shugart, H. A., Tezer, O.: Phys. Rev. 176, 25 (1968)

^bLurio, A., Prodell, A. G.: Phys. Rev. 101, 79 (1956).

^cDaly, R. T., Jr., Holloway, J. H.: Phys. Rev. 96, 539 (1954).

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^fSchwartz, C.: Phys. Rev. 99, 1035 (1955).

^gMufti, A. R., Cameron, J. A., Waddington, J. C., Summers-Gill, R. G.: Can. J. Phys. 46, 177 (1968).

TABLE IIIB

Hyperfine anomalies of some halogens from recent NMR data.

Element	State	Isosopic Pair	g_1/g_2	A_1/A_2	$\Delta \%$	Ref.
Cl		35-37	0.832 394 48(8)			(a)
P	3/2			1.201 307 8(2)	-0.003 80(2)	(b)
P	1/2			1.201 357 (13)	0.000 3(11)	(c)
Br		79-81	1.077 935 5(3)			(d)
P	3/2			1.077 935 8(2)	-0.000 03(4)	(e)

(a) O. Lutz, Phys. Letters 31A, 528 (1970).

(b) J. H. Halloway, B. B. Aubry, J. G. King, R.L.E. Quarterly Report,
April 1956, p. 35.

(c) J. G. King and V. Jaccarino, Phys. Rev. 84, 852 (1951).

(d) O. Lutz, Phys. Letters 31A, 384 (1970).

(e) H. H. Brown and J. G. King, Phys. Rev. 142, 53 (1966).

TABLE IV

Ratio of magnetic moment of Hg isotope to that of Hg 199 optical pumping.
(From M. Mc Dermott, unpublished, July 1972.)

Isotope	μ/μ_{199}
193 m	0.160 940 9(10)
195 m	0.158 854 4(5)
197 m	0.156 265 7(4)
199 m	0.154 292 1(9)
201	0.369 138 8(3)
195	1.070 350 8(14)
197	1.042 478(2)

These may be related to μ_p by the measurement of Cagnac (J. Phys. Rad. 19, 863 (1958)).

$$\mu(199)/\mu_p(\text{H}_2\text{O}) = 0.178\,270\,6(3).$$

TABLE V
Recent measurements of nuclear moments by optical methods (preliminary compilation by G. Fuller, to be published in a future revision of the Nuclear Moment Tables.).

Nucleus	T(1/2)	I	$\mu, \mu/\mu_N$	$Q, Q^1/Q^2$	Reference
⁵⁹ Co				$\pm 0.49 \underline{3}$ $\pm 0.42^* \underline{3}$	Murakawa, JPSJ <u>27</u> , 1690, 1969. *Includes shielding.
²³ Na			$+2.218 \underline{13}$		Draganescu-Stud. Cercet. Fig. 19, 859 (1967), Phys. Abst. 71 #7078(1968)
¹³⁵ Ba				$\pm 0.17 \underline{2}$	Becker, ZP <u>216</u> , 142, 1968.
¹³⁷ Ba				$\pm 0.26 \underline{3}$ (using ¹³⁷ / ₁₃₅ =+ 1.54)	Becker, ZP <u>216</u> , 142, 1968.
¹⁵² Eu			negative	positive	Heinecke, PL <u>31B</u> , 295, 1970.
¹⁵⁴ Eu				positive (¹⁵⁴ / ₁₅₂ =+1.24 <u>10</u>)	Heinecke, PL <u>31B</u> , 295, 1970. Judd, PR <u>128</u> , 1733, 1962.
¹⁵⁹ Tb				$\pm 1.18 \underline{12}$	Dekker, Physica <u>46</u> , 119, 1970.
¹⁶⁵ Ho			$+ 3.97^h \underline{5}$		Sugar, JOSA <u>58</u> , 1519, 1968.
¹⁸⁵ Re				$\pm 2.36 \underline{50}$	Krause, Naturwssn. <u>56</u> , 84, 1969.
¹⁸⁷ Re			+	$\pm 2.24 \underline{50}$	Krause, Naturwssn, <u>56</u> , 84, 1969.
¹⁹⁹ Hg			$\pm 0.506 \underline{3}$		Draganescu-Stud. Cercet. Fig. 19, 859 (1967), Phys. Abst. 71 #7078 (1968)
¹⁹⁵ Tl	1.2 h		$+ 1.56 \underline{4}$		Goorvitch, PR <u>188</u> , 1897 1969.
²⁰³ Tl			$203/205=0.9912 \underline{10}$		Odintsov-O & S <u>9</u> , 75, 1960.
²⁰⁶ Bi	6.3 d		$+4.50$ $206/209 + 1.104$		Magnante, JOSA <u>59</u> , 836, 1969.
²⁰⁹ Bi	$> 10^{18} \text{ y}$			$-0.379 \underline{15}$	Eisler PL <u>28E</u> , 256, 1968.
²⁰⁹ Bi	$> 10^{18} \text{ y}$		$+4.23 \underline{10}$ $+ 3.7^+ \underline{5}$	$-0.4 \underline{1}$ $-0.79 \text{ to } - 20$	Crooker, CJP <u>48</u> , 730, 1970. † Recalculated from earlier data.
²⁰⁹ Bi	$> 10^{18} \text{ y}$			$-0.41 \underline{4}$	George, JOSA <u>60</u> , 869, 1970.

