^{123}Cd level scheme

H. Huck, A. Jech, G. Martí, M. L. Pérez, J. J. Rossi,* and H. M. Sofía
Departamento de Física, Comisión Nacional de Energia Atómica, 1429 Buenos Aires, Argentina
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Fast neutrons were produced with deuteron beams of 27 MeV and 800 nA from the ^{9}Be(^{2}H,n) reaction. These neutrons induced, in turn, natural-uranium fission. Samples of ^{123}Ag were obtained by means of on-line mass separation techniques applied to the fission products. The half-life of the β^- decaying ^{123}Ag was measured to be 0.35 ± 0.04 s in agreement with previously reported data. The energy level scheme of ^{123}Cd was built from the obtained experimental results and is reported for the first time. Spins and parities for the most important states were suggested based upon logfT values obtained from measured γ-ray transition intensities. The most important characteristics are discussed and nuclear structure properties are inferred.

I. INTRODUCTION

Odd-mass Cd nuclei systematically show low-lying excited states having low-spin and positive parity ($\frac{1}{2}^+,\frac{3}{2}^+,\frac{5}{2}^+$) levels coexisting with some high-spin negative-parity levels ($\frac{7}{2}^-,\frac{9}{2}^-,\frac{11}{2}^-$), as can be seen in Fig. 1. This mixing of low- and high-spin states of different parity is the origin of the two β^--decaying isomeric states in all the odd-mass neutron-rich Cd isotopes from $A=115$ to $A=121$, which is the last isotope known and studied.[1] The two half-lives observed and measured in β^- decay of ^{123,125}Cd (Refs. 2 and 3) show the same systematical behavior for these nuclei.

It is possible to describe the structure of the low-lying levels ($\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{11}{2}^-$) in Cd isotopes as quasiparticle states within the framework of the BCS formalism.

From the shell model, it can be seen that the neutron levels $d_{5/2}$, $g_{7/2}$, $s_{1/2}$, and $d_{3/2}$ will be filled with 70 neutrons (^{118}Cd). From here on the $h_{11/2}$ shell is the only possibility for adding neutrons. However, the ground states from ^{115}Cd to ^{123}Cd change from $\frac{1}{2}^+$ to $\frac{3}{2}^+$, while the $\frac{11}{2}^-$ level is, for all these isotopes, an excited state. This implies that two neutrons prefer to form a pair in the $h_{11/2}$ orbital while the odd neutron occupies the $s_{1/2}$ or $d_{3/2}$ levels.

To explain this result theoretically, it is necessary to increase the pairing strength a little for the $h_{11/2}$ level with respect to the other levels in the shell.

Systematics also show $\frac{7}{2}^-$ and $\frac{9}{2}^-$ states lying above the $\frac{11}{2}^-$ state. This odd-parity triplet has been exhaustively investigated[4–6] and different models have been used in an effort to explain their puzzling behavior throughout the different Cd isotopes. Other states up to 1 MeV of excitation energy might be described as one quasiparticle plus pairing proton vibrational states of the even-even neighboring Cd. This is supported by a 2^+ level at $\cong$500 keV present in all Cd isotopes from $A=114$ to $A=122$.[7]

The main objective of the present work is to construct the energy level scheme of ^{123}Cd, trying to obtain some information about its nuclear structure. The isomeric high-spin state was confirmed in Ref. 3 and its position is suggested in the proposed level scheme.

II. EXPERIMENT

The ^{123}Ag activity was obtained as a mass-separated fission product from the fast-neutron fission of natural U by using an isotope separator on-line with the TANDAR[8] accelerator. The experimental setup is shown in Fig. 2. A complete description of its performance may be found in Ref. 9.

Two hyperpure germanium detectors, closely placed to the radioactive samples, allowed direct on-line measurements. These detectors had a 40% efficiency with 1.95 keV FWHM resolution and a 30% efficiency with 2.00 keV FWHM resolution (at 1.33 MeV energy). Single spectra together with triple γ-γ-t coincidence and multiscaling spectra were recorded on-line and analyzed off-line. Prompt and delayed coincidence relations were also analyzed off-line.

