第28卷 第1期
2004年1月

高 能 物 理 与 核 物 理
HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS

Vol.28, No.1
Jan., 2004

High-Spin States and Negative Parity Levels in Neutron-Rich ^{116,118,120}Cd Nuclei *

XIAO Shu-Dong[1] ZHU Sheng-Jiang[1;1)] YANG Li-Ming[1] J.H.Hamilton[2]
A.V.Ramayya[2] J.K.Hwang[2] ZHANG Zheng[1] JIANG Zhuo[1] CHE Xing-Lai[1]
U Yong-Nan[1] I.Y.Lee[3] J.O.Rasmussen[3] W.C.Ma[4]

1 (Department of Physics, Tsinghua University, Beijing 100084, China)
2 (Department of Physics, Vanderbilt University, Nashville, TN 37235, USA)
3 (Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA)
4 (Department of Physics, Mississippi State University, MS 39762, USA)

Abstract High spin states in neutron-rich ^{116,118,120}Cd nuclei have been investigated by observing high-fold prompt γ-ray coincidence events from the spontaneous fission of ^{252}Cf with the Gammasphere detector array. The yrast bands have been extended with spin up to 18 ℏ in ^{118}Cd and 16 ℏ in ^{116,120}Cd respectively. The band structures are calculated using the cranked shell model and possible origination for the backbends in the yrast bands is discussed. Proposed 5^- and 7^- levels are observed in each of these cadmium isotopes, and possible explanation for the negative states is discussed based on systematic comparison. A quasi-rotational band based on 7^- level in ^{118}Cd has been established.

Key words high-spin state, band-crossing, negative parity level

The neutron-rich ^{116,118,120}Cd nuclei, whose proton numbers ($Z = 48$) are close to the magic number $Z = 50$, have much deformed neutron structures with $N = 68$—72, and generally the single particle motion is relatively stronger than the collective one. Therefore their nuclear structures at low and high spin states should exhibit complex characteristics. In early reports, the low-lying states in ^{116,118,120}Cd have been studied through the β-decay measurements[1—4] and the light ion nuclear reaction such as the reaction ^{114}Cd(t, p)^{116}Cd[5]. However, as these neutron-rich nuclei cannot be formed by usual heavy ion nuclear reaction, it is difficult to investigate their high spin states. In a recent report, the higher energy levels of ^{116}Cd have been observed with spin up to 10 ℏ from quasielastic and deep-inelastic heavy ion collisions[6]. Another feasible method is to measure the prompt γ-rays of spontaneous fission of the heavy nuclei such as ^{252}Cf or ^{248}Cm[7,8]. By using this method, the yrast levels have been observed with spin up to 10 ℏ in ^{116}Cd[9], 14 ℏ in ^{118}Cd[9] and 8 ℏ in ^{120}Cd[10] respectively, but not performed with large detector array. On the other hand, the low-lying states of cadmium isotopes demonstrate vibrational structures. Some theoretical works using interacting boson model (IBM) have been performed[11]. Some 5^- states with their energy about 2.5MeV have been observed in even-even Cd isotopes, for examples, in ^{108}Cd[1,12], ^{110}Cd[1], ^{112}Cd[1,13,14], ^{114}Cd[1] and ^{116}Cd[2,5]. A prominent characteristic for the 5^- levels in some of these Cd isotopes is proposed as quadrupole-octupole coupled (QOC) states[2,12,14]. Following the development of large and efficient γ-ray multidetector array, it is possible to observe higher-spin states in neutron-rich nuclei formed as fission fragments in spontaneous or induced fission. In this letter, we report on observation of the new high spin states in ^{116,118,120}Cd by using this method. The yrast band structure is extended , and some negative parity levels

Received 16 May 2003
* Supported by Major State Basic Research Development Program (G2000077400), National Natural Science Foundation of China (19975028), U.S. Department of Energy (DE-FG05-88ER40407)
1) E-mail: zhushj@mail.tsinghua.edu.cn

have been proposed in the three cadmium isotopes.

