Eur. Phys. J. A **7**, 347–353 (2000)

THE EUROPEAN PHYSICAL JOURNAL A

Evidence for deformation in $^{113-116}$Cd isotopes

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Received: 21 December 1999 / Revised version: 16 February 2000
Communicated by B. Herskind

Abstract. High-spin states in $^{113-116}$Cd have been investigated with the fusion-fission reaction ^{28}Si + ^{176}Yb at 145 MeV. The experiment has been performed with the Eurogam2 array. New rotational bands based on two quasi-particle states have been observed for even-even cadmium isotopes. A new level scheme based on the $11/2^-$ isomeric state is proposed for ^{115}Cd and the one of ^{113}Cd has been extended to spin $(31/2^-)$. The decoupled bands identified in both odd-A nuclei are interpreted as being built upon a low-Ω $h_{11/2}$ quasi-neutron configuration. Microscopic Hartree-Fock + BCS calculations confirm the prolate deformation in this mass region especially for the odd cadmium isotopes.

PACS. 21.60.Ev Collective models – 21.60.Jz Hartree-Fock – 23.20.Lv Gamma transitions and level energies – 25.70.Jj Fusion and fusion-fission reactions – 27.60.+j $90 \leq A \leq 149$

1 Introduction

For long time cadmium isotopes lying close to stability ($111 \leq A \leq 114$), studied by radioactivity, have been considered as good examples of quadrupole vibrator with spherical shape, the even-even ones, namely ^{112,114}Cd, exhibiting the typical two-phonon triplet states and the odd-A ones, ^{111,113}Cd, the corresponding weak-coupling states [1]. Consequently several phenomenological calculations have described the even-even nuclei in the framework of the anharmonic vibrator model coupling two holes of protons $(\pi g_{9/2})^{-2}$ to an even-even Sn core [2] or of the generalized *spdf* IBA-1 model with configuration mixing of the normal and intruder states [3]. At high spin, lighter nuclei have been investigated using heavy-ion fusion-evaporation reactions [3–8]. The observation of decoupled bands in odd $^{103-111}$Cd isotopes [4–7,9] has pointed out that these nuclei are weakly prolate deformed. The existence of this axial deformation ($\beta \sim 0.1$) has been shown by Hartree-Fock + BCS microscopic calculations in even-even cadmium isotopes [10].

The heavier even-even cadmium isotopes, $^{114-122}$Cd, have been produced at intermediate spins by fission [11] or transfer reactions [12]. For nuclei closer to the stability in this mass region, heavy-ion induced fission has recently allowed the population of high spin states which can not be populated otherwise. The new generation of large arrays of high-efficiency Compton-suppressed Ge detectors permits the study of these high spin states [13]. In the present work, high-spin states in $^{113-116}$Cd have been investigated. New rotational bands have been observed in even-even cadmium and new level schemes built above the $11/2^-$ isomeric state are proposed for ^{113}Cd and, for the first time, for ^{115}Cd. Preliminary results of this work have been reported in [14].

2 Experiment

The experiment was performed at the Vivitron accelerator, which delivered a ^{28}Si beam at 145 MeV. The target consisted of a foil of 1.5mg/cm^2 of ^{176}Yb deposited on a 15 mg/cm^2 gold backing. Prompt γ-rays emitted by the deexcitation of the fission fragments were detected using the Eurogam2 spectrometer [15] which consisted of 15 large escape suppressed Ge detectors at backward and forward angles respectively, and 24 escape suppressed "clover" Ge detectors near 90° relative to the beam direction. The data were recorded in an event-by-event mode with the

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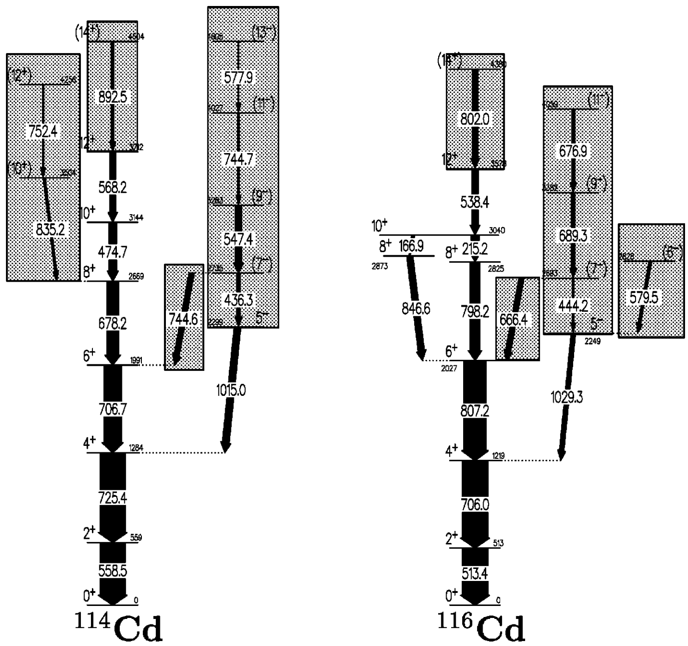

