nuclear charge of the incident ion. One should probably have used the effective charge but in the region where Eq. (2) is valid no corrections were deemed necessary. One interesting feature of this plot is the odd-even charge effect. While these variations are within the extreme experimental errors for large Z, the even charge species appear to belong to a separate curve systematically above that of the odd charge group. For the purpose of illustration the two curves have been shown. The same sort of behavior is also suggested in the saturation region. No obvious reason for such a splitting, if it is indeed real, can be offered at this time. The errors indicated are relative and for the larger Z ions the size of the point exceeds the estimated error. The absolute values of K may be in error by as much as 10%.

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Nuclear Spin and Hyperfine Interaction of In^{113m}†

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The hyperfine structure of the 1.7-hr, 393-kev metastable state of In^{113} has been studied by use of the atomic-beam magnetic-resonance technique. The nuclear spin is found to be $\frac{1}{2}$ and the magnetic dipole moment to be -0.21050 ± 0.00002 nm, subject to a possible hyperfine anomaly. The hyperfine separation in the atomic $P_{\frac{1}{2}}$ state is measured to be 781.084 ± 0.010 Mc/sec.

INTRODUCTION

THE isotope In^{113} has long held the interest of nuclear physicists. The energy levels, the conversion coefficients, and the lifetime of the 393-kev isomeric state have received attention both from experimentalists[1–6] and theoreticians.[7,8]

A major triumph of the shell model of the nucleus was the explanation of such isomeric states. In the case of In^{113m}, the isomerism is described as being due to the existence of a large spin difference between the ground state, which has a measured spin of 9/2,[9] and the first excited state, for which the shell model predicts a spin of $\frac{1}{2}$. The ground state is assumed to arise from a proton hole in the $g_{9/2}$ shell, the filling of which would complete the proton magic number 50. The isomeric state, according to the model, is due to the closely competing $(p_{\frac{1}{2}})^1$ configuration.

The predicted spin difference of 4 is consistent with the semiempirical rules[10] and theoretical treatments[7,8] of gamma-ray emission and electron conversion.

It is of interest to measure the spin of the excited state by a direct method and thus further confirm the theoretical predictions.

THEORY OF THE METHOD

The Zeeman splitting of the hyperfine levels of the atomic $P_{\frac{1}{2}}$ state was studied. The principles of the method have been so adequately described[11,12] that a complete review is unnecessary. It is desirable, however, in the interest of clarity, to set down a few pertinent concepts and equations used in interpreting the data.

In the scheme which Zacharias[11] originally applied in his studies of K^{40}, an atom in the atomic beam is successively deflected by two strong, inhomogeneous magnetic fields. These deflections are in the same direction unless an appropriate change of magnetic substate occurs between them. This change of state must be such that in the strong field of the second deflecting magnet the effective magnetic moment of the atom will be equal but of opposite sign to that in the first. Under this condition, the atom will be refocused through a slit where it can be detected. Suitable changes of state are induced by an appropriate radio-frequency field introduced into the gap of the homogeneous magnet. These observable transitions are indicated in the hyperfine diagram (Fig. 1).

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[1] S. W. Barnes, Phys. Rev. **56**, 414 (1939).
[2] J. L. Lawson and J. M. Cork, Phys. Rev. **57**, 982 (1940).
[3] D. A. Thomas, S. K. Haynes, and C. D. Broyles, Phys. Rev. **82**, 961 (1951).
[4] T. B. Cook, Jr., and S. K. Haynes, Phys. Rev. **86**, 190 (1952).
[5] G. A. Graves, L. M. Langer, and R. D. Moffat, Phys. Rev. **88**, 344(1952).
[6] S. B. Burson, H. A. Grench, and L. C. Schmid, Phys. Rev. **115**, 188 (1959).
[7] M. E. Rose, G. H. Goertzel, B. I. Spinrad, J. Harr, and P. Strong, Phys. Rev. **83**, 79 (1951).
[8] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
[9] D. A. Jackson, Z. Physik **80**, 59 (1933).
[10] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
[11] J. R. Zacharias, Phys. Rev. **61**, 270 (1942).
[12] L. S. Goodman and S. Wexler, Phys. Rev. **99**, 192 (1955).