The levels of ^{116,118,120}Cd nuclei were studied in spontaneous fission of ^{252}Cf. The experiment was carried out at the Lawrence Berkeley National Laboratory. Prompt γ-γ-γ coincidence studies were carried out with Gammasphere of 102 Compton-suppressed Ge detectors. The ^{252}Cf source of strength ~60 μCi was sandwiched between two Ni foils of thickness 10 mg/cm^2, and placed at the center of the Gammasphere detector array. A total of 5.7×10^{11} triple- and higher-fold coincidence events were collected. These data have higher statistics than the earlier measurements in Refs. [15,16] by a factor of ~15. The coincidence data were analyzed with the Radware software package[17]. The detailed information of experiment was presented in other papers[18—20].

In the spontaneous fission experiment, identification of γ-rays belonging to a particular nuclide is very complicated, since many transitions from high or low spin states of the different neutron-rich nuclei in mass region A = 100—150 intermix in the fission yields. One often observes γ-rays of the same or similar energy in different nuclei. Adopting the technology of γ-γ-γ-coincidence in data-analysis will give us more convenience in identifying the transitions that are very weak. Furthermore, there are always more than one pair of correlated partners with the production of given nuclide in spontaneous fissions. By gating on the known γ-rays in different partner isotopes, one can identify the transitions of interest in a particular isotope. For example, in this work, the partners of ^{118}Cd are ^{132}Sn (2n) and ^{134}Sn (4n) (numbers in parentheses here indicate the number of neutrons emitted after fission). When we gate on the γ-rays of ^{118}Cd, some γ-rays of ^{132}Sn (2n) and ^{134}Sn (4n) also appear in the coincidence spectrum. As an example, Fig.1 shows a coincidence spectrum of ^{118}Cd generated by double gating of the transitions at 488.1 and 677.4 keV. One can see the γ-peaks at 426.5, 545.7, 561.2, 584.1, 655.2, 704.8, 749.6, 772.3, 775.1 (mixed with 772.3), 788.0, 960.5 and 1058.3 keV in ^{118}Cd as well as the partner γ-peaks at 375 keV in ^{132}Sn (2n) and 1222 keV in ^{130}Sn (4n).

The level schemes of ^{116,118,120}Cd observed in the present work are shown in Fig.2. The yrast bands are extended with spin up to 16 ħ in ^{116,120}Cd and 18 ħ in ^{118}Cd

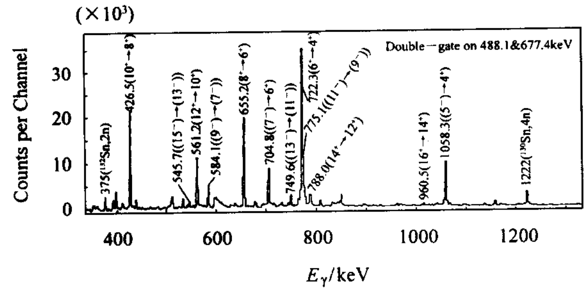

Fig.1. Coincidence spectrum obtained by double gating on the 488.1 and 677.4 keV in ^{118}Cd.

respectively. In the earlier data of ^{116}Cd, the 8^+ (2825 keV) and 10^+ (3040 keV) levels as well as the two transitions at 798 ($10^+\to8^+$) and 215 ($10^+\to8^+$) keV in the yrast band reported in Ref. [6] are different from those in Ref. [9]. Our data confirmed the result in Ref. [6]. A second 8^+ level at 2873.7 keV along with two weak linking transitions at 846.8 and 166.9 keV reported in Ref. [6] and the level at 2249.2 keV along with the 1029.6 keV linking transition reported in Refs. [1,2] are also confirmed. Besides, we add three new levels at 3579.1, 4379.4 and 5342.4 keV above the 10^+ levels in the yrast band. A new level at 2249.2 keV along with two side transitions, 666.3 and 444.0 keV are also observed. In ^{118}Cd, we confirmed the yrast band up to 14^+ reported in Ref. [9] and two side levels at 2223.8 and 2642.6 keV with much stronger linking transitions of 1058.3 and 704.8 keV to the yrast band observed in Ref. [1]. We also add two new levels at 5329.2 and 6408.3 keV above the 14^+ level. In ^{120}Cd, all the levels and transitions above the 6^+ level at 2033.8 keV are newly observed.

