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Nuclear Spins and Magnetic Dipole Moments of 50-Day In^{114m} and 54-Min In^{116m}[†][*]

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The nuclear spins and moments of 50-day In^{114m} and 54-min In^{116m} were measured in an atomic beam magnetic resonance apparatus. The spins were $5\hbar$ for both nuclides. Magnetic moments of 4.7±0.1 nuclear magnetons for In^{114m} and 4.4±0.1 nm for In^{116m} were obtained. Both moments are shown to be positive. Multiple-quantum transitions were observed, and their effect on the accuracy of the results is discussed.

IN the continuation of this laboratory's program of measurement of spins and moments of radioactive nuclei, the Zeeman structures of the hyperfine interaction of the nuclear species 50-day In^{114m} and 54-min In^{116m} have been studied in the atomic $P_{\frac{1}{2}}$ state. The atomic beam magnetic resonance apparatus has been described.[1]

A. THEORY OF THE METHOD

The theory of the method is that outlined in reference 1 and other papers referred to therein with the exception that a different method of determining the sign of the magnetic moment was used. This method is available for the isotopes studied because of the relatively small g_J of the $P_{\frac{1}{2}}$ state and the comparatively large nuclear magnetic moment of these species. The reduced Breit-Rabi equation applicable here is[2]

$$\Delta\nu=(\nu-g_Ik)(\nu-g_Jk)\bigg/\left[\left(\nu-\frac{g_Jk}{2I+1}\right)-\frac{2I}{2I+1}g_Ik\right], \quad (1)$$

where k is a measure of the external field, and the nuclear "g factor" is given by g_I. Equation (1) relates the hyperfine splitting $\Delta\nu$, the resonance frequency ν, and g_I. Within the limits of accuracy considered (neglecting hyperfine anomalies), one obtains[3]

$$\mu_I{}^A=\left(\frac{\Delta\nu^A}{\Delta\nu^{115}}\right)g_I{}^{115}I^A\left(\frac{2I^{115}+1}{2I^A+1}\right), \quad (2)$$

where A designates either isotope $114m$ or $116m$, which gives μ_I of the radioactive species in terms of I and the nuclear constants of an isotope of the same nuclear charge and atomic state (i.e., In^{115}). Because of the small value of g_J, one can show by direct substitution that only the assumption of a positive magnetic dipole moment will lead to a solution of Eqs. (1) and (2) at the resonance of highest frequency measured for both In^{114m} and In^{116m} (i.e., 30 Mc/sec).

B. EXPERIMENTAL

1. Preparation of Source

Sufficient specific activity of the 50-day In^{114m} was obtained by irradiating 5-mil foils of In in the Argonne CP-5 reactor for a period of six months. Approximately two grams per loading were used in the graphite oven from which the beam was obtained.

High levels of In^{116m} activity were produced by 3-hour irradiations of 25 mg of In foil. In order to reduce the handling time and exposure of personnel to this hot sample, the 25 mg of In was inserted into the graphite oven before irradiation and the loaded oven was placed in the high neutron flux.

2. Apparatus

Because of the high intensity of radiation present with the 54-min In^{116m}, extensive shielding and semi-remote handling equipment were required. This equipment and the relatively high temperature of the graphite oven necessary to produce a beam of indium necessitated extensive changes in the oven end of the apparatus:

(a) The previous design[1] of the machine was modified so that the oven mount rides on ways into the oven compartment. Mounted on this flange are the controls for lateral position, for the tilt of the slit and for the direction of the slit channel.

(b) Shields of lead and dense concrete block were used to minimize radiation hazard during loading of the oven and operation of the experiment with the 54-min In.

(c) The atomic magnetic moment of the $P_{\frac{1}{2}}$ state of In is $\frac{1}{3}$ that of the $S_{\frac{1}{2}}$ state of Cs atoms used in previous experiments. The smaller magnetic moment and the higher velocity (corresponding to higher oven temperatures) of the beam reduce the deflection attainable. This necessitated a reduction of the widths of the oven and collimating slits to three mils and the obstacle wire and collector slit to five and six mils respectively.

A bank of ten windowless gas-flow Geiger counters was constructed for use in these experiments. This allowed several collected samples to be counted simultaneously with high efficiency.

[†] Work performed under the auspices of the U. S. Atomic Energy Commission.

[*] For preliminary accounts of this work see L. S. Goodman and S. Wexler, Phys. Rev. **100**, 1245, 1796 (A) (1955).

[1] L. S. Goodman and S. Wexler, Phys. Rev. **99**, 192 (1955).

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[3] E. Fermi and E. Segrè, Z. Physik **82**, 729 (1933).