TABLE V (continued)

Nucleus	T(1/2)	I	$\mu, \mu^1/\mu^2$	$Q, Q^1/Q^2$	Reference
U^{233}	0.2 My		± 0.73	± 7.9	Bauche Arnoult quoted in J.P. <u>30</u> Coll. Cl, 78, 1969.
U^{233}	0.2 My		(+ 0.73) (using $\mu/Q = 0.152$ <u>15</u>)	+ 4.8	
Pu^{241}	13y		-0.673 <u>15</u> 241/239=-3.365 <u>20</u>		Gerstenkorn, Physics <u>42</u> , 581, 1969.
Bk^{249}	314d		± 5.1 <u>7</u>	± 4.7 <u>10</u>	Conway, UCRL 19530, P. 200, 1970. Worden, JOSA <u>59</u> , 1526A, 1970.
Es^{253}	20d	7/2	+ 5.1 <u>13</u>	± 5.1 <u>10</u>	Conway, UCRL 19530, P. 200, 1970. Worden, JOSA <u>60</u> , 1297, 1970.
Pu^{241}	13y		241/239=-3.367 <u>20</u> 241/239=-3.362 <u>20</u>		Edelstein, PL <u>33A</u> , 233, 1970.

TABLE VI

On-line measurements of short-lived nuclei by optical pumping.

Element	Mass No.	I	μ n.m.	Q barn	Ref.
Hg	187	3/2	0.58(3)	1	(a)
Hg	183	1/2	0.513(9)		(b)
Hg	185	1/2	0.449(4)		(b)
K	37	3/2	+0.203 20(6)		(c)
Na	20	2	+0.369 4(10)		(d)
Na	21	3/2	+2.46(8)		(e)
Li	8	2	+1.653		(e)

(a) Bonn, et al., Phys. Letters 36B, 41 (1971).

(b) Bonn et al., Phys. Letters 38B, 308 (1972).

(c) U. Kopf, et al., Zeitz. für Physik 226, 297 (1969).

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TABLE VII. Values of the experimental quadrupole moments Q_{exp} (without correction factor C) and of the corresponding corrected moments Q_{corr} [see Eq. (9)]. The values of $C = 1/(1-R)$ are listed in the fourth column of the table. Q_{exp} and Q_{corr} are in units of $b = 10^{-24} \text{ cm}^2$. The references for the values of Q_{exp} are listed in the table.

Nucleus	Atomic State	Q_{exp}	$1/(1-R)$	Q_{corr}
Al ²⁷	3p	+0.149(2) ^a	0.941	+0.140(2)
Cl ³⁵	3p ⁵	-0.06213(2) ^b	1.045	-0.06493(2)
Cl ³⁶	3p ⁵	-0.0172(4) ^c	1.045	-0.0180(4)
Cl ³⁷	3p ⁵	-0.07894(2) ^b	1.045	-0.08249(2)
Cu ⁶⁵	3d ⁹ 4s ²	-0.161(3) ^d	1.218	-0.196(4)
Cu ⁶⁵	3d ¹⁰ 4p	-0.228(5)	0.851	-0.194(4)
Cu ⁶³	3d ⁹ 4s ²	-0.172(4) ^d	1.218	-0.209(5)
Ga ⁶⁷	4p	+0.22 ^f	0.886	+0.195
Ga ⁶⁸	4p	+0.0313(16) ^g	0.886	+0.0277(14)
Ga ⁶⁹	4p	+0.190 ^h	0.886	+0.168
Ga ⁷¹	4p	+0.120 ^h	0.886	+0.106
Ga ⁷²	4p	+0.59 ^f	0.886	+0.52

a) H. Lew and G. Wessel, Phys. Rev. 90, 1 (1953).

b) V. Jaccarino and J. G. King, Phys. Rev. 83, 471 (1951).

c) C. H. Townes and L. C. Aamodt, Phys. Rev. 76, 691 (1949).

d) W. Fischer, H. Hühnermann, and K. J. Kollath, Z. Physik 200, 158 (1967).

e) J. Ney, Z. Physik 196, 53 (1966); H. Bucka (private communication).

f) V. J. Ehlers, T. Kabasakal, H. A. Shugart, and O. Tezer, Phys. Rev. 176 25 (1968).

g) V. J. Ehlers and H. A. Shugart, Phys. Rev. 127, 529 (1962).

h) G. F. Koster, Phys. Rev. 86, 148 (1952).

