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Spin and Nuclear Moments of 6.7-Hour Cd^{107}†

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The Zeeman and hyperfine structure of the $(5s5p)\ ^3P_1$ state of 6.7-h Cd^{107} has been determined by optical double resonance. Positive identification of the isotope was obtained through the observation of the decay of the Zeeman resonance signals. The nuclear spin (I), magnetic hyperfine-structure coupling constant (A), and the quadrupole coupling constant (B), are $I=\frac{5}{2}$, $A(^3P_1)=-854.2\pm1.0$ Mc/sec, and $B(^3P_1)=-166\pm3$ Mc/sec. Neglecting possible hyperfine structure anomalies and quadrupole shielding effects, the corresponding nuclear moments are $\mu_{107}=-0.6162(8)\ \mu_N$ and $Q_{107}=+0.77(10)$ b. These moments are compared with the predictions of the configuration mixing model of Noya, Arima, and Horie. The ratio of the Cd^{107} and Cd^{109} quadrupole moments is $Q_{107}/Q_{109}=0.993(20)$; this result is independent of the shielding corrections.

I. INTRODUCTION

The measurement reported here[1] is the second in a series directed toward a determination of the nuclear spins and moments of the isotopes of cadmium and zinc. The first paper,[2] hereafter referred to as I, deals with 470-day Cd^{109}. In this paper we report on the determination of the spin and moments of 6.7-h Cd^{107}. The optical double-resonance technique that was used in this work is described in I. The electronic ground state of cadmium and the other Group II elements is $(ns^2)\ ^1S_0$, making them unsuitable for atomic-beam studies. The $(nsnp)\ ^3P_1$ state is optically connected to the ground state with a weak electric dipole transition. This state exhibits both magnetic dipole and electric quadrupole hyperfine structure. In the case of cadmium, the $(5s^2)\ ^1S_0 \leftrightarrow (5s5p)\ ^3P_1$ transition occurs at 3261 Å with an oscillator strength[3] $f=0.002$. The corresponding double-resonance linewidth is about 130 kc/sec, allowing precise determination of the hyperfine structure of the $^3P_1$ state. Cadmium is relatively inert and can be easily handled in quartz without appreciable loss of material, making it possible to produce resonance scattering cells with very small samples.

There are eleven known isotopes and isomers of cadmium with nonzero nuclear spin and half-lives of about 1 h or more. It is hoped that the double-resonance technique can be successfully applied to many of these cases. The detailed study of the moments in such a sequence should be particularly instructive. It is especially important to note that such a series of measurements will provide precise values for the ratios of the nuclear quadrupole moments. These ratios would, of course, be independent of the large uncertainties in the theoretical value of the atomic electric field gradient at the nucleus.

The important differences between this experiment and the similar one on Cd^{109} arise primarily from the much shorter half-life of Cd^{107}, 6.7 h[4] as compared to 470 days.[5] The new techniques of production and handling which were required are discussed in detail.

II. EXPERIMENTAL TECHNIQUES

A. Isotope Production

It is essential in the double-resonance technique to obtain a high concentration of the desired isotope in the scattering bulb. A substantial contamination of stable cadmium will seriously interfere with the observation of the radioactive isotope by trapping of the resonance radiation and by increasing the background light (see I). Even if we neglect the unfavorable differential illumination effects that result from the use of stable cadmium in the light source, we must contend with the fact that the high spin of Cd^{107} greatly reduces the intensity of the individual Zeeman resonances. The strongest intermediate field Zeeman resonance in Cd^{107} is a factor of seventy less intense than the corresponding resonance in an equal number of spin-zero atoms.

In order to achieve the chemical and isotopic purity required in this experiment, we produced the Cd^{107} by bombarding very high purity silver with 11-MeV protons. The Cd^{107} produced by the reaction $Ag^{107}(p,n)Cd^{107}$ was separated from the silver by vacuum distillation. Counting measurements indicated that 10^{14} atoms (0.02 μg) of Cd^{107} were produced in the bombardment. Great care was required in the preparation and handling of the silver target to prevent contamination by comparable quantities of stable cadmium. Considerable experimentation was required to develop the techniques that were ultimately successful. In the course of this

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[1] First reported by M. N. McDermott, F. Byron, Jr., and R. Novick, in Bull. Am. Phys. Soc. **7**, 25 (1962).