3. Collection and Counting of Radioactivity

To measure the intensity of the radioactive beam which passed through the detector slit, the atoms were deposited on a copper collector which was maintained at liquid nitrogen temperatures. Eight samples were collected at different settings of the radio-frequency and then withdrawn through vacuum locks and counted. In general, the counting rates at the resonance were 100–300 counts per minute. These counting rates were found after collection times of five minutes for the 54-min In^{116m} and 20 minutes for the 50-day In^{114m}. The signal-to-noise ratio varied from about three at 8 Mc/sec to two at the 30-Mc/sec resonance.

C. RESULTS AND CALCULATIONS

Resonances observed in In^{114m} and In^{116m} are listed in Tables I and II, respectively, along with the corresponding transitions in the nonradioactive In^{115} nuclide present in the beam. The measurement of the resonances near 8 Mc/sec was apparently straightforward and normal for the two radioactive isotopes. The spins of both In^{114m} and In^{116m} were unambiguously established as $5\hbar$ by the positions of these transitions.

In the vicinity of 14 Mc/sec, the resonance curves for normal In^{115} and for the radioactive species In^{114m} were quite steep at the low-frequency end and tapered off slowly on the high-frequency side. The observation was not attempted for In^{116m}. The shape and position of the peak for In^{115} were observed to be very sensitive to the radio-frequency power. In the vicinity of 30 Mc/sec, several rf peaks were observed with an In^{115} beam for a given setting of the homogeneous field. The strength of these resonances also was markedly sensitive to the rf power, and considerably more power was required than was originally estimated to observe any resonance at all. All of these resonances were much sharper than that at 8 Mc/sec. This peculiar behavior of In species is apparently connected with the fact that the only resonances which we were able to observe were the result of multiple-quantum transitions.[4] Because of the large hyperfine interaction of all of the isotopes used in the study, and the relatively low field (about 10 000 gauss) of our deflecting magnets, atoms in states taking part in the normal Zacharias-type "flop-in" resonance were not refocusable. The state with $m_F=-(F-1)$ (and perhaps a few states above it) has too small an effective magnetic moment in a field of 10 000 gauss to be appreciably deflected in our apparatus. Deflections are sufficient to allow refocusing only for transitions between the state with $m_F=-F$ and those other states of the hyperfine pattern with $F=I+J$ which have relatively high effective magnetic moments in the deflecting fields. In the present apparatus, identification of the states taking part in the observed multiple-quantum transitions is very difficult.

TABLE I. Observed transition frequencies in In^{114m} and In^{115}.

ν^{114m} (Mc/sec)	ν^{115} (Mc/sec)
7.299 ± 0.020	8.000 ± 0.010
14.650 ± 0.020	16.061 ± 0.020
27.847 ± 0.020	30.455 ± 0.020

$\Delta\nu^{114m}=9700\pm200$ Mc/sec; $\mu^{114m}=+4.7\pm0.1$ nm

In the case of the resonance of lowest frequency measured, the one from which the spin was determined, the Zeeman levels are approximately equally spaced and the frequency of the multiple-quantum transition is practically identical with the normal "flop-in" frequency. The fact that only multiple-quantum transitions are observable does not, therefore, cause any complication in the determination of the spin.

At higher homogeneous magnetic fields, where multiple-quantum transitions of different order were separable (and several were observed in normal indium at different values of the rf power), there was no way to be sure that the resonance peak of the radioactive isotope was of the same multiplicity as that of the peak of In^{115} used for calibration. However, for a given rf power and a given setting of the homogeneous field, prominent resonances were observed at two frequencies near 30 Mc/sec for both of the radioactive isotopes and for the normal In^{115}. A large change in rf power could change the signal-to-noise ratios of the two peaks. Consequently, in a search for the resonances of a radioactive isotope, the rf power level was maintained the same as that used for setting the homogeneous field with the In^{115} resonance. Two prominent resonances were then observed with approximately the same signal-to-noise ratios as two corresponding resonances in In^{115}. It is *assumed* that the resonances in the active species were of the same multiple-quantum order as the corresponding ones in In^{115}. With the aid of this assumption it is then possible to calculate the hyperfine interaction and the magnetic dipole moment, and to determine the sign of the magnetic moment. The hyperfine structure constant is thereby estimated to be 9700 ± 200 Mc/sec for the 50-day In^{114m} isotope and 9000 ± 200 Mc/sec for 54-min In^{116m}. Using the Fermi-Segrè relation[3] between hfs and magnetic moment, μ_I of In^{114m} is calculated to be 4.7 ± 0.1 nm and μ_I of In^{116m} 4.4 ± 0.1 nm. From the arguments presented in Sec. A, the nuclear moments of both species are positive. If the

TABLE II. In^{115} and In^{116m} transition frequencies.

