EPJ Web of Conferences **66**, 02085 (2014)
DOI: 10.1051/epjconf/20146602085

Nuclear Structure Studies of ^{106}Pd and ^{106}Cd with the (n,n′γ) Reaction

F.M. Prados-Estévez[1,2,a], A. Chakraborty[1,2], E.E. Peters[2], M.G. Mynk[2], A. Linnemann[3], D. Bandyopadhyay[1], N. Boukharouba[1], S.N. Choudry[1], B.P Crider[1], P.E. Garrett[4], S.F. Hicks[5], J. Jolie[3], A. Kumar[1], S.R. Lesher[1], C.J. McKay[1], M.T. McEllistrem[1], S. Mukhopadhyay[1], J.N. Orce[1], M. Scheck[1], J.R. Vanhoy[6], J.L. Wood[7], and S.W. Yates[1,2]

[1] *Department of Physics & Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA*
[2] *Department of Chemistry, University of Kentucky, Lexington, KY 40506-0055, USA*
[3] *Institut für Kernphysik, Universität zu Köln, Zülpicherstrasse 77, D-50937 Köln, Germany*
[4] *Department of Physics, University of Guelph, Guelph, Ontario, N1G2W1, Canada*
[5] *Department of Physics, University of Dallas, Irving, TX 75062, USA*
[6] *Department of Physics, United States Naval Academy, Annapolis, MD 21402, USA*
[7] *School of Physics, Georgia Institute of Technology, Atlanta, GA 30332-0430, USA*

Abstract. Excited states in ^{106}Pd and ^{106}Cd have been studied using the (n,n′γ) reaction. The data include level lifetimes, spins, branching ratios, and multipole mixing ratios, and give a comprehensive view of excitations with spin $\leq 6\hbar$. The determined $E2$ strengths show serious discrepancies with the quadrupole phonon structure expected in these nuclei.

1 Introduction

Quadrupole shape vibrations are considered in collective models to be fundamental degrees of freedom of nuclei. Several candidates in the $_{48}$Cd and $_{46}$Pd region have been proposed as good examples of spherical quadrupole shape vibrators. However, a recent program of systematic study of even-mass stable Cd isotopes concluded that these nuclei are very poorly described by vibrational models [1–3]. This conclusion was based upon lifetime measurements of excited states in ^{110,112,114}Cd [4–6] which allowed the determination of $B(E2)$s that were found to be inconsistent with model calculations. The question remains as to whether the lower-mass Cd and the neighboring Pd isotopes may be examples of near-harmonic quadrupole vibrators.

Coulomb excitation experiments have been reported on ^{106,108,110}Pd [7, 8]. These studies led to the conclusion that the vibrational degrees of freedom may be important for the description of the low-lying level structure of ^{106}Pd; however, serious discrepancies were found in the decay properties. Many of the decay transitions are slower than predicted for a pure harmonic quadrupole vibrator, *i.e.*, in many cases the $B(E2)$s are too small by a factor of two or more when compared with the harmonic quadrupole vibrational pattern shown in Figure 1. If we allow that this deficiency is the result of "anharmonicity" that fragments the expected strength, causing it to appear from other higher-lying

[a] e-mail: francisco.prados-estevez@uky.edu

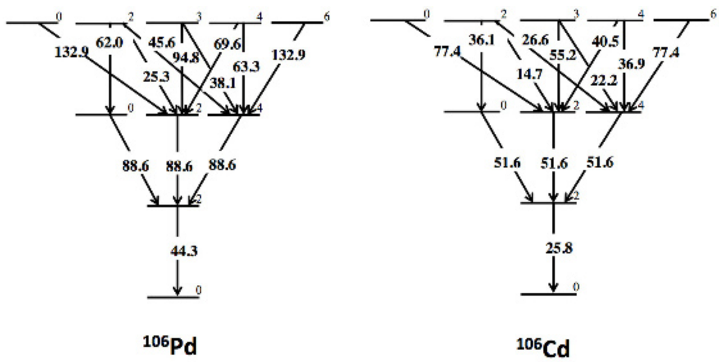


Figure 1. Low-lying levels and the reduced $E2$ transition strengths in W.u. given by the harmonic spherical-vibrator model for ^{106}Pd and ^{106}Cd. The reduced transition rates are normalized to the experimental values of 44.3(15) and 25.8(3) W.u. for the one-phonon to ground-state transitions for ^{106}Pd [9] and ^{106}Cd [9], respectively.