[2] M. N. McDermott and R. Novick, Phys. Rev. **131**, 707 (1963).

[3] F. Byron, Jr., M. N. McDermott, and R. Novick, Bull. Am. Phys. Soc. **7**, 26 (1962).

[4] L. A. Delsasso, L. N. Ridenour, R. Sherr, and M. G. White, Phys. Rev. **55**, 113 (1939).

[5] J. R. Gum and M. L. Pool, Phys. Rev. **80**, 315 (1950).

work we attempted to make "empty" cells. In spite of all of our precautions, we were never able to make a cell that was completely free of stable cadmium; Zeeman resonances were observable in every cell that was properly evacuated.

The cross sections[6] for $Ag^{107}(p,n)Cd^{107}$ and $Ag^{109}(p,n)Cd^{109}$ are nearly equal at the proton energy that was available for this work. Since natural silver is composed[7] of 51.35% Ag^{107} and 48.65% Ag^{109}, a (p,n) reaction on natural silver will produce nearly equal amounts of Cd^{107} and Cd^{109}. This caused some concern initially since it was expected that the two isotopes would have the same spin and comparable magnetic moments. The identity of the spins implies that the low-field Zeeman spectra of the two isotopes are indistinguishable. This clearly complicates the spin determination. If the magnetic moments and quadrupole moments are nearly equal, then the intermediate field Zeeman resonances can only be resolved at large values of the magnetic field. It can be readily shown that if the magnetic moments differ by only 1%, then the Zeeman patterns for the two isotopes become resolved at fields greater than about 100 G. Accordingly, new coils capable of producing fields of about 250 G were constructed and installed on the apparatus. In addition, two runs were made with a cyclotron target made from separated (99.6%) Ag^{107}. Unfortunately, only 100 mg of Ag^{107} was available in the form of a metallic powder. The yield of Cd^{107} from this target was not sufficient and we resorted to a natural silver target.[8] The moments of Cd^{107} and Cd^{109} turned out to be sufficiently different so that the spectra were clearly resolved at fields of about 100 G.

The target was normally exposed to a total charge of some 400 μA-h which resulted in Cd^{107} activities of the order of 400 mCi. This yield was in reasonable agreement with an extrapolation of the yield calculations of Martin *et al.*[9] for 22-MeV protons. The intensities of the double-resonance signals in Cd^{107} and Cd^{109} were roughly equal after a correction for the decay of Cd^{107}, which indicated that the two isotopes were produced in equal amounts as expected. The Cd^{107} activity can easily be distinguished from that for Cd^{109} since Cd^{107} has a 0.32% positron branch[10] lacking in Cd^{109}. A sodium-iodide crystal spectrometer and single-channel analyzer were used to make the identification. The activity produced was estimated by comparing the number of annihilation gamma rays from the Cd^{107} and from a calibrated Na^{22} source.

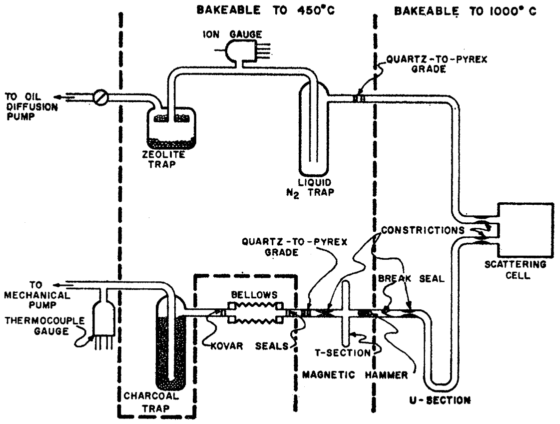

FIG. 1. Vacuum apparatus used for preparing scattering cells.

B. Scattering Cell Preparation

The target adopted is a solid $\frac{3}{4}$-in.-diam silver slug with one end milled at a small angle to the axis. After it is machined the slug is placed in a quartz vessel and baked under vacuum at 850°C for 12 h. Upon completion of the baking the vessel is sealed off while still hot and under vacuum. At 850°C the vapor pressure of cadmium is in excess of two atmospheres so that surface contamination is quickly removed. It is also quite likely that any cadmium contamination originally present in the 0.005-in.-thick surface layer where the activity is produced is significantly reduced.[11]

Shortly before the slug is to be bombarded it is removed from the quartz container and soldered to a water-cooled copper probe. The solder used is a silver-copper eutectic and the soldering operation is carried out in a hydrogen atmosphere. At no time after removing the slug from the quartz capsule is it necessary to handle the surface to be bombarded.