ν^{116m} (Mc/sec)	ν^{115} (Mc/sec)
7.298 ± 0.020	8.000 ± 0.010
27.934 ± 0.020	30.455 ± 0.020

$\Delta\nu^{116m}=9000\pm200$ Mc/sec; $\mu^{116m}=4.4\pm0.1$ nm

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[4] P. Kusch, Phys. Rev. **101**, 627 (1956); **93**, 1022 (1954). He has studied multiple-quantum transitions in potassium. Theoretical treatments have been given by H. Salwen, Phys. Rev. **99**, 1274 (1955); M. N. Hack, Phys. Rev. **104**, 84 (1956); and Besset, Horowitz, Messiah, and Winter, J. phys. radium **15**, 251 (1954).

order of the multiple-quantum transitions differs by one unit, the values of the hyperfine interactions and the magnetic moments will be in error by about 10%, but the sign of the moment would not be affected.[5]

It is difficult to justify rigorously the assumption that the multiple-quantum order is the same for the two species. One might expect that, since the spins and hyperfine interactions of all three isotopes are of comparable size, the refocussing conditions and transition probabilities might be similar. Although the theory of the multiple-quantum transitions has been investigated, the multiple resonances observed in the present experiment are not well enough separated to make the theory in its present state readily applicable.[4]

D. DISCUSSION

According to the shell model of the nucleus, the most probable proton-neutron configuration of both of the odd-odd indium isotopes studied is $g_{\frac{1}{2}}$, $s_{\frac{1}{2}}$.[6] In order to estimate the magnetic moment of this configuration, one assumes that the values of the intrinsic magnetic moments of the nucleons in the free state are largely suppressed when the nucleons are bound in the nucleus.[7] It is further taken without proof that the amount of suppression is the same as in nuclei in the same states in neighboring odd-even and even-odd nuclei. The calculation is then carried out in the standard manner.[8]

For the estimation of the magnetic moments of In^{114m} and In^{116m} the intrinsic moment for the $g_{9/2}$ proton hole was calculated from the measured moment of In^{115} The intrinsic moment of the odd neutron ($s_{\frac{1}{2}}$ state) was taken from Sn^{117}. The moment calculated in this manner is $\mu=4.5$ nm for both radioactive nuclides, in good agreement with our experimental values (Tables I and II).

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[5] In a concurrent independent determination, P. B. Nutter [Phil. Mag. 1, 587 (1956)] also found $I^{116m}=5\hbar$ and $\mu^{116m}=+4.21\pm0.08$ nm.

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[7] F. Bloch, Phys. Rev. 83, 839 (1951). See also H. Miyazawa, Progr. Theoret. Phys. Japan 6, 263 (1951) and A. de-Shalit, Helv. Phys. Acta 24, 296 (1951).

[8] E. H. Bellamy and K. F. Smith, Phil. Mag. 44, 33 (1953).

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Formation of Cd^{115} Isomers in High-Energy Fission of Bismuth*

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The relative yields and recoil properties of the Cd^{115} isomers independently formed in the 450-Mev proton fission of bismuth have been measured. The 43-day Cd^{115m} isomer has a higher yield and smaller range than the 53-hr Cd^{115}. Cd^{115m} is also formed in a higher deposition energy process than Cd^{115}. These results are explained in terms of the high-spin states of the fission fragments resulting both from the high bombarding energy and from the fission act proper.

I. INTRODUCTION

THE formation of isomeric pairs has been studied in a variety of nuclear reactions over a wide range of bombarding energies.[1–9] The relative yield of the two isomers has been found to depend on the spin of the excited product nucleus prior to the gamma-ray cascade by which the latter de-excites to the observed isomers.[1] The isomer formed predominantly is the one with spin closest to that of the excited product nucleus. The spin of the latter depends in turn on a number of factors such as the spin of the target nucleus, and the spin and orbital angular momentum of the bombarding particle and of any ejected particles. For reactions induced by thermal neutrons, the spin of the target nucleus is the controlling factor in determining the spin of the excited product nucleus.[2] As the bombarding energy is increased, the compound nucleus can be formed in higher angular momentum states and the ensuing evaporation of nucleons can finally lead to a wide range of spin states of the excited product nucleus.[8] This situation is reflected in the large variation in relative yield of isomers that has been observed for different reactions and bombarding energies.[3–8] As the bombarding energy is raised beyond the range of

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