Spin and parities (J^π) for the new levels in the yrast bands are assigned based on observed regular level spacings and systematic comparison with the neighboring isotopes. Up to the 6^+ states, the level energies show behaviors of regular collective bands. The ratios of $E(4^+)/E(2^+)$ calculated as 2.37, 2.39 and 2.38 in ^{116}Cd, ^{118}Cd and ^{120}Cd respectively, give a vibrational and weakly rotational feature (with small deformation parameters). At the medium spin states between 6^+ and 12^+, the level spacings show irregularities and the structure variation happens. Plots of alignment angular moment i_x as a function of rotational frequency $\hbar\omega$ are shown in Fig.3. Band crosses (backbends) are sharply occurred at $\hbar\omega\approx0.27$ MeV for ^{116,120} Cd and $\hbar\omega\approx0.32$ MeV for ^{118}Cd respec-

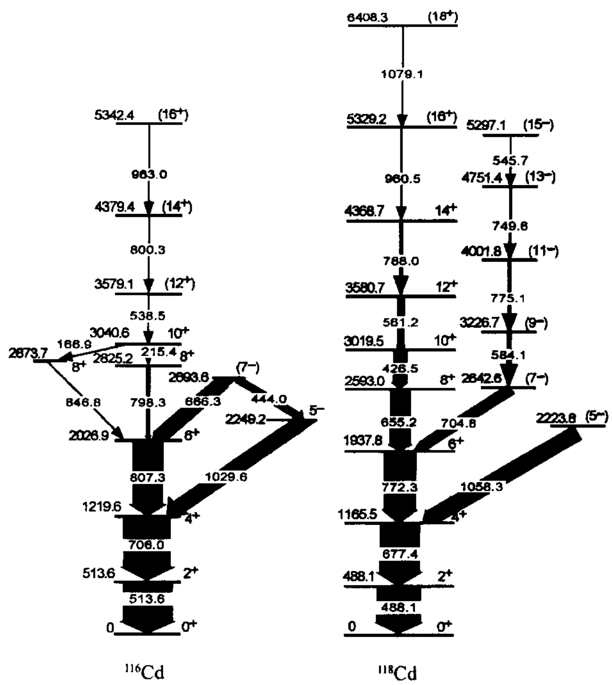

Fig.2. Level schemes assigned to ^{116,118,120}Cd in the present work. Transition and excitation energies are given in keV. The widths of the arrows are representative of the intensity of the transitions.

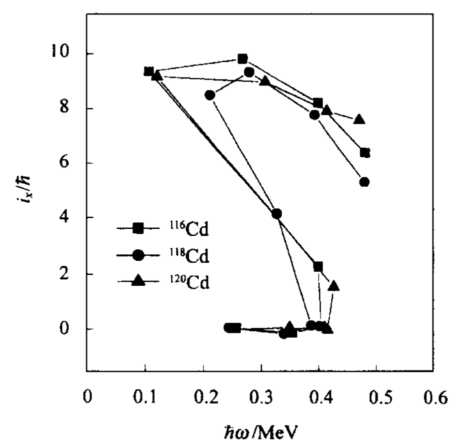

Fig.3. Alignments of angular moment i_x as a function of rotational frequency $\hbar\omega$ for the yrast bands in Cd isotopes.

tively. In order to make an appropriation interpretation of the observed backbends of yrast bands, we have employed the cranked shell model calculation to determine whether the proton orbital or the neutron orbital is responsible for the band crossings at the observed rotational frequencies. The calculation method is same as in Ref. [18]. The standard parameters used in the calculation for ^{118}Cd were as follows: quadrupole deformation $\beta_2 = 0.22$[1], hexadecapole deformation $\beta_4 = 0$, paring gap parameter $\Delta p =$ 0.6615 and $\Delta n = 1.4864$, Fermi levels for protons and neutrons $\lambda_p = -9.7107$ and $\lambda_n = -7.0269$. The calcu-

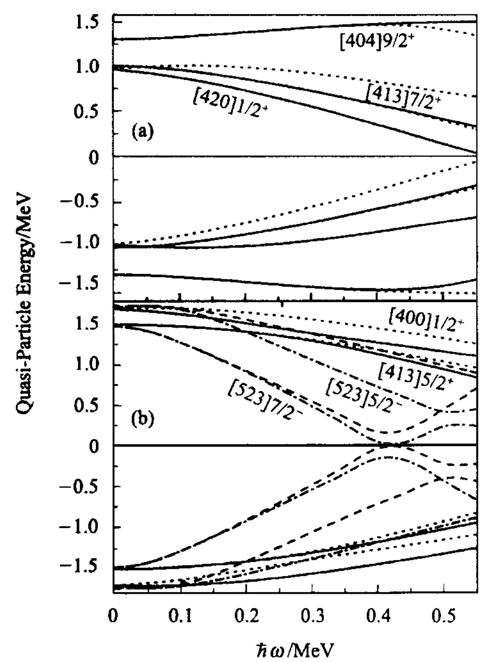

Fig.4. Cranked Wood-Saxon quasi-particle energy diagrams for neutrons (a) and for protons (b) calculated. The parity and signature (π, α) of the levels are: $(+, +1/2)$—solid lines; $(+, -1/2)$—dotted lines; $(-, +1/2)$—dot-dashed lines; $(-, -1/2)$—dashed lines.