Upon completion of a bombardment the surface of the silver exposed to the proton beam is filled until about three-quarters of the activity is removed. The file used is cleaned and baked under vacuum at 600°C prior to use. In practice the total amount of silver removed is always less than 0.5 g. This weight corresponds to the removal of a uniform surface layer of 0.005 in. or less.

The filings are transferred to a quartz vacuum system illustrated schematically in Fig. 1. The quartzware is baked under vacuum for at least 24 h at 400°C before a run and the part of the apparatus near to and including the scattering cell is given an additional bake at 1000°C for 12 h. The *T* section is blown open immediately before the silver filings are introduced and is sealed shut immediately afterward. The quartz break-seal allows the filings to be introduced without break-

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[6] J. P. Blaser, F. Boehm, P. Marmier, and D. C. Peaslee, Helv. Phys. Acta **24**, 3 (1951).

[7] J. R. White and A. E. Cameron, Phys. Rev. **74**, 991 (1948).

[8] The silver was obtained from Cominco Products, Inc., Spokane, Washington, and was specified to have a cadmium contamination of less than 1 part in 10^7.

[9] J. A. Martin, R. S. Livingston, R. L. Murray, and M. Rankin, Nucleonics **13**, 28 (1955).

[10] H. Bradt, P. C. Gugelot, O. Huber, H. Medicus, P. Preiswerk, and P. Scherrer, Helv. Phys. Acta **18**, 351 (1945).

[11] We calculate a reduction of a factor of 5 in the cadmium concentration up to a depth of 0.005 in., based on the diffusion coefficient $D=8\times10^{-9}$ cm²/sec [W. Seith and E. Peretti, Z. Elektrochem. **42**, 570 (1936)].

ing the vacuum in the cell. When a good fore-pump vacuum is achieved in the *T* section, the section is sealed off from the pump and the break-seal is opened. The cadmium can then be driven from the silver filings by heating the bottom of the *T* section with either a hand torch or a small oven. The activity is distilled from the *T* section to the *U* section and the *T* section is removed. After the final distillation from the *U* section into the cell, the *U* section is removed. The activity is followed at all times by an end-window Geiger counter. In early trials the *U* section and the cell were kept at liquid-nitrogen temperatures during the transfer. It was discovered, however, that this resulted in excessive foreign gas contamination of the cell and the use of traps of any sort was abandoned. Even without trapping only a small fraction of the cadmium distills past the cell. A final and important step has been to spark the cell vigorously with a high-frequency discharge produced by a Tesla coil. Only after this procedure does it seem possible to maintain a low pressure of background gas in a sealed-off cell. The sparking is maintained until it does not result in an appreciable pressure rise in the cell. Cells produced in this fashion appear to last for a time limited only by the diffusion of atmospheric helium into the cell.

The total time elapsed from the end of the bombardment to the completion of a cell is about 1 h. This procedure for producing scattering cells thus limits the isotopes which can be studied to those with half-lives of about 1 h or more.

C. Double-Resonance Apparatus

The scheme used for optical excitation and detection is identical to that described in I. Unpolarized light from a cadmium resonance lamp is directed along the static magnetic field and that component of the light scattered at right angles and polarized parallel to the field (π light) is detected by a photomultiplier. With this arrangement any transition which results in a change in the scattered π light can be detected. A resonance is observed by holding the rf-frequency constant and varying the magnetic field. The Helmholtz pair which provides the field differs from that described in I (see above). Fields up to 250 G can be produced with the new coils, and the fields are homogeneous to 1 part in 10^5 over the cell. The scattering cell is considerably smaller than that used in I. It is cylindrical with an outer diameter of 25 mm and a length of 28 mm. The rf magnetic field is produced with a single loop of 1-in. aluminum strip which surrounds the cell and is perforated to permit the passage of light. It is worthwhile noting that the cell temperatures of 200–220°C which result in the largest signals for Cd^{107} and Cd^{109} are only slightly above the optimum temperatures for a cell containing an excess of natural cadmium. The quantities of cadmium produced are considerably less than the amount required to form a monolayer on the inner surface of the cell, so it is not at all clear, *a priori*, that the optimum temperatures will be the same in both cases.