Fig. 1. Partial high-spin level schemes of ^{114,116}Cd. New transitions observed in this work are enclosed in gray rectangles. Relative intensities of the transitions are indicated by the thickness of the corresponding arrows.

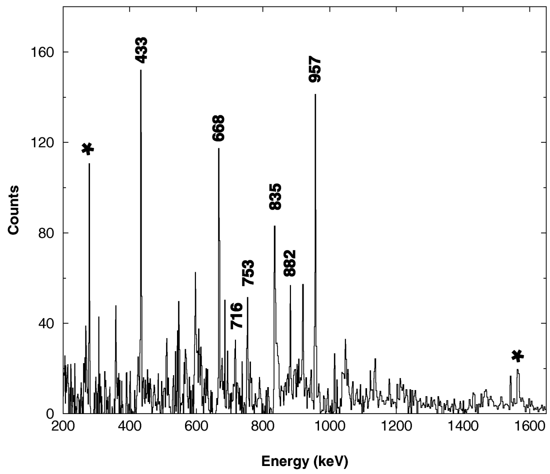

Fig. 2. Spectrum obtained from double gate on the two first transitions above the $11/2^-$ isomer in ^{113}Cd. The new transitions are labelled by their energies. The two peaks marked with a star belong to the complementary fragment ^{85}Kr.

requirement that a minimum of five unsuppressed Ge fired in prompt coincidence. A total of 540 million coincidence events were collected. The off-line analysis consisted of both γ-γ-γ sorts and multiple-gated spectra [16]. More than 130 nuclei have been obtained as fission fragments [17]. The relative production yield of the even-even Cd isotopes is about half of those of the most-produced even-even fission-fragments (Mo and Ru isotopes) [18] and the cadmium mass region reached extends from A = 110 to A = 118 with a maximum yield at mass 114.

For the assignment of new structures to odd cadmium isotopes we have used the identification method based on prompt coincidences between complementary nuclei. In our case, cadmium and krypton isotopes are complementary fragments. This method was applied initially for the study of spontaneous fission [19] and has recently been extended to that of heavy-ion induced fission reactions [13]. Because of the lack of statistics, no directional correlation information has been obtained and spin and parity assignments of the new states can not be extracted. However, in the new structures, spin and parity values have been tentatively assigned from comparisons with neighbouring isotopes.

3 Results

Yrast bands in the even-even isotopes ^{114,116}Cd have been previously identified [11] and have been extended in this work up to spin (14 ħ). The identification in this case is based on unambiguous coincidence relationships with low-lying transitions $4^+ \rightarrow 2^+ \rightarrow 0^+$.

A new rotational band built on the 5^- state [20] has been established in both nuclei ^{114}Cd and ^{116}Cd respectively up to spin (13 ħ) and spin (11 ħ). A second connection to the yrast band is proposed via a $(7^-) \rightarrow 6^+$ transition. Additional side band has also been observed above the 8^+ state in ^{114}Cd. The partial level schemes of ^{114,116}Cd are presented in Fig. 1. The relative intensities have been measured from spectra gated on the lowest transitions.

The neutron-rich odd cadmium isotopes exhibit long-lived isomeric state based on a $\nu h_{11/2}$ configuration. The ^{113,115}Cd nuclei have never been populated at very high spin. Only two states above the $11/2^-$ isomer have been previously identified in ^{113}Cd by ^{110}Pd(α,nγ) reaction [21] and by gating on the transitions (551 and 842 keV) deexciting these states, we obtain the spectrum shown in Fig. 2. We can see the new transitions labelled by their energies and the two first ones of the complementary fragment ^{85}Kr, 269 and 1544 keV [22]. We have extended the level scheme based on the long-lived isomeric state $11/2^-$ [20] up to spin (31/2 ħ), and assigned two rotational bands built on the $(21/2^+)$ and $(19/2^+)$ states as shown in Fig. 3.

