Spin and Nuclear Moments of 2.3-Day Cd^{115} and of 43-Day Cd^{115m}†

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The Zeeman structure and hfs in the $(5s5p)^3P_1$ state of 2.3-day Cd^{115} and 43-day Cd^{115m} have been determined by the optical double-resonance technique. The nuclear spin I, magnetic dipole coupling constant A, and electric quadrupole coupling constant B, are: $I(115)=1/2$, $A(115)=-4484(2)$ Mc/sec; $I(115m)=11/2$, $A(115m)=-657.6(6)$ Mc/sec, $B(115m)=+131(6)$ Mc/sec. If nuclear structure and quadrupole shielding effects are neglected, the corresponding nuclear moments are: $\mu(115)=-0.6469(3)\mu_N$, $\mu(115m)=-1.0437(10)\mu_N$, $Q(115m)=-0.61(8)$ b. The ratio of the Cd^{115m} and Cd^{109} quadrupole moments is $Q(115m)/Q(109)=-0.79(3)$; this result is independent of shielding corrections. The Cd^{115} nuclear moment is compared with the moment predicted for a $(3s_{1/2})^1(1h_{11/2})^2$ neutron assignment with cofiguration mixing. The Cd^{115m} moment is compared with the moments predicted for both a $(3s_{1/2})^0(1h_{11/2})^3$ and a $(3s_{1/2})^2(1h_{11/2})^1$ assignment. Both isomers were produced by (n,γ) reactions on Cd^{114}. The longer-lived isomer, 43-day Cd^{115m}, was separated from the Cd^{114} with an electromagnetic mass separator; about 10^{11} atoms were obtained in the resonance cell. No mass separation was performed on the Cd^{115}, but it was identified from the decay of the resonances over a 6-day period. The half-life deduced from the observed decay is $T_{1/2}=41(7)$ h, as compared with the accepted value of 56 h.

I. INTRODUCTION

THIS is the fourth in a series of papers devoted to the nuclear spins and moments of the radioactive isotopes of the Group II elements.[1–3] Previously we have reported on Cd^{109} (Ref. 1), Cd^{107} (Ref. 2), and Zn^{65} (Ref. 3). In this paper we report on 2.3-day Cd^{115} and 43-day Cd^{115m}.

The ground state of the Group II elements is $(ns^2)^1S_0$ and exhibits no hfs. However, the metastable $(nsnp)^3P_1$ state has both magnetic dipole and electric quadrupole hfs interactions and may be studied by the optical double-resonance technique.

The neutron shell-model configuration in Cd^{115} is $(2d_{5/2})^6(1g_{7/2})^8(3s_{1/2})^m(1h_{11/2})^n$ in addition to a magic core of 50 neutrons, where $m+n=3$. The order in which the $3s_{1/2}$ and $1h_{11/2}$ shells are filled depends on both the single-particle and pairing energies. The single-particle energy of the $3s_{1/2}$ neutron level is slightly less than that of the $1h_{11/2}$ level. If we denote this difference by ΔW and the difference between the pairing energies in these two states by ΔP, then the $(3s_{1/2})^1(1h_{11/2})^2$ configuration will have the lowest energy if $\Delta P>\Delta W$. Experimentally, one finds that the ground states of the odd neutron neuclei in that portion of the periodic table where the $1h_{11/2}$ shell is partially filled have spin one-half.[4] This demonstrates conclusively that $\Delta P>\Delta W$, and we therefore would expect $I(115)=1/2$.