TABLE VIII

Theoretical and experimental values of the fine-structure splittings Δv (in cm^{-1}) of the first three excited np states of each of the alkali atoms, and the ratios $\rho \equiv \Delta v_{\text{theor}}/\Delta v_{\text{expt}}$.

State		Δv_{theor}	Δv_{expt}	ρ
Li	2p	0.969	0.34	2.85
Li	3p	0.311	0.10	3.11
Li	4p	0.134	...	...
Na	3p	18.731	17.196	1.089
Na	4p	6.099	5.63	1.083
Na	5p	2.729	2.52	1.083
K	4p	62.90	57.72	1.090
K	5p	20.14	18.76	1.074
K	6p	9.00	8.41	1.070
Rb	5p	265.36	237.60	1.117
Rb	6p	87.88	77.50	1.134
Rb	7p	40.18	35.09	1.145
Cs	6p	652.86	554.11	1.178
Cs	7p	203.89	181.01	1.126
Cs	8p	93.35	82.64	1.130

* Sternheimer & Peierls, Phys. Rev. A 4, 1723 (1971).

TABLE IX

Values of Q as corrected for quadrupole shielding
by Schaefer, Klemm, and Harris.

Nucleus	Electronic state	Q in barns
B^{10}	$2P_{3/2}$	0.080 35
B^{11}	$2P_{3/2}$	0.038 56
C^{11}	$3P_2$	± 0.032 17
O^{17}	$3P_2$	-0.025 26

TABLE X

HFS of Mu-mesic Atoms

The magnetic hyperfine structure constant in keV. The upper row for each isotope is for the muon in the $s-1/2$ state and the lower row for a $p-1/2$ muon. Column 1 lists the calculated value for the Single Particle Model with the Schmidt moment. The other columns (2-6) list the calculated values for models all adjusted to have the experimental moment listed under the isotopes as follows: 2, Point Nucleus; 3, Configuration Mixing; 4, Projection Model; 5, Projection Model plus Phonon $g_R=0$; 6, Projection Model plus Phonon $g_R=Z/A$. The last column lists the measured values (from Ref. 23).

	1	2	3	4	5	6	7	Ref.
41Nb93 9/2+ $\mu = 6.1671$	1.63 .365	2.32 .426	1.48 .332	1.48 .331	1.48 .331	1.55 .347		
49In113 9/2+ $\mu = 5.5233$	1.91 .556	2.61 .637	1.58 .457	1.58 .456	1.58 .456	1.67 .481		
49In115 9/2+ $\mu = 5.5351$	1.91 .555	2.60 .637	1.58 .457	1.58 .457	1.57 .457	1.66 .481	$1.65 \pm .15$ $.55 \pm .20$	a)
51Sb121 5/2+ $\mu = 3.359$	1.44 .436	1.64 .431	1.04 .312	1.04 .313	1.04 .313	1.18 .354		
51Sb123 7/2+ $\mu = 2.546$	.847 .226	1.23 .326	1.07 .297	1.07 .297	1.05 .293	1.17 .327		
53I127 5/2+ $\mu = 2.8091$	1.47 .476	1.40 .399	.940 .296	.930 .294	.918 .291	1.11 .352	$0.87 \pm .09$ $0.33 \pm .08$	a)
55Cs133 7/2+ $\mu = 2.5789$	.908 .277	1.34 .405	1.21 .378	1.18 .369	1.17 .367	1.21 .380	$1.16 \pm .17$ $.55 \pm .22$	a)
57La139 7/2+ $\mu = 2.7781$	.944 .304	1.50 .481	1.29 .429	1.30 .431	1.30 .431	1.30 .432	$1.22 \pm .15$	b)
59Pr141 5/2+ $\mu = 4.28$	1.61 .598	2.41 .811	1.47 .541	1.47 .544	1.47 .544	1.48 .544	$1.52 \pm .06$	c)
63Eu151 5/2+ $\mu = 3.463$	1.67 .680	2.04 .772	1.23 .499	1.24 .503	1.23 .498	1.43 .583	$.80 \pm .27$	e)
63Eu151 7/2+ $\mu = 2.58$	1.02 .389	1.52 .575	1.30 .503	1.31 .508	1.27 .493	1.51 .576		