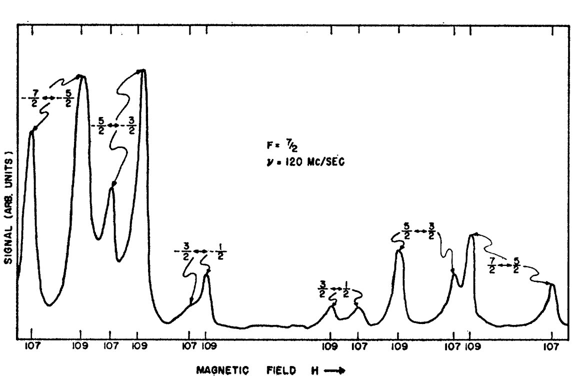

FIG. 2. Zeeman spectrum in the $F=\frac{7}{2}$ state of Cd^{107} and Cd^{109}. The numbers along the abscissa indicate the isotopic assignment. The fractions on the curve indicate the magnetic quantum numbers for each of the transitions.

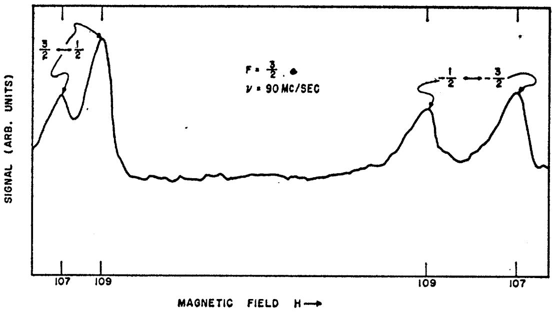

FIG. 3. Zeeman spectrum in the $F=\frac{3}{2}$ state of Cd^{107} and Cd^{109}. The numbers along the abscissa indicate the isotopic assignment. The fractions on the curve indicate the magnetic quantum numbers for each of the transitions.

III. MEASUREMENTS

A. Spin and Lifetime

The presence of approximately equal quantities of Cd^{109} and Cd^{107} made a spin determination at low fields quite difficult (see above). However, we were able to observe[12] the decay of a fraction of the resonance signal at a frequency corresponding to $g_F/g_J=2/7$. The decay time was consistent with a 6.7-h half-life. It is necessary to argue that the intensity of a resonance in the state $F=I+1$ is expected to be greater than that in $F=I-1$ to establish that $I=\frac{5}{2}$ from this observation (see I). A complete confirmation is obtained, however, by observing the Zeeman resonances at higher fields. One set of four resonances and another set of twelve resonances were observed (see Figs. 2 and 3); the sets are symmetric about the frequencies expected for levels with $g_F/g_J=\frac{2}{5}$ and $g_F/g_J=2/7$, respectively. The resonances labeled 107 in Figs. 2 and 3 were observed to

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[12] M. N. MeDermott and R. Novick, Bull. Am. Phys. Soc. **6**, 427 (1961).

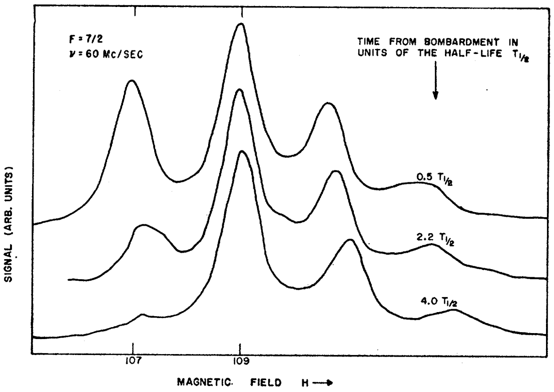

FIG. 4. Part of the $F=\frac{7}{2}$ Zeeman spectrum for Cd^{107} and Cd^{109}, showing the decay of the Cd^{107} resonances. The numbers 107 and 109 indicate the isotopic assignment.

decay appreciably in a matter of hours, clearly indicating that they were produced by Cd^{107} atoms; the other resonances did not decay and were consistent with the known hyperfine structure of Cd^{109}. From the multiplicity and field dependence of the Cd^{107} lines we can unambiguously state that the nuclear spin of Cd^{107} is $\frac{5}{2}$.