The collector assembly was operated with three different time schedules in order to vary the activity ratios according to the half-lives and the parental relations of the Ag, Cd, In, and Sn isotopes present in the $A=123$ isobaric chain.

The half-life measurements were performed from eight consecutive spectra recorded with time intervals of 0.1 s in the multiscaling mode, after each 2 s collection time of the ^{123}Ag activity.

Energy calibrations were made using the standard lines of ^{241}Am, ^{57}Co, ^{133}Ba, ^{137}Cs, ^{60}Co, ^{22}Na, and ^{24}Na sources. Single and double escape γ-ray lines from the last source were also employed.

Efficiency calibrations over the range 0.2–3.0 MeV were performed by collecting mass 138 activity on-line with the same geometry as used during measurements.[10] The low-energy part of the efficiency calibration curve was completed with ^{241}Am, ^{133}Ba, and ^{57}Co standard sources.

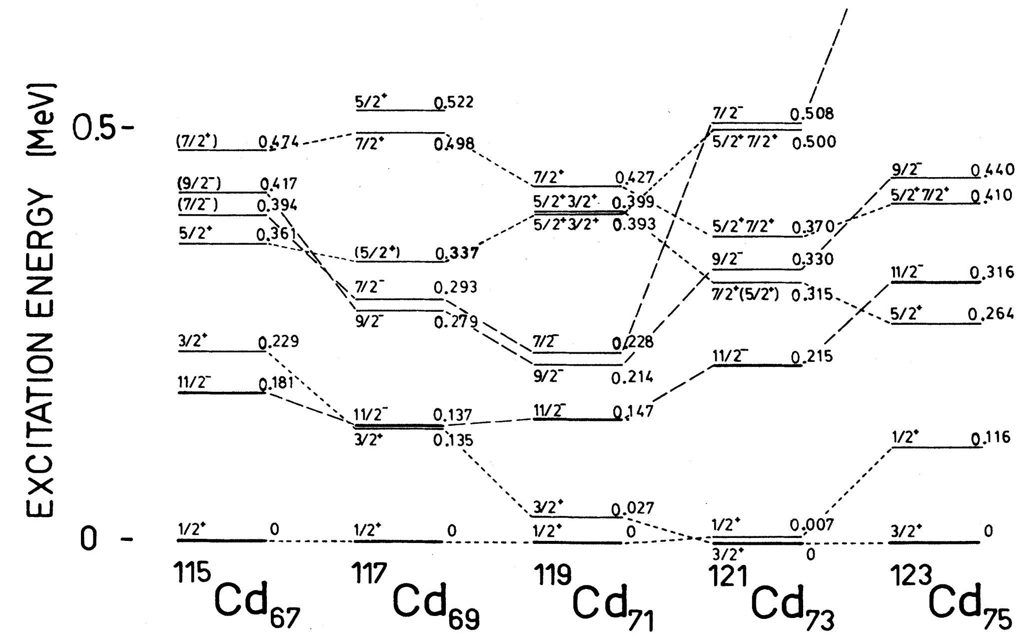

FIG. 1. Systematics of the low-lying excitation levels in odd-mass Cd nuclei from $A = 115$ to $A = 123$. Data for ^{123}Cd are from the present work. (---) positive-parity levels, (– – –) negative-parity levels.

III. EXPERIMENTAL RESULTS

Identification of γ-rays associated with the ^{123}Ag decay was performed using the activity ratios obtained from three single γ-ray spectra recorded with three different velocities of the collector tape. The identification was easily performed since the half-life of ^{123}Ag decay (0.35 s) is substantially shorter than the daughter activities $^{123}Cd^{g,m}$ (2.12 s, 1.81 s), (Refs. 2 and 3) $^{123}In^{g,m}$ (48 s, 6.0 s), and ^{123}Sn (40.1 s). Figure 3 shows the low-energy part of the single γ-ray on-line spectrum recorded with the collecting tape moving so as to produce the maximum enhancement of ^{123}Ag activity with respect to the ^{123}Cd, ^{123}In, and ^{123}Sn activities.