For an atom with electronic angular momentum $J=\frac{1}{2}$, the frequency ν at which the $\Delta F=0$ transition occurs is given implicitly by the relation[13]

$$\Delta\nu=\frac{(\nu-g_I k)(g_J k-\nu)}{\nu-g_I k-[(g_J-g_I)k/(2I+1)]}, \quad (1)$$

where $k=\mu_0 H/h$, and g_I is the nuclear g factor defined by $g_I=-\mu_I/\mathrm{I}$. In these expressions and in Eq. (2), g_J is the electronic g factor, I the nuclear spin, H the intensity of the homogeneous magnetic field, μ_0 the Bohr magneton, and μ_I is the nuclear magnetic dipole moment.

The nuclear g factor is a measure of the hyperfine separation $\Delta\nu$. Although one cannot calculate the proportionality constant precisely, the Fermi-Segrè relation[14] relates, to a sufficiently good approximation, the $\Delta\nu$'s and g_I's of isotopes with the same nuclear charge and atomic state. For indium atoms in the $P_{\frac{1}{2}}$ atomic state, the relationship between the g factors for the isotopes 113m and 115 becomes

$$\frac{\Delta\nu^{113m}}{\Delta\nu^{115}}=\frac{(2I_{113m}+1)g_I{}^{113m}}{(2I_{115}+1)g_I{}^{115}}. \quad (2)$$

In the present experiment, g_J was known,[15] and the resonance frequency was measured at a number of known field intensities. From these data, the values of I and $\Delta\nu$ could be extracted by use of Eqs. (1) and (2).

APPARATUS

The atomic beam apparatus previously described by Goodman and Wexler[12] was used for the present experiment. Extensive modifications were made in the oven end of the machine to facilitate the higher oven temperatures required and to allow for simpler decontamination techniques.

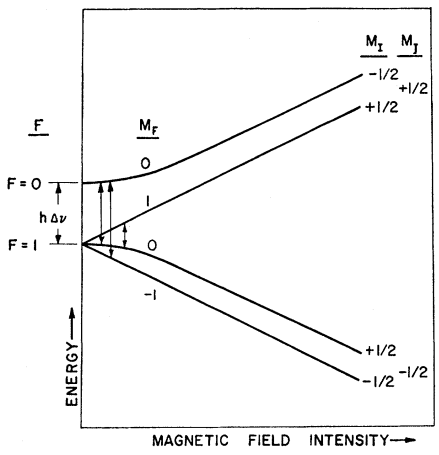

FIG. 1. Magnetic field dependence of the energy levels of In^{113m} in its $P_{\frac{1}{2}}$ atomic ground state.

The collector system employed liquid-nitrogen-cooled copper receivers onto which the beam was allowed to condense. The collector tube, which had passed through a vacuum lock sealed with O rings and vacuum grease, was replaced with a more compact, greaseless, differentially pumped unit.

A bank of ten identical windowless gas-flow Geiger counters was constructed so that a number of collected samples could be counted simultaneously.

The rf equipment used included a General Radio 805-C signal generator, a Hewlett-Packard 608-A oscillator, a surplus radar jammer, and an Airborne Instruments 124-C power oscillator, along with appropriate amplifiers (where necessary) for signal generation. A Berkeley Model 5570 frequency counter and Model 5575 range extender, a Collins 51J-4 receiver, and a Hewlett-Packard Model 540-A transfer oscillator, with normal beating techniques, were used for frequency measurement.

SOURCE PREPARATION

It was decided to prepare the isomer under study by decay from 119-day Sn^{113}. The Sn^{113} decays by electron capture essentially 100% to the isomeric state of the In^{113}. The Sn^{113} was formed by neutron capture (1.3b cross section) in the 1% abundant Sn^{112}. This scheme has the advantage of long source life even though the isomer studied decays with a half-life of 1.7 hours. An additional advantage is the absence of any interfering activities. The only activity present (besides the $Sn^{113}-In^{113m}$) after a month's decay was found to be 2.0-year Sb^{125}, which could be completely boiled off at a temperature low enough that very little tin was lost.