TABLE X (continued)

	1	2	3	4	5	6	7	Ref.
81Tl 203 1/2+ $\mu = 1.61169$	1.16 .613	1.19 .631	.768 .407	.774 .410	.770 .408	.777 .412	.665 $\pm$.075	f)
81Tl 203 1/2+ ($w = 0.4$)					.699 .370	.823 .430		
81Tl 205 1/2+ $\mu = 1.62754$	1.15 .612	1.19 .635	.774 .411	.779 .413	.779 .413	.779 .413	.580 $\pm$.015	e)
81Tl 205 1/2+ ($w = 0.4$)					.710 .377	.824 .437		
83Bi209 9/2- $\mu = 4.0794$	1.64 .893	3.04 1.67	2.06 1.12				1.92 $\pm$.14	e)

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- e) R. A. Carrigan, Jr., P. D. Gupta, R. B. Sutton, M. N. Suzuki, A. C. Thompson, R. E. Cote, W. V. Prestwick, A. K. Gaigalas, and S. Raboy, Bull. Am. Phys. Soc. 13, 65 (1968); Phys. Rev. Letters 20, 874 (1968).
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TABLE XI

Recent Results from the Bonn Atomic Beams Group

Isotope	Atomic State	A. Miscellaneous Measurements				Ref.
		A Factor MHz	μ_I (uncorr.) nm	B Factor MHz	Q Barn	
C 11			-0.964			a
C 13	3P_2	149.056(10)	.7020(4)			a
	3P_1	2.839(17)	(neglecting HFS anomaly)			
Ho 165	$^4I_{15/2}$	800.5828(14)	4.094(44)	-1668.10(9)		b
Hf 177	3F_2	113.4331(2)	0.75(8)	624.338(3)	4.3(6)	c
Hf 179	3F_2	-71.4272(2)	-0.61(6)	705.498(3)	4.9(7)	c
Ta 181	$^4F_{3/2}$	509.0801(8)		-1032.251(8)		d
Ta 181	$^4F_{5/2}$	313.4681(8)		-834.820(12)		d
Ir 191	$^4F_{9/2}$	57.62(6)		470.9(5)		e
Ir 193	$^4F_{9/2}$	62.50(6)		426.8(5)		e

		B. Precision Measurements of Some Alkalis				
		$g_I/g_J \times 10^4$		μ_I (uncorr.) nm		
Li 7	$^2S_{1/2}$	-5.904 2725(15)		3.255 989(2)		
Na 23	$^2S_{1/2}$	-4.018 439(13)		2.216 014(9)		
K 39	$^2S_{1/2}$	-0.708 8607(3)		0.390 908 831(23)		
K 41	$^2S_{1/2}$	-0.389 0818(15)		0.214 563 3(8)		

(a) G. Wolber, H. Figger, R. A. Haberstroß and S. Penselin, Phys. Letters 29A, 461 (1969).

(b) G. Merzyn, S. Penselin and G. Wolber, Zeit. für Physik 252, 412 (1972); also R. A. Haberstroß, T. I. Moran and S. Penselin, Zeit. für Physik 252, 420 (1972).

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FIGURE CAPTIONS

Figure 1.

Hyperfine structure for transition $P_{3/2}$ to $S_{1/2}$ for $I = 3/2$. A_p is the A-factor for the P state and A_s that for the S-state. Quadrupole effects are neglected.

Figure 2.

H.F.S. levels in a magnetic field for the case $J = 1/2$, $I = 3/2$. Transition α can be measured to determine I , β at low field can determine Δv . The difference $\nu_\delta - \nu_\gamma = 2g_I \mu_B H$ can be used to determine g_I .

Figure 3.

A plot of σ_3 , of the relative difference in magnetic shielding between the nucleus in a free atom and in a + ion in dilute solution, as a function of Z . Comparable data for the K^+ ion is not available. The hollow circle points represent the difference between g_I for neutral K^{39} and various K salts in strong solutions reported in the literature. The two values for $KCOOH$ may conceivably be due to effects of different paramagnetic catalysts in the two experiments.

HFS PATTERN FOR CASE $I=3/2$ FOR TRANSITION
 $P_{3/2}$ TO $S_{1/2}$

HFS LEVELS IN A MAGNETIC FIELD FOR $J=1/2$,
 $I=3/2$

MAGNETIC SHIELDING OF WATER vs Z