The half-life value measured in the decay of ^{123}Ag was 0.35 ± 0.04 s in agreement with Refs. 2 and 11. The γ-rays used for these decay measurements were the 264 keV and the 409 keV transitions. The half-life of the level at 264 keV (see the level scheme of ^{123}Cd in Sec. IV), was also measured with off-line delayed coincidences giving a

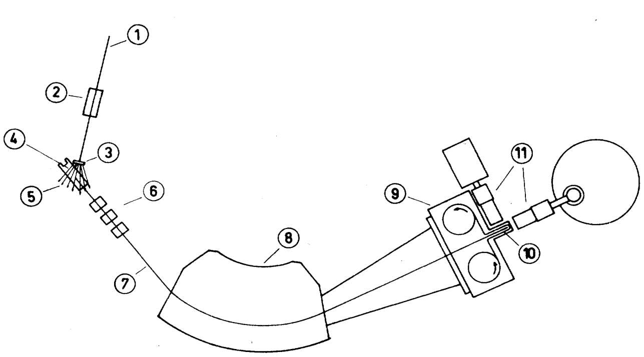

FIG. 2. Schematic view of the experimental array used to perform the present work. 1—deuteron beam; 2—focusing quadrupole; 3—Be target; 4—ion source; 5—fast-neutron flux; 6—focusing electrostatic lenses; 7—fission products beam; 8—analyzing magnet; 9—activity collector; 10—moving tape collector; 11—HP-Ge detectors.

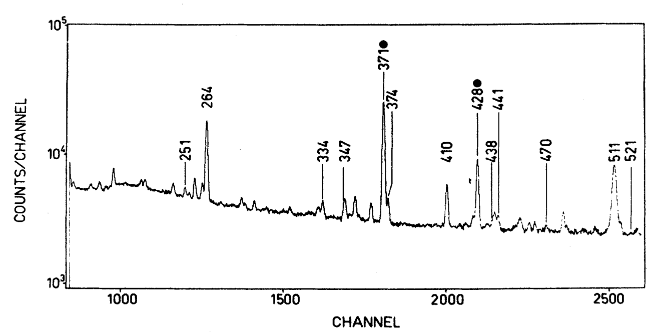

FIG. 3. Low-energy part of the γ-ray spectrum recorded for the $A = 123$ isobars showing the transitions between levels of ^{123}Cd populated in the decay of ^{123}Ag. The recording was performed with the collecting tape moving continuously so as to enhance the ^{123}Ag decay activity with respect to ^{123}Cd, ^{123}In, and ^{123}Sn decay activities. The most intense transitions following the decay of ^{123}Cd are labeled with dots. The positrons-annihilation 511 keV transition is also shown. The γ-ray transitions are in keV.

value of 80±15 ns. The decay curve is shown in Fig. 4.

Results for the decay of the ^{123}Ag are summarized in Table I where the observed γ-ray energies and intensities, along with their errors, the coincidence relations, and the relative positions in the energy level scheme, are presented.

IV. DECAY SCHEME OF ^{123}AG AND ENERGY LEVEL SCHEME OF ^{123}CD

The decay scheme of ^{123}Ag, and the energy level scheme of ^{123}Cd, are proposed from the present experimental results and they are shown in Fig. 5.

The level scheme is based upon γ-γ coincidence relations, energy sums, and intensity balances. Gamma rays with no coincidences were placed in the scheme as transitions to previously established levels.

The β-feeding percent intensity to each level was calculated from relative intensities deduced from the singles

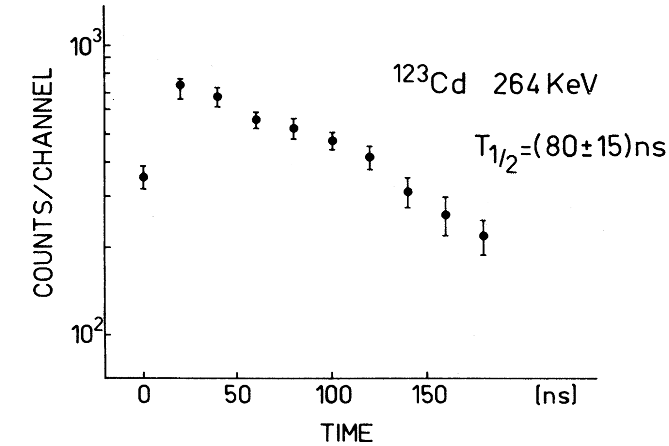

FIG. 4. Decay curve of the 264 γ-ray transition. The half-life corresponds to the level positioned at 264 keV in the level scheme shown in Fig. 5.