Concerning the ^{115}Cd isotope, no transition was known above the $11/2^-$ isomer before our studies. Gating on the two first transitions of the complementary ^{83}Kr fragment (1122 and 1144 keV) [23], we obtained the spectrum presented in Fig. 4. Besides γ-rays belonging to ^{83}Kr (204 and 897 keV), the other transitions can be associated with the complementary cadmium isotopes. We observe the main transitions of the fission fragments with respectively 7 and 5 neutrons evapored : ^{114}Cd (558 and 725 keV) and ^{116}Cd (513 and 706 keV), and above all, candidate transitions for ^{115}Cd appear clearly at 519 and 777 keV energies. Furthermore a coincidence relationship between these two transitions has been established. The coincidence spectrum double-gated on these 519 and 777 keV transitions is displayed on Fig. 5. Six new transitions clearly appear, namely 446, 645, 661, 677, 791 and 919 keV. The new level

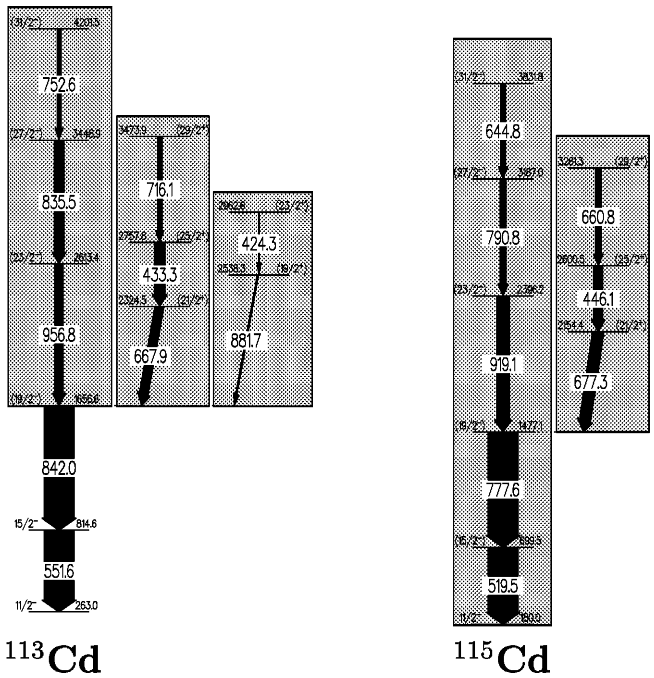

Fig. 3. Partial high-spin level schemes based on the long-lived isomeric state $11/2^-$ [20] of ^{113,115}Cd. New transitions observed in this work are enclosed in gray rectangles. Relative intensities of the transitions are indicated by the thickness of the corresponding arrows.

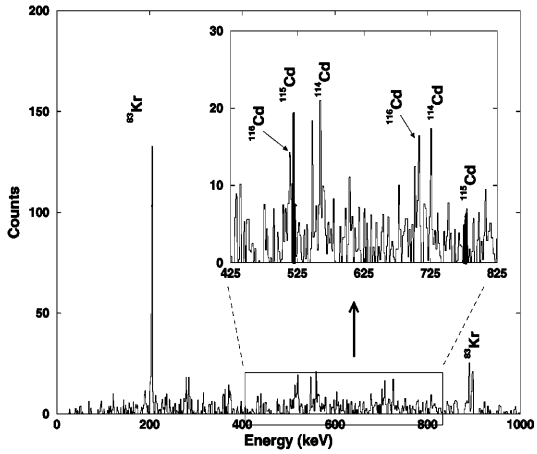

Fig. 4. Spectrum obtained from double gate on the two first transitions of ^{83}Kr, 1122 and 1144 keV. The transitions belonging to ^{83}Kr and to the complementary fission fragments cadmium isotopes, ^{114}Cd (7n evaporation), ^{115}Cd (6n evaporation), ^{116}Cd (5n evaporation) are indicated.

scheme based on the long-lived isomeric state $11/2^-$ [20] proposed for ^{115}Cd is presented in Fig. 3.