We made a semiquantitative determination of the Cd^{107} lifetime by carefully observing the decay of one of the resonances. In Fig. 4 we show part of the $F=\frac{7}{2}$ Zeeman spectrum as observed at various times after bombardment. From such observations we were able to construct the decay curve shown in Fig. 5. Here we have normalized the Cd^{107} resonance amplitude to that of Cd^{109} in order to eliminate the effects of instrumental fluctuations. The line drawn in Fig. 5 was obtained by a least-squares fitting procedure and corresponds to a half-life of 7.1±0.5 h. This lifetime is in excellent agreement with the accepted value of 6.7 h and clearly precludes the possibility of an incorrect assignment.

B. Hyperfine Structure

Complete resonance spectra were obtained for both the $F=\frac{7}{2}$ and $F=\frac{3}{2}$ states (Figs. 2 and 3). The distortion of the individual resonances is caused by unfavorable combinations of sweep time and integration time. This distortion and the accompanying shift of the resonance can largely be avoided when observing single resonances. The gross asymmetry of the spectra shown in Fig. 2 arises from the fact that the different magnetic sublevels are not equally illuminated.

We have chosen to base the determination of the hyperfine structure constants on measurements of the $(\frac{7}{2},\frac{5}{2}\leftrightarrow\frac{7}{2},\frac{7}{2})$, $(\frac{7}{2},-\frac{5}{2}\leftrightarrow\frac{7}{2},-\frac{7}{2})$, $(\frac{3}{2},\frac{1}{2}\leftrightarrow\frac{3}{2},\frac{3}{2})$, and $(\frac{3}{2},-\frac{1}{2}\leftrightarrow\frac{3}{2},-\frac{3}{2})$ resonances, since they are easily separated from nearby resonances in Cd^{109}. Observations were made at frequencies of 90 and 120 Mc/sec for which the magnetic fields at resonance range from 102 to 222 G.

A total of 13 resonances have been used in a least-squares determination of the best values of the hyperfine interaction constants (see I). We find

$$A=-854.2\pm 1.0 \text{ Mc/sec},$$

$$B=-166\pm 3 \text{ Mc/sec}.$$

The errors quoted are believed to be limits of error and are based principally on the internal consistency of the data.

We have determined the sign of A by a separate experiment in which the incident resonance radiation is circularly polarized. The change in the relative intensities of the resonances compared to those obtained with unpolarized incident radiation is identical to that seen in Cd^{109}.[2] This demonstrates conclusively that the hyperfine structure is inverted and consequently that A is negative. In particular, the disappearance of the resonance occurring at the lowest field in the $F=\frac{7}{2}$ spectrum (when the excitation results from right circularly polarized light directed antiparallel to the static field) is sufficient to establish this result.

IV. NUCLEAR MOMENTS

A. Measured Moments

We can combine the measurement of the dipole interaction constants in Cd^{107} and Cd^{111} and the known magnetic moments of Cd^{111} to obtain the moment of Cd^{107} in the following way[13]:

$$\mu_{107}=\mu_{111}(I_{107}/I_{111})(A_{107}/A_{111}).$$

For[14]

$$A_{111}=-4123.81(1) \text{ Mc/sec}$$

and[15]

$$\mu_{111}=-0.59501(8)\mu_N$$

we find a value for the Cd^{107} moment of $\mu_{107}=$

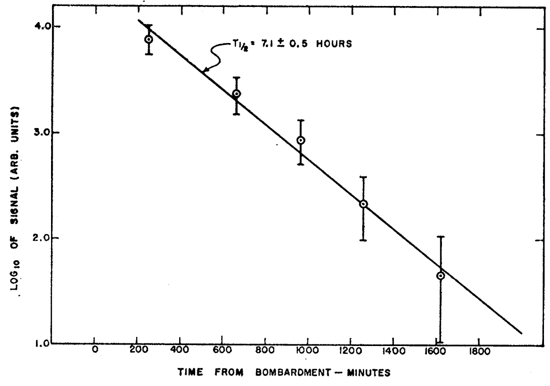

FIG. 5. Decay curve for one of the Cd^{107} resonances. The Cd^{107} signal has been normalized to one of the Cd^{109} resonances in order to reduce the effect of instrumental fluctuations.

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[13] H. Kopfermann, *Nuclear Moments* (Academic Press Inc., New York, 1958), 2nd edition.