TABLE I. Gamma ray energies and intensities following the decay of ^{123}Ag ($T_{1/2}=0.35$ s). The last column indicates the relative position in the level scheme shown in Fig. 5. The intensities are in percent of decays from the parent nucleus.

Energy (keV)	Energy (keV)	Intensity	Error	Coincidences gamma rays (keV)	Levels (keV) Initial-Final
116.41	0.03	8.30	0.10	347,438,556	116-0
123.67	0.06	6.30	0.37	251,621	440-316
250.78	0.05	2.30	0.16	124	691-440
263.87	0.02	39.30	0.34	440,1265,1976,1726 2337,2523,2638,2647	264-0
334.05	0.05	1.40	0.35		
347.38	0.06	4.30	0.37		464-116
374.00	0.10	5.80	0.23	No coincidences	691-316
409.79	0.03	14.50	0.50	334,600,652	410-0
437.54	0.20	2.20	0.26	116	554-116
441.05	0.10	3.80	0.26	264	705-264
470.19	0.10	1.40	0.46		1061-591
520.80	0.40	0.70	0.20		
553.50	0.20	1.10	0.25		554-0
556.10	0.20	1.80	0.30		673-116
591.30	0.05	9.00	0.45	470	591-0
600.31	0.15	1.90	0.28	410	1010-410
621.30	0.30	2.50	0.90		1063-440
651.58	0.15	1.60	0.37	410	1061-410
672.40	0.15	0.90	0.17		673-0
689.10	0.15	4.70	0.38	No coincidences	1006-316
743.40	0.10	4.80	0.36		744-0
1096.50	0.20	1.90	0.38		
1234.30	0.20	2.00	0.42		2240-1006
1248.95	0.20	2.30	0.51		
1265.15	0.15	3.40	0.43	264	1529-264
1528.18	0.30	2.90	0.37		1529-0
1725.90	0.20	1.80	0.40		2787-1061
1976.00	0.20	4.30	0.61	264	2240-264
2337.10	0.25	2.10	0.48	264	2601-264
2523.50	0.30	1.50	0.37	264	2787-264
2638.40	0.25	2.70	0.57		2902-264
2646.70	0.30	1.40	0.38	264	2910-264
2902.70	0.40	1.20	0.39		2902-0
2909.50	0.40	0.80	0.19		2910-0

γ-ray spectrum shown in Fig. 3, supposing no β feeding to the ground and isomeric states. LogfT values have been calculated using the formulas and tables of Ref. 12, while the Q_β value for the β^- transition from the ^{123}Ag to the ^{123}Cd was obtained from extrapolated values of ^{115,117,119,121}Ag β decays using the data taken from Ref. 13.

The spins and parities suggested were based upon logfT values, systematics considerations, and the probable spins and parities of the levels connected by the γ transitions with the level involved. A few levels have up to three possibilities, while no spin suggestions were made for more than this level of uncertainty.

The proposed scheme for the decay of ^{123}Ag with 0.35 s half-life includes 31 γ-ray transitions, accounting for 95.1% of the total γ-ray intensity measured. Those γ rays are arranged in a scheme with 21 excited states.