The neutron assignment in the isomeric state may be either $(3s_{1/2})^0(1h_{11/2})^3$ or $(3s_{1/2})^2(1h_{11/2})^1$, both of which can yield an 11/2 spin. The former configuration will be favored if $\Delta P>2\Delta W$. The value of ΔW may be estimated from Cd^{113} where a single neutron is excited from the $(3s_{1/2})$ ground state to a $(1h_{11/2})$ metastable state giving $\Delta W=0.26$ MeV. The pairing energy in a level may be estimated from the binding energy of successive isotopes where only a single shell is filling.[5] Thus the pairing energy $P(nl_J)$ is given by $P(1h_{11/2})=\mathrm{BE}(Cd^{112})+\mathrm{BE}(Cd^{114})-2\mathrm{BE}(14\text{-yr } Cd^{113m})=2.0(6)$ MeV. This is in good agreement with the theoretical estimate of Noya, Arima, and Horie, who find $P(1h_{11/2})=2.09$. Using their model we find $P(3s_{1/2})=1.40$ MeV. This gives $\Delta P=0.7$ MeV, so that in fact we believe that $\Delta P>2\Delta W$ and that the configuration $(3s_{1/2})^0(1h_{11/2})^3$ is favored for the $I=11/2$ state of Cd^{115}. The moments predicted for these configurations on the basis of the shell model with configuration mixing are compared with our experimental results in Sec. IV.

The major difference between previous experiments[1–3] and the present one is in the preparation of the sample. It was necessary to produce Cd^{115} by neutron bombardment of Cd^{114}, as there are no stable isotopes of silver with higher mass than Ag^{109} nor of palladium with higher mass than Pd^{110}, precluding proton, deuteron, and alpha-particle bombardment.

It is possible to produce more than enough material for an optical double-resonance experiment with neutron irradiation, but in general, the isotopic enrichment will be too low. As discussed in Ref. 1, we require enrichments of at least one part in 10^7 for spin-1/2 isotopes and of at least one part in 10^4 for spin-11/2 isotopes. This requirement arises from the fact that the stable isotope scatters the light as effectively as the radioactive isotope. This scattered light contributes to the noise and possibly reduces the signal through trapping of the reso-

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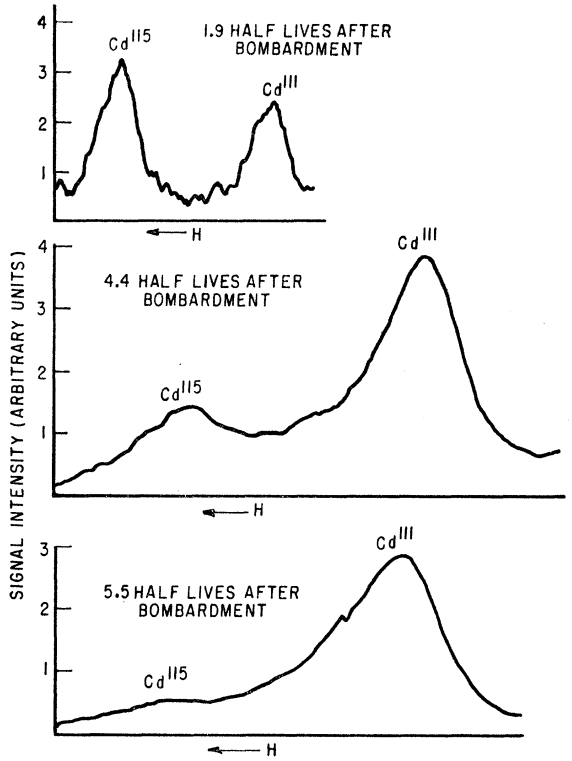

FIG. 1. Observed decay of the (3/2,3/2)↔(3/2,1/2) Zeeman resonance of Cd^{115}. The decay indicates an apparent half-life of 41(7) h.

nance radiation. In the case of high-spin isotopes the signal is further reduced by the large multiplicity of levels.

As indicated in Sec. II, the enrichment of the 43-day isomer resulting from pile irradiation was about two parts in 10^4. As this enrichment was believed to be barely sufficient, the sample was further enriched with an electromagnetic mass separator. The Argonne separator used is believed to have a resolution of 1 part in 1000 with respect to Cd^{114}, and we would expect an enrichment of 6 parts per hundred in the final sample.

II. EXPERIMENTAL

A. Production and Identification of 2.3-Day Cd^{115} and 43-Day Cd^{115m}

The isomers were produced by neutron irradiation in the AEC Materials Testing Reactor at Idaho Falls, Idaho. The target consisted of 15 mg Cd^{114}, obtained in metallic form from ORNL and sealed under vacuum in a quartz ampule. The expected enrichments were 1 part in 10 000 for 2.3-day Cd^{115}, and 2 parts in 10 000 for 43-day Cd^{115m}.