lated Routhians for protons and neutrons in ^{118}Cd are shown in Fig.4. The crossing related to the alignment of $h_{11/2}$ neutrons is predicted to occur at $\hbar\omega \approx 0.40$ MeV, whereas alignment of protons is predicted to occur at $\hbar\omega \approx 0.65$ MeV. The former value is closer to the experiment data than the later one. So the band crossings in ^{116,118,120}Cd are likely caused by alignment of a pair of neutrons. However, the calculated crossing frequencies for the alignment neutrons are still larger than the experiment values. The reason may be that these Cd nuclei do not belong to well-deformed rotors and the deformation is very soft. It is mixed with the vibration. So the back-bending curves are very sharply than those of the normal well-deformed bands. It needs more theoretical work to make proper explanation for the band crossings in these Cd nuclei.

Based on the present results and other available data[1,6,21], the energy systematic for the yrast levels in the even-mass $^{108-122}$Cd is shown in Fig.5. Generally, the level energies for each state changed smoothly with the neutron numbers. The minimizing excitation energies at $N = 70$ indicate strongest collectivity in ^{118}Cd. However, the 8^+ states in ^{110,116,118}Cd lie higher than in the neighboring even-mass isotopes and exhibit irregularities. It caused more sharply band crossing. The new level at 2921.7 keV observed in ^{120}Cd are similar with the 8^+ level at 2873 keV in ^{116}Cd[6]. Based on the systematic comparison, we tentatively assign the J^π for 2921.7 keV level in ^{120}Cd as 8^+. These second 8^+ levels could be caused by a less aligned member of the neutron $h^2_{11/2}$ multiplet as proposed in ^{116}Cd[6].

Three levels at 2249.2 keV in ^{116}Cd, at 2238.8 keV in ^{118}Cd and at 2219.3 keV in ^{120}Cd are with some similarity. All of them are fed to the 4^+ levels of the yrast bands through much stronger transitions of 1029.6, 1058.3 and 925.7 keV respectively. As the J^π of 2249.2 level in ^{116}Cd has been assigned as 5^-[2,5], we tentatively assign the J^π of 2223.8 and 2129.3 keV in ^{118,116}Cd as 5^- based on systematics. The similar 5^- level

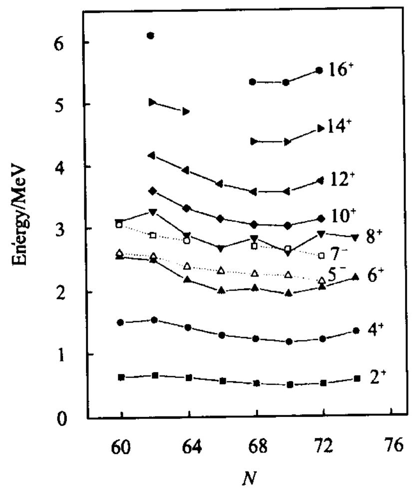

Fig.5. Systematic of the yrast levels as well as the 5^- and 7^- levels in even-mass Cd nuclei.

is also observed in the lighter even $^{108-112}$Cd isotopes[1,13,14]. The origination of 5^- state in ^{112}Cd is explained by quadrupole-octupole coupled (QOC) states of the configuration $|2^+ \otimes 3^-\rangle$[13]. The 5^- state should locate at an excitation energy close to the sum of the energies of the first excited 2^+ and 3^- states[13]. The experimental values for sum of the energies of the first excited 2^+ and 3^- states are 2435, 2423 and 2426 keV in ^{116,118,120}Cd respectively. Generally, they are close to the corresponding 5^- states. Other three levels, 2693.6 keV in ^{116}Cd, 2646.6 keV in ^{118}Cd and 2525.7 keV in ^{120}Cd, have been tentatively assigned as 7^- states based on the systematic comparison also, as the 7^- states have been observed in even $^{108-114}$Cd nuclei[1]. These 7^- states may originate from the two-quasineutron configurations, $[d_{3/2}h_{11/2}]$ or $[g_{7/2}h_{11/2}]$[13]. The energy systematic for 5^- and 7^- levels in the even-mass $^{108-122}$Cd is also shown in Fig.5. They change smoothly with the neutron numbers.