Two-gram samples of normal tin metal were irradiated in a flux of 10^{14} neutrons cm^{-2} sec^{-1} in the MTR for four to six months. The tin and 500 mg of carrier, either indium or gallium metal, were inserted into a graphite oven and set in position in the vacuum chamber. The oven was heated by electron bombardment to a temperature at which a beam of about 10^{-9} amp of normal indium (or gallium) was observed with the oxidized tungsten surface-ionization detector. The indium (or gallium) beam was used not only as a carrier for the active atoms, but also for oven alignment and measurement of the homogeneous magnetic field.

The tin was relatively involatile at the temperatures used. The carrier evaporated from the mixture as if it were in a perfect solution, i.e., the beam intensity of inactive indium (or gallium) was roughly proportional to the amount of carrier left in solution and decreased exponentially with time. The active material, unlike the carrier, was being replaced by the radioactive decay of the 119-day Sn^{113}. The oven was maintained at such a temperature that the secular equilibrium of the $Sn^{113}-In^{113m}$ system was not appreciably disturbed.

[13] S. Millman and P. Kusch, Phys. Rev. **58**, 438 (1940).
[14] E. Fermi and E. Segrè, Z. Physik **82**, 729 (1933).
[15] N. F. Ramsey, *Molecular Beams* (Oxford University Press, New York, 1956).

TABLE I. Summary of the observations on the ($F=1$, $m_F=1 \leftrightarrow F=1$, $m_F=0$) transition in In^{113m}. All frequencies are in Mc/sec. The differences in the last two columns are in kc/sec. The In^{115} transition used for field calibration was the ($F=6$, $m_F=-3 \leftrightarrow F=6$, $m_F=-4$) resonance in the metastable $P_{\frac{3}{2}}$ state.

H (gauss)	Calib. freq.	Obs. freq. for In^{113m}	$\Delta\nu$ calc. $\mu_I>0$	$\Delta\nu$ calc. $\mu_I<0$	$\nu_{th}-\nu_{ex}$ $\mu_I>0$	$\nu_{th}-\nu_{ex}$ $\mu_I<0$
10.63	5.000	5.025±0.050	345_{-140}^{+820}	360_{-140}^{+1020}	−36	−40
25.93	12.297	12.281±0.020	727±66	757±66	−14	−6
51.866	25.015	24.933±0.025	755±24	771±24	−26	−10
129.666	65.788	65.081±0.030	775.7±5.0	781.6±5.0	−32	+2
194.499	102.919	101.033±0.020	777.4±1.5	781.1±1.5	−49	−1
259.331	143.108	139.135±0.030	778.6±1.3	781.2±1.3	−56	+3
388.997	233.609	221.325±0.020	779.22±0.43	780.77±0.43	−86	−14

Thus, in contrast to the nonradioactive beam, the intensity of the In^{113m} beam did not diminish with time.

When the nonactive beam diminished below a usable value, more carrier was added to the involatile tin source and the process repeated. This could be done a number of times before the tin was depleted.

In most work with radioactive beams the source decays with the half-life being studied, so that one need make no correction for the decay of the collected samples if they are counted at the same time, independdent of the respective times of collection. For the Sn^{113}—In^{113m} source, however, in which the radioactive portion of the beam is essentially steady, the counting rates of all of the samples must be corrected back to their respective times of collection.