After irradiation the ampule used in the 2.3-day Cd^{115} experiment was cleaned, broken, and placed in the vacuum distillation system, described in Ref. 2, and all of the cadmium was distilled into the quartz resonance cell. The chemical identity of the sample is assured by the resonance fluorescence.[1] The isotopic identity is confirmed by the decay. Figure 1 shows the observed decay of the (3/2,3/2)↔(3/2,1/2) Zeeman transition assigned to Cd^{115}; here the resonance amplitude was normalized to a Cd^{111} resonance in the same bulb. From the slope of this curve we find an apparent half-life of 41(7) h as compared with the accepted value $T_{1/2}=56$ h.[6] This agreement is believed to be sufficiently good to assure the identification of the isotope.

For the reasons given previously the 43-day isomer was separated from the Cd^{114} target. In the separator the atoms were deposited on a vacuum baked platinum foil over a region 2.7 mm wide; the Cd^{114} image was displaced by 12 mm. Counting measurements 32 days (0.7 half-lives) after irradiation indicated that 4×10^{12} atoms of Cd^{115} had been deposited on the foil, implying a 0.1% over-all mass separator efficiency.

The narrow region of the foil containing the Cd^{115m} was placed in the vacuum distillation system,[2] and the cell preparation procedure described in Ref. 2 was followed. Further counting measurements on the cell indicated that 1.5×10^{11} atoms had been transferred. We believe that this low recovery, as compared with 85% in distillation from silver filings,[2] resulted from the trapping of the cadmium atoms in the platinum lattice.

The isotopic identity of the Cd^{115m} is assured by the mass separation and by the observation of the nuclear decay modes.[7] The 43-day Cd^{115m} decays partially through the 1.30- and 0.935-MeV states of In^{115}. Two strong γ-ray lines at these energies were observed with a scintillation spectrometer which had been calibrated with the 1.274-MeV Na^{22} line. The number of atoms in the cell was estimated by comparing the intensity of the indium lines with that from a calibrated Na^{22} source. The 2.3-day Cd^{115} in this sample had decayed to a negligible amount in the 36-day interval between reactor shut-down and the double-resonance observations. Observations of the double-resonance spectrum assigned to Cd^{115m} over a 2-month interval indicated a decay consistent with a 43-day half-life.

B. Double-Resonance Apparatus and Method

The apparatus was the same as that used in Ref. 3. As before, unpolarized light directed along the magnetic field was used to excite the atoms; this produced only σ excitation ($\Delta M=\pm1$). The detector polarizer was oriented to accept only π light.

In part of this work we used a lamp containing stable cadmium to illuminate the scattering cell. Unfortunately, the isotope shifts and hfs of Cd^{115} and Cd^{115m} are sufficiently large so that some of the hyperfine levels receive little illumination. In Fig. 2 we show the centers of the lines arising from the stable isotopes and those

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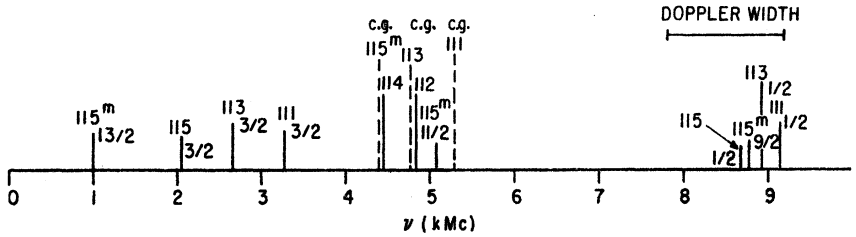

FIG. 2. Hfs and expected isotope shifts in the $^3P_1$ state of cadmium.

expected for Cd^{115} and Cd^{115m}. If the spectral width of the lamps is no more than two Doppler widths,[2] it is evident that a natural lamp will illuminate only the central state of Cd^{115m} and will weakly illuminate the $F=3/2$ state of Cd^{115}. A lamp containing separated Cd^{113} will illuminate the $F=13/2$ and $F=9/2$ states of Cd^{115m} and both hfs states of Cd^{115}. Separated Cd^{113} from ORNL and Harwell, England, was used in the construction of Cd^{113} lamps used in this work. Unfortunately, even with these lamps only some of the Zeeman transitions in Cd^{115m} were adequately illuminated. Transitions between levels which were Zeeman shifted away from the $F=3/2$ Cd^{113} line were not observable.