The main arguments supporting the construction of

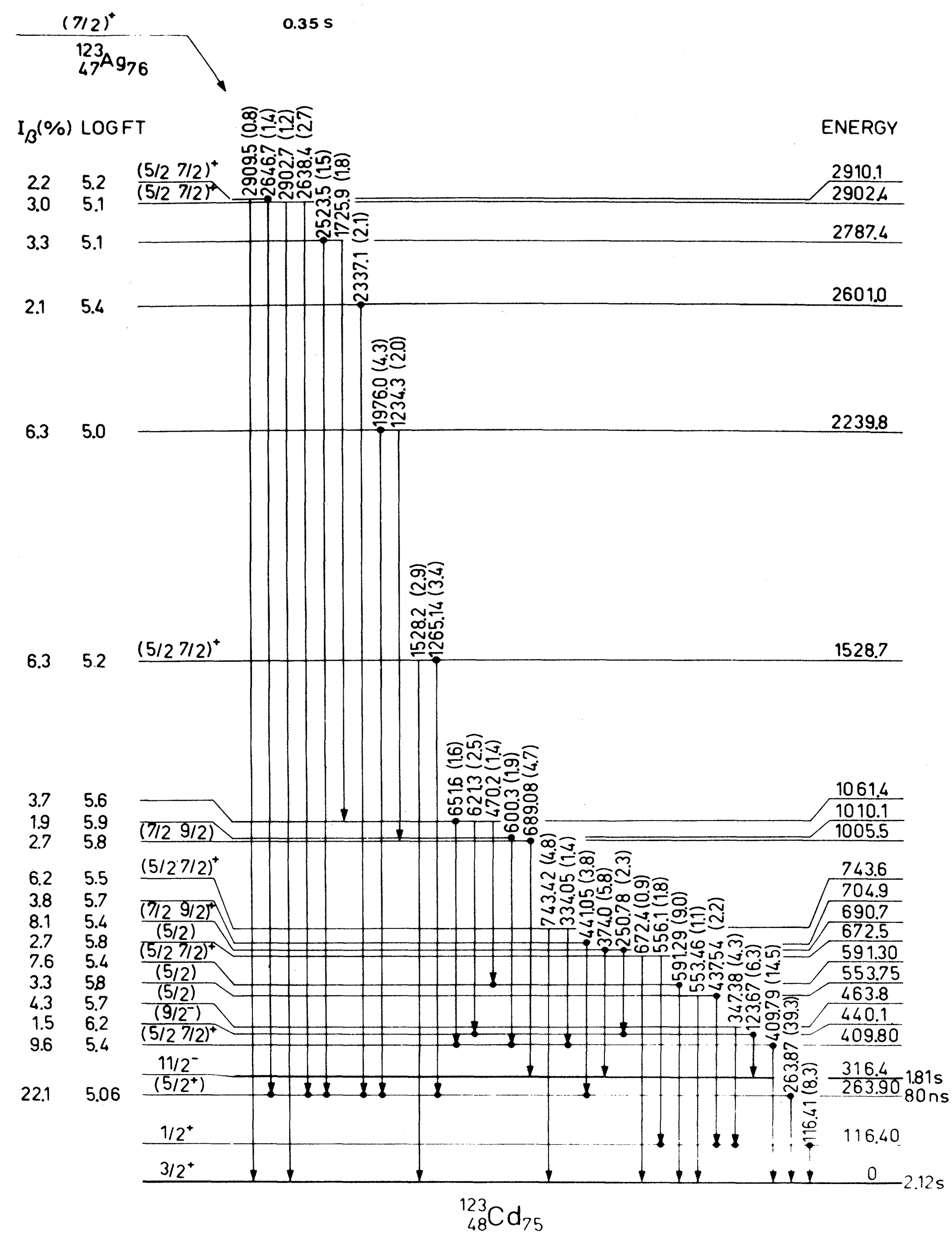

FIG. 5. Excitation energy level scheme in ^{123}Cd populated in the decay of ^{123}Ag (0.35 s) deduced from the present experiment. The γ-ray intensities are given in percent of the decays of the parent nucleus. A dot at an arrowhead indicates an observed coincidence relation, while a dot at the tail of an arrow means that the transition has been used as a coincidence gate. The Q_β value was extrapolated from data taken from Ref. 13. Energy levels and γ-ray transitions are in keV.

the level scheme were the coincidence relations of the most intense γ rays in the spectra. In decreasing order of intensity they are: the 264, 410, 116, and 124 keV transitions. From the set of γ rays shown in Table I, two subsets were considered. One of them is associated with the $\frac{3}{2}^{+}$ ground state involving the 116, 264, and 410 keV transitions. The other subset is associated with the 124 keV transition. The position of the $\frac{11}{2}^{-}$ isomeric state in the scheme was searched so that both subsets of levels had the greatest number of shared levels (as was done in ^{121}Cd by Fogelberg *et al.*[1]) This search was made in the γ-ray energy range of 260–400 keV. The suggested position at 316 keV is the most probable value consistent with the proposed scheme and with the systematics. The other two levels shared by the subsets mentioned above are the states at 1061 and 2240 keV. Also, the energy value of the metastable state was extrapolated from systematics, shortening the possible energy interval for the search to 300–350 keV.