[14] R. F. Lacey (private communication). A preliminary result appears in Quarterly Progress Report, Research Laboratory of Electronics, Massachusetts Institute of Technology, **2**, 49 (1959).

[15] W. G. Proctor and F. C. Yu, Phys. Rev. **79**, 35 (1950).

$-0.6162(8)\mu_N$. A diamagnetic correction of $+0.457\%$ is included in this result. In this derivation we have neglected the corrections arising from a possible hyperfine structure anomaly. The stated uncertainty is based solely on the uncertainty in A_{107}.

We can make use of the quadrupole interaction constant for Cd^{109} given in I, $B_{109}=-167.3\pm2.0$ Mc/sec, to obtain the ratio of the quadrupole moments, $Q_{107}/Q_{109}=B_{107}/B_{109}=0.993(20)$. The details of the connection between the quadrupole interaction constant, B_{109}, in the $^3P_1$ state of cadmium and the quadrupole moment $Q_{109}=+0.78(10)$ b are discussed in I. From the ratio of the quadrupole moments stated above we find $Q_{107}=+0.77(10)$ b.

B. Theoretical Moments

The most consistently successful model which has been applied to the calculation of nuclear moments in the mass range of cadmium appears to be the configuration mixing model of Noya, Arima, and Horie.[16] If we use the reasonable value for their nuclear pairing energy parameter, $C=30$ MeV, we find $\mu_{107}=-0.64\mu_N$. The calculated moment is in excellent agreement with the experimental value; furthermore, the correction relative to μ_{109} is in the right direction and has nearly the correct magnitude. The configuration mixing model makes the origin of the difference quite apparent. The most satisfactory zeroth order neutron configurations appear to be $(1g_{7/2})^4(2d_{5/2})^5$ for Cd^{107} and $(1g_{7/2})^6(2d_{5/2})^5$ for Cd^{109}. Although the model predicts approximately the same admixture of the $(1g_{9/2})^9(1g_{7/2})^5$ in Cd^{107} as of $(1g_{9/2})^9(1g_{7/2})^7$ in Cd^{109}, the $(1g_{9/2})^9(1g_{7/2})^5$ admixture produces a deviation from the Schmidt limit which is twice as large; all other corrections are approximately equal for the two nuclei. Without recourse to this effect it is difficult to explain why the moment of Cd^{107} should be 25% smaller than the moment of Cd^{109}.

On the basis of the extreme single-particle model, the quadrupole moment for an odd-neutron nucleus such as Cd^{107} should be zero. On the other hand, it is well known that odd-neutron nuclei usually have quadrupole moments nearly equal to those of odd-proton nuclei in the same configuration. The configuration-mixing model reproduces this effect quite well for nuclei with small distortion. The neighboring even isotopes of cadmium themselves show a well developed vibrational structure. The case for collective effects is further strengthened by the greatly enhanced quadrupole moment. We can use the single-particle approach of the configuration mixing model to obtain $Q_{107}=+0.10$ b for $C=30$ MeV and thus estimate a quadrupole enhancement factor of 8. We should like to point out that with this measurement the quadrupole moments of three different nuclear states with neutron configuration $(2d_{5/2})^5$ are known and are found to be nearly equal. The third case is the 1.25×10^{-7} sec isomer of Cd^{111} for which $Q=0.9\pm0.3$ b.[17] It is perhaps disturbing that the same model does not give both the magnetic and quadrupole moments correctly. However, it seems well established empirically that the collective effects which are so important in explaining the large observed quadrupole moments have a much smaller effect on the magnetic moments.

ACKNOWLEDGMENTS

We acknowledge, with pleasure, the important contributions made by many others to this research. Dr. Larry Feldman and the members of the Pupin Nuclear Physics Laboratory cyclotron crew cooperated wholeheartedly in the Cd^{107} production. Dr. Ralph Pinajian of ORNL helped greatly in the early attempts to bombard a separated silver isotope. Professor Howard Shugart of the University of California, Berkeley, kindly provided the computer program used in reducing the data. Jack Gorham of this laboratory displayed unusual skill and patience in making the numerous quartz pieces indispensible to this research. Bradley Perry aided substantially in the data taking and other phases of this work.

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[16] H. Noya, A. Arima, and H. Horie, Suppl. Progr. Theoret. Phys. (Kyoto) **8**, 33 (1958).

[17] H. J. Behrend and D. Budnick, Z. Physik **168**, 155 (1962).