4 Discussion

The most striking feature of our results on ^{113,115}Cd is the presence of yrast bands the transition energies of which are quite similar to that of the adjacent even-even ^{114,116}Cd as shown in Fig. 6. This pattern is typical of so-called decoupled bands and is generated by a small deformation and low-Ω high-j shell located near the Fermi level. The intruder $\nu h_{11/2}$ neutron shell with $\Omega = 1/2$, 3/2 orbitals is responsible of this phenomenon and the observation of these new decoupled bands in ^{113,115}Cd is the experimental signature of a small prolate deformation in these two nuclei.

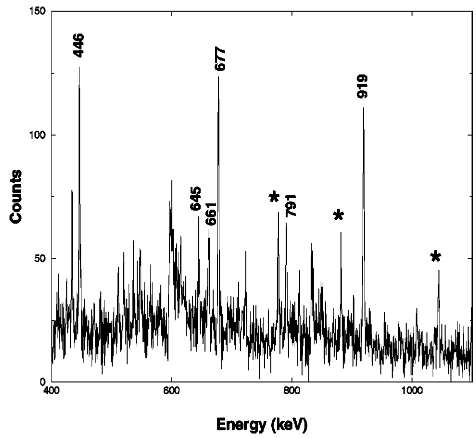

Fig. 5. Spectrum obtained from double gate on the two first transitions above the $11/2^-$ isomer in ^{115}Cd, 519 and 777 keV. The new transitions in coincidence are labelled by their energies. The three peaks marked with a star belong to the complementary fragment ^{83}Kr.

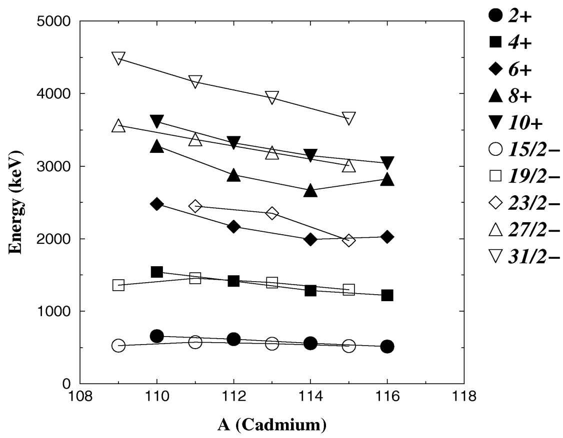

Fig. 6. Comparison between the level energies of 2^+, 4^+, 6^+, 8^+, 10^+ states in even-even $^{110-116}$Cd isotopes (filled symbols) with those of $15/2^-$, $19/2^-$, $23/2^-$, $27/2^-$, $31/2^-$ (relative to the $11/2^-$ isomeric states) in odd $^{109-115}$Cd isotopes (empty symbols).

In order to study in more detail the rotational band structures and to confirm the assignment of the aligned ($\Omega = 1/2, 3/2$) $\nu h_{11/2}$ orbital, the angular momentum alignments have been extracted as a function of the rotational frequency and compared in even-even and odd cadmium isotopes. The assumed level spins have been transformed into the rotational frame using the reference parameters [24] of $\Im_0 = 3.5\hbar^2/\text{MeV}$ and $\Im_1 = 22.0\hbar^4/\text{MeV}^3$ which give a relatively constant alignment above the first crossing for the yrast sequence of ^{110}Cd [7]. Figure 7(a) shows the experimental alignments for the yrast band in