C. Sensitivity

The limiting sensitivity of the optical double-resonance technique has been discussed in Ref. 1. It is of interest to compare the estimates there with the signals observed in the present experiment.

Double-resonance observations were made in Cd^{115m} 36 days after bombardment. Figure 3 shows the $(11/2,11/2)\leftrightarrow(11/2,9/2)$ Zeeman resonance at a magnetic field of 300 G where a signal-to-noise ratio of seventy-four was achieved. The formulas of Ref. 1 give 0.013 as the ratio of the intensity of this resonance to that in a spin-zero isotope. The observation of signals from 1.5×10^{11} atoms of Cd^{115m} would then correspond to observations of 5×10^7 even isotope atoms with a signal-to-noise ratio of 2. This is larger by 10 than the results obtained under the best possible conditions with a bulb containing stable cadmium.[1] In the Cd^{115m} cell, signals arising from the spin-zero isotopes were a factor of forty thousand stronger than the Cd^{115m} signals. This indicates that in spite of our precautions the bulb was contaminated with about 10^{14} stable cadmium atoms. The atomic scatter and radiation trapping produced by these atoms may account for the tenfold decrease in the Cd^{115m} signal.

The predicted enrichment of the Cd^{115} sample was 1.1×10^{-4}. The Cd^{113} present in the target was completely changed to Cd^{114} as a result of the large thermal neutron cross section for the $Cd^{113}(n,\gamma)Cd^{114}$ reaction. Thus the only stable odd isotope present in the target was Cd^{111}, specified by ORNL as 0.05% of the original Cd^{114} sample. As in the case of Cd^{115m} we used a Cd^{113} lamp to enhance the Cd^{115} signals with respect to those from the stable isotopes. The temperature of the cell was adjusted until the best signal-to-noise ratio was obtained. Under these conditions, the Cd^{115} signal was enhanced relative to the Cd^{111} signal presumably because of radiation-trapping effects. Thus while the ratio of the Cd^{115} to Cd^{111} in the cell was 1:10, the ratio of the signals could be increased to 3.5:1 by heating. Figure 4 shows the intensity of the $(3/2,3/2)\leftrightarrow(3/2,1/2)$ transition in the two isotopes plotted as a function of temperature. The maximum signal-to-noise ratio for Cd^{115} was about 40, and at the time the observations were made the enrichment was 50 parts per million. This corresponds to a spin-zero isotope observation with a signal-to-noise ratio of two and an enrichment of about 5 parts in 10^7. Thus by exploiting the isotope shifts and the radiation-trapping effects we were able to observe useful signals in an extremely dilute sample.

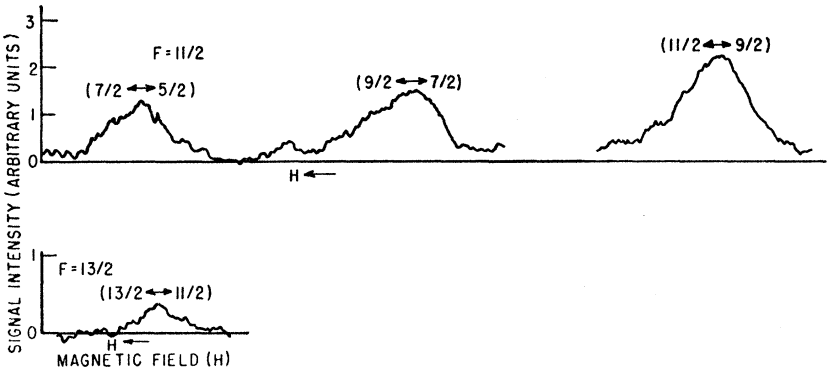

FIG. 3. Observed Zeeman resonances in Cd^{115m}.