IDENTIFICATION OF ATOMS IN THE ATOMIC BEAM

In order to establish the identity of the radioactive portion of the beam, the decay of deposited atoms was examined. With the deflecting magnets turned off and no obstacle in place, the decay half-life of atoms collected was found to be 1.7 hours, as expected for In^{113m}. In addition, the half-life of atoms refocused at 51.866 gauss by a radio-frequency signal of 24.933 Mc/sec [i.e., those undergoing the ($F=1$, $m_F=1 \leftrightarrow F=1$, $m_F=0$) transition at this field] was measured and similarly found to be 1.7 hours. These collected samples were too weak for a gamma-ray analysis, but such an analysis of a portion of the oven load showed the 393-kev In^{113m} gamma ray strongly. The only other gamma rays observed were shown to be associated with the decay of Sb^{125}. As mentioned above, the antimony was boiled off the sample prior to taking measurements, and in any case, could not influence the interpretation of the short-lived resonances observed.

TABLE II. The ($F=0$, $m_F=0 \leftrightarrow F=1$, $m_F=0$) transition in In^{113m}. All frequencies are in Mc/sec. The $\Delta F=0$ transition in the atomic $P_{\frac{1}{2}}$ ground state was used for field calibration.

H (gauss)	Calibration isotope	Calibration freq.	Obs. In^{113m} freq.	$\Delta\nu$ corr. to $H=0$
3.000	$Ga^{69,71}$	0.697	781.074±0.020	781.069±0.020
4.000	$Ga^{69,71}$	0.930	781.086±0.020	781.077±0.020
6.502	In^{115}	0.600	781.115±0.030	781.092±0.030
6.502	In^{115}	0.600	781.115±0.010	781.092±0.010

DISCUSSION OF OBSERVATIONS

The isotope used for calibration of the homogeneous magnetic field was In^{115} for some of the observations, and Ga^{69} and Ga^{71} for the remainder. For all three isotopes, atoms in both the $P_{\frac{1}{2}}$ atomic ground state and the metastable $P_{\frac{3}{2}}$ state were observed in the beam and used for calibration of the field. All calculations of the transition frequencies in In^{113m} were based on the Breit-Rabi equation.[16] For the resonances used for calibration, frequencies were calculated by the Argonne digital computers from the exact Hamiltonian.

Table I summarizes the observations on the low-frequency transition in the $P_{\frac{3}{2}}$ state of In^{113m}. Any two of the observations are sufficient to demonstrate that the nuclear spin is indeed $\frac{1}{2}$. Column 1 lists the intensity of the uniform magnetic field at which each observation was made. Column 2 gives the observed resonance frequency of the ($F=6$, $m_F=-3 \leftrightarrow F=6$, $m_F=-4$) transition in the metastable $P_{\frac{3}{2}}$ state of In^{115} which was used for the field measurement. Column 3 gives the observed transition frequency in In^{113m}. The next two columns give the inferred hyperfine separation, on the respective assumptions of negative and positive nuclear magnetic dipole moment. The last two columns list the difference between the frequencies for In^{113m} as calculated from the best value for the hyperfine interaction (781.084±0.010 Mc/sec) and the observed frequencies for both signs of the dipole moment.

The deviations for the assumption of a positive magnetic moment are all of the same sign and, particularly at higher fields, are larger in magnitude than for the assumption of a negative magnetic moment. In fact, the deviations lie within experimental error for all the observations only if the dipole moment is assumed negative. This is interpreted as strong evidence that the sign of the moment is negative.

The values of the magnetic moment calculated from the observed hyperfine splitting by use of Eq. (2) and previously published values[15,17] for $\Delta\nu$, I, and μ_I

[16] G. Breit and I. I. Rabi, Phys. Rev. **38**, 2082 (1931).

[17] T. G. Eck, A. Lurio, and P. Kusch, Phys. Rev. **106**, 954 (1957).

for In^{113} and In^{115} are -0.210505 ± 0.000021 nm and -0.210485 ± 0.000025 nm, respectively. This is the so-called apparent value. A hyperfine anomaly[15] probably exists, but cannot be measured with the present arrangement.

Table II lists the data on the observations made on the ($F=0$, $m_F=0\leftrightarrow F=1$, $m_F=0$) transition. The relatively field-independent character of the observed frequency assures its identification as the transition between substates with $m_F=0$. The last column gives the observed hyperfine splitting corrected to zero field.