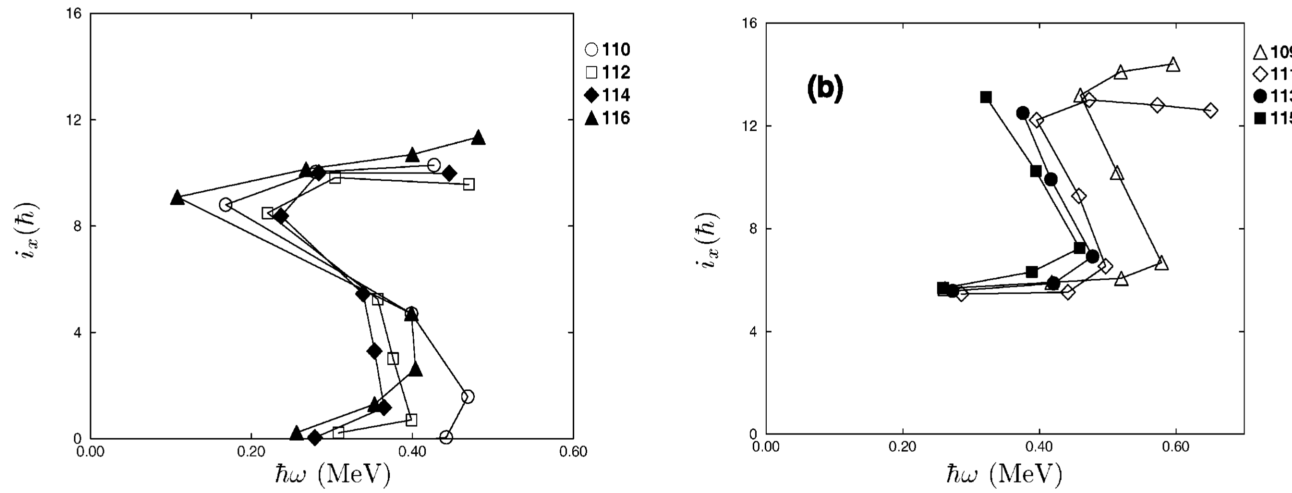

Fig. 7. Experimental alignments for the yrast bands : (a) in the even-even cadmium isotopes, the symbols correspond to : ^{110}Cd (circles, [8]), ^{112}Cd (squares, [3]), ^{114}Cd (filled diamonds, this work and [12]), ^{116}Cd (filled triangles, this work and [12]) ; (b) in the odd cadmium isotopes, the symbols correspond to : ^{109}Cd (triangles, [7]), ^{111}Cd (diamonds, [7]), ^{113}Cd (filled circles, this work and [21]) and ^{115}Cd (filled squares, this work).

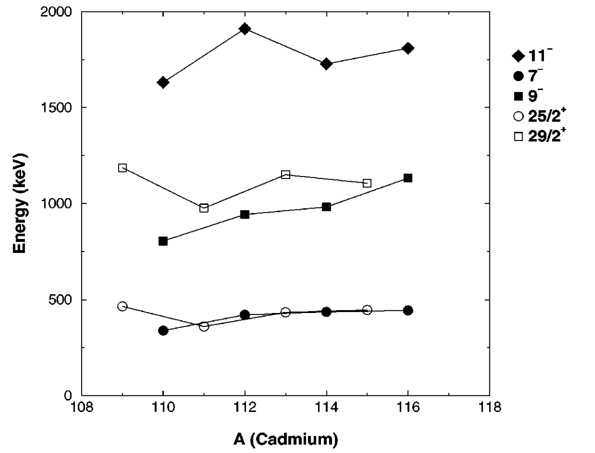

Fig. 8. Comparison between the level energies of 7^-, 9^-, 11^- states (relative to the 5^- state) in even-even $^{110-116}$Cd isotopes (filled symbols) with those of $25/2^+$, $29/2^+$ (relative to the $21/2^+$ state) in odd $^{109-115}$Cd isotopes (empty symbols).

the even-even cadmium isotopes, $^{110-116}$Cd. The initial alignment is zero and all curves display a backbending at a rotational frequency of $\hbar\omega \sim 0.38$ MeV and a gain in alignment of about $10\,\hbar$. Concerning the $h_{11/2}$ bands in the odd cadmium isotopes, the alignment plots are shown in Fig. 7(b) for $^{109-115}$Cd. The initial alignment is about $5.5\,\hbar$. The crossing frequency is higher ($\hbar\omega \sim 0.45$ MeV) than for the even-even nuclei with a gain in alignment of about $8\,\hbar$. This delayed alignment is due to the blocking of the single neutron $h_{11/2}$.

Another important result of the present work concerns the observation of excited bands based on 5^- levels in ^{114,116}Cd and $(21/2^+)$ in ^{113,115}Cd. It is interesting to note, as shown in Fig. 8, the similarity of the evolution of the excitation energies of 7^-, 9^- states (relative to the 5^- state) in even-even cadmium and that of $25/2^+$, $29/2^+$ (relative to the $21/2^+$ state) in odd-A ones. In the lighter cadmium isotopes, this 5^- band has been interpreted as a two quasi-particle (qp) semi-decoupled band $\nu h_{11/2}$ ($\Omega = 1/2, 3/2$)$\otimes\nu g_{7/2}$ ($\Omega = 7/2$). Then the observed similarity suggests that the lateral bands based on the $(21/2^+)$ state in ^{113,115}Cd could be interpreted as a 3 qp semi-decoupled band $(\nu h_{11/2})^2_{10^+} \otimes \nu g_{7/2}$ ($\Omega = 7/2$).