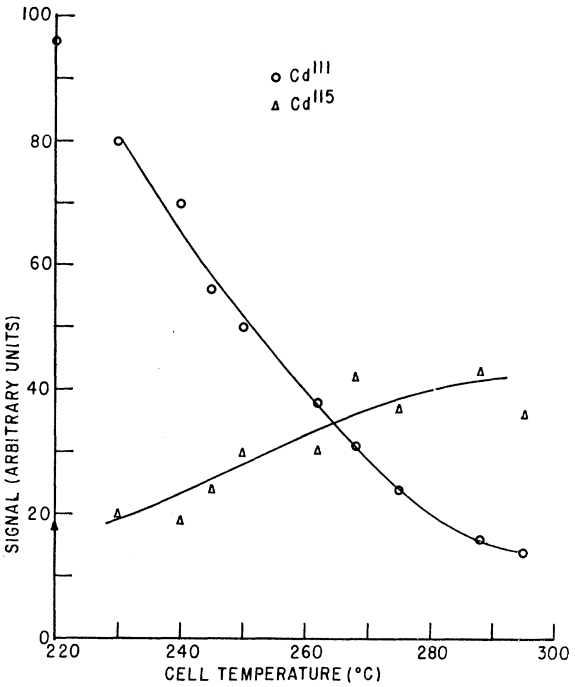

FIG. 4. Zeeman signals from Cd^{115} and Cd^{111} as a function of cell temperature.

III. OBSERVATIONS

A. Cd^{115} Spin and Magnetic Dipole Interaction

Low-field Zeeman transitions were observed in the Cd^{115} cell at fields corresponding to $g_F/g_J=2/3$ and at no others. Such a Zeeman spectrum can be produced only in the $F=3/2$ state which occurs when the nuclear spin is one-half. Population differences cannot be produced in the $F=1/2$ state by the optical double-resonance technique employed here, so that transitions in this state are unobservable. Unfortunately, since stable Cd^{111} also has $I=1/2$, it was necessary to extend the observations into the intermediate-field region to separate the Cd^{111} and Cd^{115} spectra. At magnetic fields of about 300 G, two resonances were observed in the neighborhood of the $(3/2,3/2)\leftrightarrow(3/2,1/2)$ Zeeman transition. One of these agreed exactly with the known spectrum of Cd^{111}, and the other was identified as a Cd^{115} resonance through the rate at which it decayed. No resonances attributable to Cd^{113} were observed in this work, in agreement with our expectations based on the known large Cd^{113} thermal neutron cross section. The $(3/2,-3/2)\leftrightarrow(3/2,-1/2)$ transition was Zeeman shifted beyond the lamp spectrum. These observations definitely establish the Cd^{115} nuclear spin as $I=1/2$. This is in agreement with the earlier assignment based on the $\log(ft)$ value of the nuclear decay.[7]

Transitions observed with circularly polarized light, shown in Fig. 5, indicated that the Cd^{115} hfs is inverted.[1,2] Thus the nuclear magnetic moment is negative, and the last odd neutron is in a state with $I=l+1/2$. This is in agreement with the $s_{1/2}$ shell-model assignment.

The intermediate-field dependence of the transition implied a magnetic dipole interaction constant of $A(115)=-4484(2)$ Mc/sec. This result has not been corrected for cross-Zeeman hyperfine interaction with the $^3P_2$ and $^3P_1$ fine structure states. This interaction is much smaller than the uncertainty of the measurement.

B. Cd^{115m} Spin and Hyperfine Interaction Constants

Low-field Zeeman transitions were observed at fields corresponding to $g_F/g_J=2/13$, $2/11$, and $4/143$, establishing the spin of Cd^{115m} uniquely as $I=11/2$, in agreement with the earlier assignment based on the $\log(ft)$ value of the nuclear decay.[7]

Transitions observed in the $F=13/2$ state with circularly polarized light indicated that the Cd^{115m} hfs is inverted. Thus the nuclear magnetic moment is negative, and the last odd neutron is in a state with $I=l+1/2$. This is in agreement with the $h_{11/2}$ shell-model assignment.