0^+, 2^+, 3^+, and 4^+ states, then the challenge is to identify the $E2$ strength from many higher-energy 0^+, 2^+, 3^+, and 4^+ states to the two-phonon states.

We performed studies of the low-lying structures of ^{106}Pd and ^{106}Cd via γ-ray spectroscopy following inelastic neutron scattering. These measurements, performed at the University of Kentucky Accelerator Laboratory provide a detailed characterization of the low-lying excited states, including excitation energies, spins, parities, branching ratios, transition multipolarities, and level lifetimes. This wealth of information allows the determination of $E2$ strengths and affords comparisons with the predicted phonon structure to be drawn.

2 Experimental Setup

Angular distribution measurements were performed at 2.2 (2.6), 2.7 (3.3) and 3.5 (3.7) MeV for ^{106}Pd (^{106}Cd). A HPGe detector (relative efficiency >50%) with an annular BGO Compton suppression shield was rotated through angles from 40° to 150°. Level spins and multipole mixing ratios were deduced by comparing the measured angular distributions with calculations from the statistical model code CINDY [10]. Branching ratios were also obtained from the angular distribution data. Level lifetimes were extracted from each angular distribution using the Doppler-shift attenuation method with the methodology described in Refs. [11, 12]. The γ-ray excitation functions of the levels in ^{106}Pd and ^{106}Cd were measured over a range of neutron energies from 2.0 to 3.8 MeV in 0.1-MeV steps, at 90° with respect to the beam direction. The γ-ray thresholds and shapes of the excitation functions were used to identify new levels and to place transitions in the level scheme. Along with the angular distribution data, the excitation functions also contribute to the determination of spins. The excitation function yields, corrected for γ-ray detection efficiency, were compared to statistical model calculations using the code CINDY [10], which also predicts the change in the level cross sections as a function of bombarding energy.

A γ-γ coincidence measurement was carried out for ^{106}Pd at a neutron energy of 3.3 MeV with four HPGe detectors placed ~ 6 cm from the center of the sample in a co-planar arrangement [13]. Events were recorded when at least two detectors registered coincidences within a 100-ns time window. The data were sorted off-line into 4k × 4k prompt and random-background matrices with 40-ns coincidence time gates. The random background matrix was then subtracted from the prompt matrix. The off-line coincidence data analyses were performed using the RADWARE software package [14].

The γ-γ coincidence data were used to build the level scheme of ^{106}Pd, and also to determine relative intensities in complex regions of the γ-ray spectrum.

3 Experimental Results and Conclusions

Figure 2 shows the summing of $B(E2;\ 2^+ \rightarrow 0_2^+)$(blue), $B(E2;\ 2^+ \rightarrow 2_2^+)$, $B(E2;\ 4^+ \rightarrow 2_2^+)$, $B(E2;\ 3^+ \rightarrow 2_2^+)$, $B(E2;\ 0^+ \rightarrow 2_2^+)$(black), $B(E2;\ 2^+ \rightarrow 4_1^+)$, $B(E2;\ 4^+ \rightarrow 4_1^+)$, and $B(E2; 3^+ \rightarrow 4_1^+)$ (red) values (in W.u.) in ^{106}Pd between ~ 1550 and ~ 2900 keV excitation energy, compared with the harmonic oscillator predictions for the three-phonon triplet. It is evident, by summing $B(E2)$ values for the transitions feeding the two-phonon triplet, that ^{106}Pd is not a good candidate for a quadrupole vibrational nucleus. Although a quintuplet of levels with appropriate spins is present, their decay strengths are inconsistent with the three-phonon interpretation. A deficit in $E2$ strength exists in all cases, except possibly for the $2^+_{3ph} \rightarrow 2^+_{2ph}$ transition, and we must conclude that fragmentation into high-lying states cannot account for the observed deficiency.