The systematics of the odd-mass Cd nuclei indicates a $\frac{3}{2}^{+}$ ground state and a $\frac{1}{2}^{+}$ state at higher energy close to the ground state. The level at 116 keV is a good candidate to be the $\frac{1}{2}^{+}$ state, both due to the systematics and to the absence of β feeding from the $(\frac{7}{2}^{+})$ ground state of ^{123}Ag. There are two possible spins for the level at 264 keV; $\frac{5}{2}^{+}$ and $\frac{7}{2}^{+}$, due to the strong γ transition to the ground state. If the position of the $\frac{11}{2}^{-}$ metastable state at a higher energy is correct, a $\frac{5}{2}^{+}$ is the only possibility. The half-life of 80±15 ns measured for this level would be compatible with a $E2$ transition to the ground state with a hindrance factor of 4. This is the only level with such a half-life.

For the 410 keV level, spins $\frac{5}{2}^{+}$ or $\frac{3}{2}^{+}$ are suggested because it has a significant β feeding and it depopulates by a strong transition to the ground state.

The systematics also shows the existence of two other levels of negative parity besides the $\frac{11}{2}^{-}$ level, these levels have spin and parity $\frac{7}{2}^{-}$ and $\frac{9}{2}^{-}$. Here, the levels at 440 and 1005 keV are suggested as the most probable candidates to be the $\frac{9}{2}^{-}$ and the $\frac{7}{2}^{-}$ states, respectively.

V. DISCUSSION

The ground state of the even Cd isotopes can be assumed a to be a coherent two proton-hole state. This state is described by the first root of the random-phase approximation (RPA) of the pairing force for protons where the strength of the interaction is adjusted in such a way as to reproduce the correct energy of the boson. In the same way, the first 2^{+} excited state at about 0.5 MeV that appears in the even Cd isotopes can be thought of as being a quadrupole pairing vibration of the hole pair of protons.

On the other hand, the $\frac{1}{2}^{+}$, $\frac{3}{2}^{+}$, and $\frac{11}{2}^{-}$ levels in ^{115}Cd can be reproduced through a BCS calculation plus a proton-neutron quadrupole interaction utilizing a reasonable set of single-particle levels. However, in order to obtain the correct energy spectrum for the odd-mass Cd isotopes, it was necessary to increase the pairing strength a little for the $\frac{11}{2}^{-}$ level. This results in that neutron pairs find a lower energy filling to the $\frac{11}{2}^{-}$ level because of the pairing interaction, while the odd neutron occupies the $\frac{1}{2}^{+}$ or the $\frac{3}{2}^{+}$ level, reproducing the correct ground states of the odd Cd isotopes from $A=115$ to $A=123$.

For the calculation, the neutron single-particle energies were obtained from Ref. 14 and the results are shown in Fig. 6.