In order to interpret our experimental results microscopic Hartree-Fock calculations [25] have been performed for ^{110,112,114,116}Cd using the Skyrme SLy4 effective interaction [26]. Deformation energy surfaces have been obtained using $r^2\,Y_{2\,0}$ and $r^2\,Y_{2\,2}$ quadrupole constraints in order to investigate the possibility of triaxial shapes for these isotopes. Pairing correlations have been taken into account within the BCS approximation using a density dependent zero range interaction to generate a pairing field peaked at the surface of the nucleus [27]. Since the BCS method fails to describe residual pairing correlations around magic particle numbers, we have used the Lipkin-Nogami prescription [28] to construct a basis set of wave functions in the Q_0-γ plane. The potential energy surfaces (PES) obtained are displayed in Fig. 9. The four isotopes present for the equilibrium a small prolate shape characterized by a mass quadrupole moment of $\sim 400\,\mathrm{fm}^2$. These nuclei are rather soft against the gamma degree of freedom and, for ^{116}Cd, although the absolute minimum corresponds to an axial deformation, the valley in the γ direction is very shallow. We have checked that the projection onto the good particle numbers (neutron and proton numbers respectively) [29] in the framework of the Generator Coordinate Method (GCM) does not significantly modify the deformed shapes. The projected PES are quite similar to the unprojected ones but the general softness of the isotopes is slightly increased by the projection in accordance with the previous work for strontium isotopes [29,30].

From these calculations we have extracted the quasiparticle energies as function of the mass quadrupole moment. The neutron orbitals versus the axial quadrupole