Figure 2 shows the ($F=1$, $m_F=1\leftrightarrow F=1$, $m_F=0$) transition as observed with the homogeneous magnetic field set at 194.5 gauss. Figure 3 shows the relatively field-independent transition ($F=0$, $m_F=0\leftrightarrow F=1$, $m_F=0$) as it appeared at 4 gauss. Its displacement from

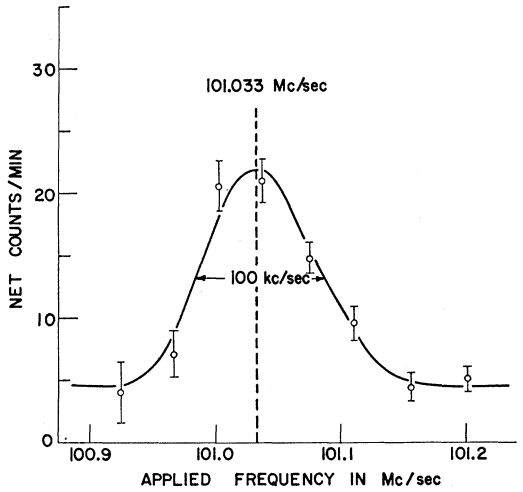

FIG. 2. The ($F=1$, $m_F=1\leftrightarrow F=1$, $m_F=0$) transition in the $P_{\frac{1}{2}}$ state of In^{113m} as observed at 194.5 gauss.

the hyperfine separation at this field is calculated to be only +9 kc/sec.

DISCUSSION

The nuclear spin of the metastable 393-kev level of In^{113} is found to be $\frac{1}{2}$, and is presumably due to the promotion of one $p_{\frac{1}{2}}$ proton up to complete the $g_{9/2}$

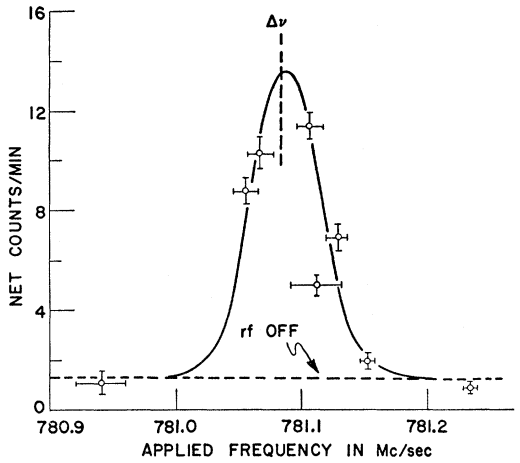

FIG. 3. The ($F=0$, $m_F=0\leftrightarrow F=1$, $m_F=0$) transition in the $P_{\frac{1}{2}}$ state of In^{113m} as observed at 4 gauss.

proton shell. In the simple shell model, such a configuration would give rise to a magnetic moment of -0.264 nm. This is to be compared with the experimental value of -0.21050 ± 0.00002 nm, subject to a possible hyperfine anomaly. (Such corrections are normally less than 0.5%.) It is of interest to compare this result with those found for neighboring nuclei with $(p_{\frac{1}{2}})^1$ configurations as ground states. Of such isotopes, Y^{89}, Rh^{103}, Ag^{107}, Ag^{109}, and Ag^{111} have moments measured to be [18–20] -0.137, -0.088, -0.113, -0.130, and -0.145 nm, respectively. It is seen that although all of these moments are in qualitative agreement with the Schmidt value quoted above, that of In^{113m} lies closest to the shell-model value.

The hyperfine separation in the atomic $P_{\frac{1}{2}}$ ground state is found to be 781.084 ± 0.010 Mc/sec.

ACKNOWLEDGMENT

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[18] E. Brun, J. Oeser, H. H. Staub, and C. G. Telschow, Phys. Rev. **93**, 172 (1954).
[19] P. B. Sogo and C. D. Jeffries, Phys. Rev. **98**, 1316 (1955).
[20] G. K. Woodgate and R. W. Hellwarth, Proc. Phys. Soc. (London) **A69**, 581 (1956).