A new cascade based on the 2642.6 keV (7^-) level in ^{118}Cd has been established. It forms a quasi-rotational band as the energy spacings above the 4001.8(11^-) keV level are irregular. More work is needed to do in order to understand the detailed character for this band.

References

1 Firestone Richard B. Table of Isotopes CD-ROM (1998), Lawrence Berkeley National Laboratory, University of California
2 WANG Y B et al. Phys. Rev., 2001, **C64**:054315
3 Aprahamian A et al. Phys. Rev. Lett., 1987, **59**:535
4 Fogelberg B et al. Phys. Lett., 1971, **B36**:334
5 Watson D L et al. J. Phys., 1987, **G13**:1443
6 Juutinen S et al. Phys. Lett., 1996, **B386**:80
7 ZHU S J. Trends in Nucl. Phys., 1992, **9**(2):8(in Chinese)
(朱胜江. 核物理动态, 1992,**9**(2):8)
8 Hamilton J H, Ramayya A V, ZHU S J et al. Prog. Part. Nucl. Phys., 1995, **35**:635
9 Durell J L. Proc. Int. Conf. on Spectroscopy of Heavy Nuclei, 1989, Crete, Greece 1990, 307
10 ZHU S J, Lee I Y. High Energy Phys. and Nucl. Phys., 1993, **17**: 353(in Chinese)
(朱胜江,Lee I Y. 高能物理与核物理, 1993,**17**:353)
11 LONG G L, ZHU S J, SUN H Z. J. Phys., 1995, **G21**:331
12 Gade A, Brentano P von. Phys. Rev., 2002, **C66**:014304
13 Drissi S et al. Nucl. Phys., 1997, **A614**:137
14 Garrett P E et al. Phys. Rev., 1999, **C59**:2455
15 ZHU S J et al. Chin. Phys. Lett., 1998, **15**:793
16 ZHU S J et al. Phys. Lett., 1995, **B357**:273
17 Radford D C. Nucl. Instr. Meth., 1995, **A361**:297
18 ZHU S J et al. Phys. Rev., 1999, **C59**:1316
19 ZHU S J et al. Phys. Rev., 1999, **C60**:051304
20 ZHU S J et al. Phys. Rev., 2001, **C65**:014307
21 Zamfir N V et al. Phys. Rev., 1995: **C51**:99

丰中子核^{116,118,120}Cd的高自旋态和负宇称能级研究*

肖树冬[1]　朱胜江[1;1)]　杨利明[1]　J.H.Hamilton[2]　A.V.Ramayya[2]　J.K.Hwang[2]
张征[1]　姜卓[1]　车兴来[1]　禹英男[1]　I.Y.Lee[3]　J.O.Rasmussen[3]　W.C.Ma[4]

1(清华大学物理系　北京　100084)
2(Department of Physics, Vanderbilt University, Nashville, TN 37235, USA)
3(Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA)
4(Department of Physics, Mississippi State University, MS 39762, USA)

摘要　通过对^{252}Cf自发裂变产生的瞬发γ射线的多重符合测量,对丰中子核^{116,118,120}Cd的高自旋态进行了研究. 实验是利用美国罗仑兹伯克利实验室的超级γ球探测装置进行的. ^{118}Cd的晕带自旋扩展到18$\hbar$,而^{116,120}Cd的晕带扩展到16$\hbar$. 利用推转壳模型对带结构进行了计算,对这几个核晕带很陡的回弯现象做了讨论. 在每个核中观测到了5^-和7^-能级,对其特性进行了讨论. 在^{118}Cd中还观测到一个基于7^-能级的准转动带.

关键词　高自旋态　带交叉　负宇称能级

2003-05-16 收稿
* 国家重点基础研究发展规划项目(G2000077400),国家自然科学基金(19975028),美国能源部(DE-FG05-88ER40407)资助

1) E-mail: zhushj@mail.tsinghua.edu.cn