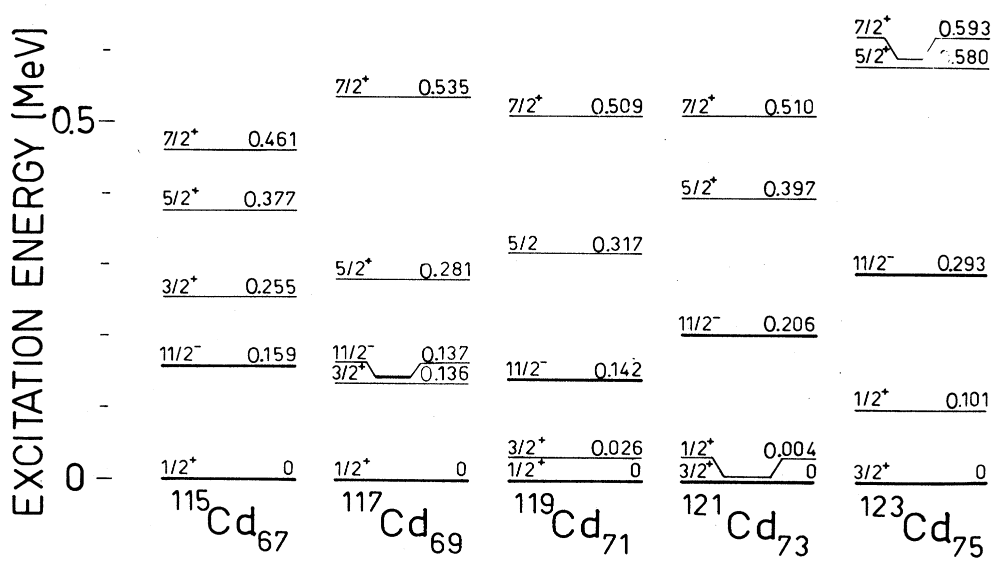

FIG. 6. Results of the BCS plus proton-neutron interaction calculations applied to the low-energy odd-mass Cd nuclei. Single-particle energies were taken from Ref. 14. The strength of the proton-neutron interaction used in the calculation was adjusted with the odd-mass Cd nuclei from $A=115$ to $A=123$.

The enhancement of the $\frac{11}{2}^-$ pairing force could be explained by the contribution to the pairing strength coming from the quadrupole particle-hole neutron interaction. Other levels might probably be explained by coupling the odd neutron to the first 2^+ excited state of the even Cd (two coherent hole protons coupled to angular momentum 2).

The ^{123}Cd nucleus has one more level coexisting with the low-lying levels mentioned before ($\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{11}{2}^-$). The structure of the level at 264 keV seems to be very difficult to understand. The strong β feeding from the probable $\frac{7}{2}^+$ ground state in the parent nucleus, together with the strong γ transition to the $\frac{3}{2}^+$ ground state, make a spin assignment of $\frac{5}{2}^+$ or $\frac{7}{2}^+$ very probable. Our calculation is not able to explain this level since the prediction is above 1 MeV in energy. It could be understood as $\frac{3}{2}^+$ coupled to a pairing phonon collective state, but with an abnormally delayed γ decay. A value of $\frac{7}{2}^+$ is less probable than $\frac{5}{2}^+$, because the 1.81 s half-life measured[3] for the $\frac{11}{2}^-$ isomeric state at a higher energy precludes such a possibility. One way to elucidate this problem would be to progress in the study of the odd-mass Cd systematics, and actually, there is also a $\frac{11}{2}^-$ metastable state in ^{125}Cd.[3]

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*Deceased on June 21, 1988.

[1]B. Fogelberg and P. Hoff, Nucl. Phys. **A391**, 445 (1982).
[2]H. Mach, R. L. Gill, D. D. Warner, A. Piotrowski, and R. Moreh, Phys. Rev. C **34**, 1117 (1986).
[3]H. Huck *et al.*, Phys. Rev. C **39**, 997 (1989).
[4]Z. Matumoto, T. Tamura, and K. Sakurai, J. Phys. Soc. Jpn. **44**, 1062 (1978).
[5]S. Ohoya, N. Mutsura, Z. Matumoto, and T. Tamura, Nucl. Phys. **A334**, 382 (1980).
[6]R. F. Casten and G. J. Smith, Phys. Rev. Lett. **431**, 337 (1979).
[7]*Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).
[8]E. Perez Ferreira *et al.*, Nucl. Instrum. Methods **184**, 161 (1981).
[9]M. Ballestero *et al.*, Nucl. Instrum. Methods Phys. Res. B **26**, 125 (1987).
[10]E. Achterberg *et al.*, Nucl. Instrum. Methods **116**, 453 (1973).
[11]P. L. Reeder, R. A. Warner, and R. L. Gill, Phys. Rev. C **27**, 3002 (1983).
[12]N. B. Gove and M. J. Martin, Nucl. Data Tables **10**, 206 (1971).
[13]The 1983 Atomic Mass Table, Nucl. Phys. **A432**, 140 (1985).
[14]R. A. Uher and R. A. Sorensen, Nucl. Phys. **86**, 1 (1966).