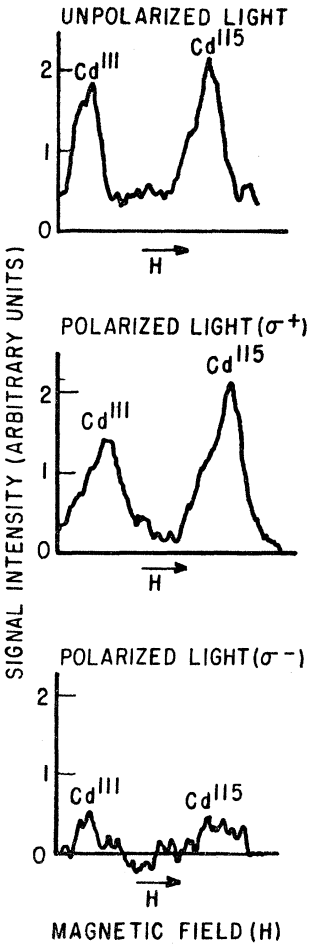

FIG. 5. Circular polarization observations of the $(3/2,3/2)\leftrightarrow(3/2,1/2)$ Zeeman transition in Cd^{115}. These resonances indicate that the $^3P_1$ hfs of Cd^{115} is inverted.

We observed individual intermediate-field Zeeman resonances in the $F=11/2$ and $F=13/2$ states at two different magnetic fields. The transition intensities in the $F=9/2$ state were too small to observe at intermediate field. The observations gave

$$A(115m)=-657.6(6)\ \text{Mc/sec},$$
$$B(115m)=+131(6)\ \text{Mc/sec}.$$

These results have not been corrected for perturbations from neighboring fine structure states.

IV. NUCLEAR MOMENTS AND COMPARISON WITH THEORY

The magnetic moments can be determined from $A(115)$ and $A(115m)$ if we neglect the effect of finite nuclear size. That is, we assume the ratio of the nuclear g factors of 2 isotopes is equal to the ratio of their A factors. For $A(111)=-4123.81(1)$ Mc/sec[8] and $\mu(111)=-0.59501(8)\mu_N$,[9] we find

$$\mu(115)=\mu(111)\left[\frac{I(115)}{I(111)}\right]\left[\frac{A(115)}{A(111)}\right]=-0.6469(3)\mu_N,$$

and

$$\mu(115m)=\mu(111)\left[\frac{I(115m)}{I(111)}\right]\left[\frac{A(115m)}{A(111)}\right]$$
$$=-1.0437(10)\mu_N.$$

The stated uncertainties are based solely on the uncertainties of $A(115)$ and $A(115m)$.

The ratio $Q(115m)/Q(109)$ is just the ratio $B(115m)/B(109)=-0.79(3)$ where the value of $B(109)$ is taken from the level-crossing work.[10] This value is independent of shielding corrections. The details of the connection between the quadrupole interaction in the $^3P_1$ state of cadmium and the nuclear quadrupole moment are discussed in Ref. 1. Using the ratio of the quadrupole moments and taking $Q(109)=+0.78(10)$ b,[1] we find $Q(115m)=-0.61(8)$ b.

The most successful model for predicting the nuclear moments in the medium mass nuclei is the shell model with configuration mixing.[5] If we use the value of the pairing energy parameter which best fits the binding energy data in this region, $C=30$ MeV, we find for Cd^{115} $\mu=-1.02\ \mu_N$.

As discussed earlier, there are two possible neutron configurations for Cd^{115m}: $(3s_{1/2})^2(1h_{11/2})^1$ and $(3s_{1/2})^0(1h_{11/2})^3$. The moment estimated for the former is $\mu=-1.37\mu_N$, and that for the latter is $\mu=-1.22\ \mu_N$. On the basis of the estimates of the pairing and single-particle energies we expect that the $(3s_{1/2})^0(1h_{11/2})^3$ assignment is favored. It would be satisfying if the moment predicted for one of the configurations was in good agreement with the experiment, while that predicted for the other was in disagreement. Unfortunately, both of the theoretical moments are in such poor agreement with experiment that we cannot make a definite assignment on the basis of the moments.

The Cd^{115m} quadrupole moment will be discussed in a later paper.

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