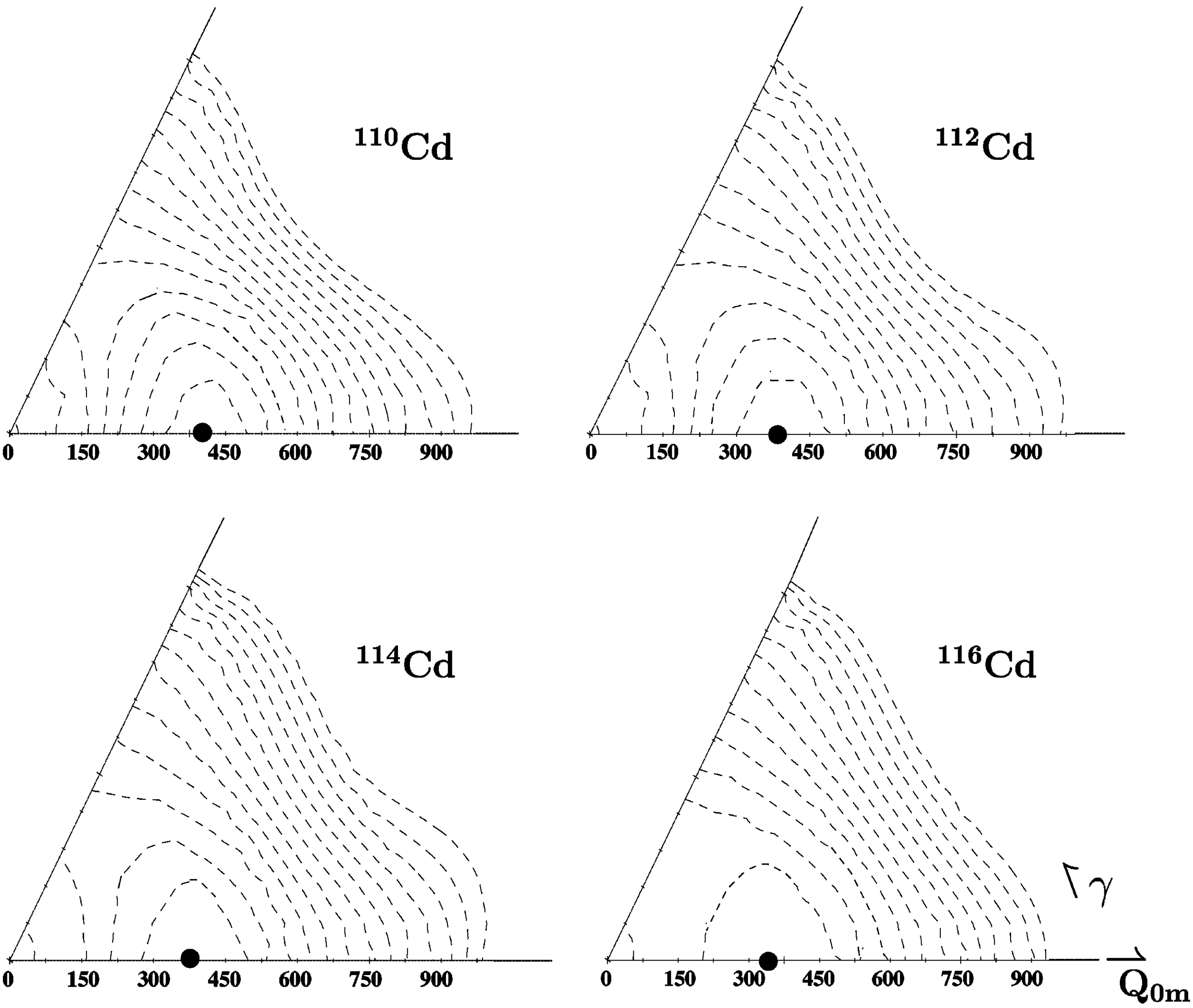

Fig. 9. Potential energy surfaces for ^{110,112,114,116}Cd obtained in HF + BCS calculations using the SLy4 effective nucleon-nucleon force. The distance between two contour lines corresponds to a variation of 0.2 MeV. The shape coordinate corresponds to the mass quadrupole moment in fm^2. The minima are indicated by bullets.

deformation are presented in Fig. 10 for ^{114}Cd. The $h_{11/2}$ $\Omega = 1/2$ and $h_{11/2}$ $\Omega = 3/2$ orbitals are closed to the Fermi level as well as the $g_{7/2}$ $\Omega = 7/2$ as expected. To have an idea of the deformation in odd ^{113,115}Cd isotopes we have extracted from our calculations, at prolate deformation, the potential energies for ^{112,114}Cd corresponding to the 0 qp state and those corresponding to the 1 qp state ($\nu h_{11/2}$ $\Omega = 1/2$). In Fig. 11 are represented the curves we have obtained for ^{112,114}Cd and ^{113,115}Cd (^{112}Cd + 1 qp and ^{114}Cd + 1 qp respectively). One observes, for the odd-A nuclei, a clear stabilization of the deformation around a value of 450 fm^2 slightly larger than that of the ^{112,114}Cd even-even cores.

If we compare the $Q_{0\mathrm{charge}}$ obtained in our HF + BCS calculations and the Q_0 values extracted from experimental Q_{2^+} and $Q_{11/2^-}$ values [31] under the rotational assumption, the agreement is rather good as shown in Table 1 knowing that the absolute uncertainty on the experimental quadrupole moments is most likely underestimated. Concerning the $21/2^+$ state in odd-A nuclei, experimental $Q_{21/2^+}$ have been obtained in light ^{105,107}Cd isotopes by time-dependent perturbed angular distributions [32] and, from these measurements, the two-proton hole one-neutron particle $\pi(g_{9/2})^{-2}_{8^+} \otimes \nu d_{5/2}$ configuration has been proposed. In our case, this configuration can not be completely excluded but it is unlikely because, for ^{113,115}Cd, the neutron orbital $\nu d_{5/2}$ is far from the Fermi level as shown in Fig. 10.

5 Conclusion

The structure of neutron-rich cadmium nuclei has been investigated at high spin with a fusion-fission reaction induced by heavy-ions. New yrast bands built on the $\nu h_{11/2}$ isomer have been identified in ^{113}Cd and ^{115}Cd. Moreover, bands built upon multi-quasiparticle excitations have been observed in even-even cadmium (2qp) and in odd-A ones (3qp). We have interpreted our results in terms of decoupled rotational bands from comparisons between energies

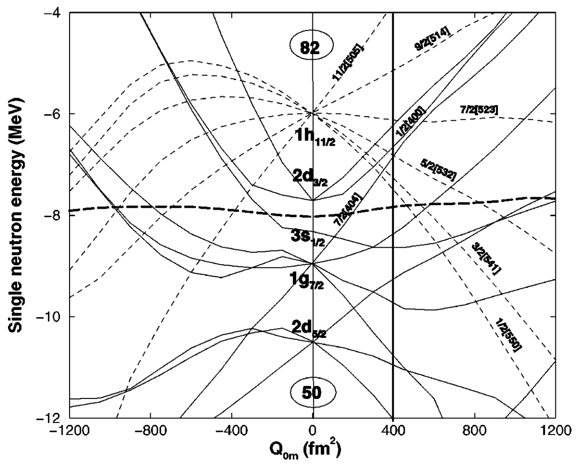

Fig. 10. Single neutron energies as function of the mass quadrupole moment for ^{114}Cd extracted from our Hartree-Fock + BCS calculations. The long-dashed line represents the Fermi level and the vertical line the mass quadrupole moment corresponding to the minimum. The solid lines correspond to the positive parity orbitals and the dashed lines to the negative parity orbitals.

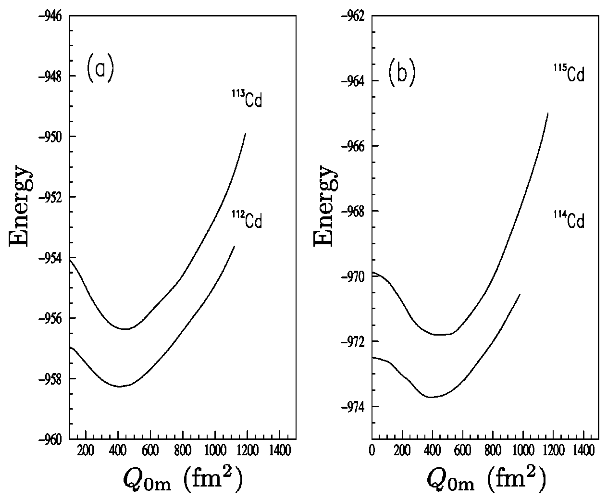

Fig. 11. Potential energy curves at prolate deformation extracted from the Hartree-Fock calculations for : (a) ^{112}Cd and ^{113}Cd (^{112}Cd + 1 qp $\nu h_{11/2}$ $\Omega = 1/2$) and (b) ^{114}Cd and ^{115}Cd (^{114}Cd + 1 qp $\nu h_{11/2}$ $\Omega = 1/2$).

in even-even and odd cadmium isotopes. This interpretation is in agreement with the one done for the lighter cadmium isotopes described as weakly prolate deformed nuclei. At low spin, the $^{111-114}$Cd isotopes seem to behave like vibrators but at higher spin, our observation of decoupled bands in ^{113,115}Cd shows the emergence of a deformation in these nuclei. Moreover, our static microscopic Hartree-Fock + BCS calculations using the SLy4 effective force show a weakly prolate deformation for these cadmium isotopes. To get a deeper insight of the deformation properties of cadmium isotopes, a dynamical microscopic approach is highly desirable. Directional correlation measurements will be necessary to assign unambiguously spin and parity of the new levels.

Table 1. Comparison of the charge quadrupole moments extracted from experimental Q_{2^+} and $Q_{11/2^-}$ values [31] (Q_{0c}^{exp}) and obtained in our Hartree-Fock + BCS calculations (Q_{0c}^{th}). The values of the β parameters are extracted from the theoretical quadrupole moments through the formula $Q_0 = \frac{3}{\sqrt{5\pi}} ZeR^2\beta(1 + 0.36\beta)$.

	112	113	114	115
Q_{0c}^{exp} (fm^2)	129 ± 14	184 ± 20	133 ± 14	140 ± 15
Q_{0c}^{th} (fm^2)	161	193	159	200
β^{th}	0.127	0.150	0.124	0.153

The advent of large arrays of Ge detectors combined with the use of heavy-ion induced fission reactions has allowed the possibility to investigate high spin states in nuclei in this mass region. Thus, similar results have been recently obtained in the neighbouring Pd isotopes [33], ^{112,113,115,118}Pd produced via the fusion-fission reaction ^{12}C + ^{238}U, corroborating the fact that, at high spin, these neutron-rich Cd and Pd isotopes present a small prolate deformation. From these investigations, a clearer idea of the structure of nuclei in this mass region is now emerging.

During completing this manuscript we have been acquainted that experimental results on the ground state bands have been recently obtained in these cadmium isotopes [34] and are in perfect agreement with our results.

The Eurogam project was funded jointly by IN2P3 (France) and the EPSRC (U.K.). We thank the crew of the Vivitron. We are very indebted to A. Meens for preparing the targets, G. Duchêne and D. Prévost for their help during the experiment. This work has been supported in part by the collaboration agreement Bulgarian Academy of Sciences-CNRS under contract No. 2937 and by the Bulgarian National Science Fund under contract No. Ph565.

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