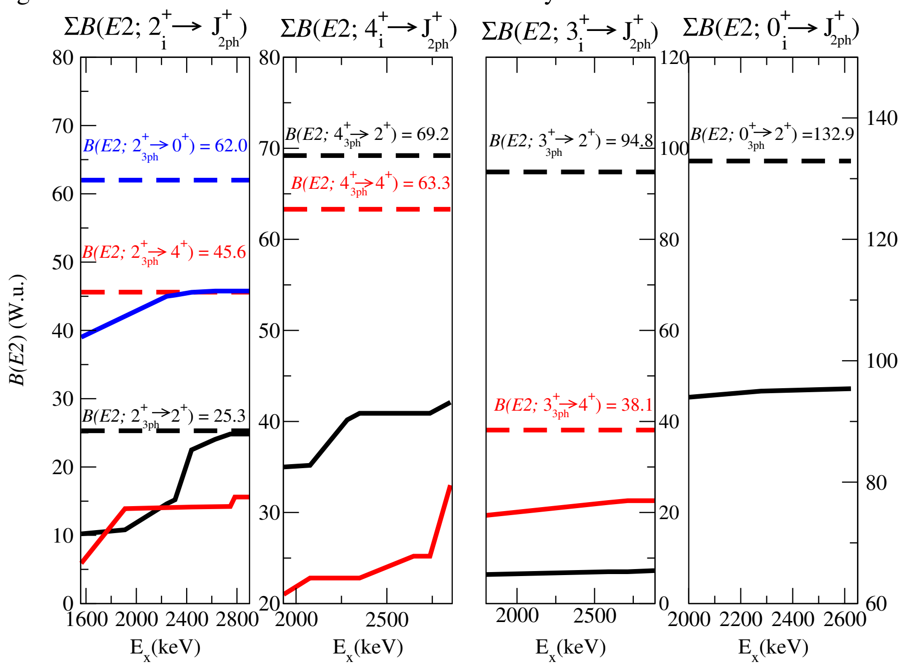
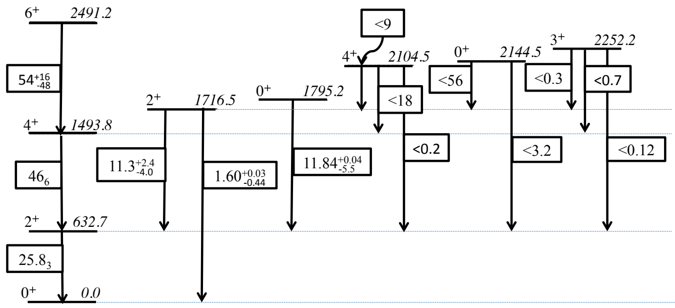


Figure 2. Cumulative sums of $B(E2;2^+\rightarrow 0_2^+)$(blue), $B(E2;2^+\rightarrow 2_2^+)$, $B(E2;4^+\rightarrow 2_2^+)$, $B(E2;3^+\rightarrow 2_2^+)$, and $B(E2;0^+\rightarrow 2_2^+)$(black); $B(E2;2^+\rightarrow 4_1^+)$, $B(E2;4^+\rightarrow 4_1^+)$, and $B(E2;3^+\rightarrow 4_1^+)$(red) values (in W.u.) *vs.* excitation energy. Each plot shows the expected harmonic oscillator values (dashed lines) in ^{106}Pd.

Figure 3 shows the low-lying "phonon" structure in ^{106}Cd, where the $B(E2)$s are given in the boxes. It is evident that the phonon structure in ^{106}Cd also experiences difficulties, showing a large deficiency in the $E2$ strength for the decays from the two-phonon states, particularly for the $2_2^+ \rightarrow 2_1^+$ and $0_2^+ \rightarrow 2_1^+$ transitions, whose $B(E2)$s are only ~21% of the expected values shown in Figure 1. For decays from the three-phonon states, only upper limits in the $E2$ strengths have been determined, but it is clear that the phonon structure collapses here as well.

Giannatiempo et al. [15] have performed interacting boson approximation-2 model calculations of the positive-parity levels in many even-A Pd isotopes, including ^{106}Pd. While these detailed calculations in the $U(5)$ limit of the model reproduce many of the features of the low-lying structure of ^{106}Pd, they fail to explain the $E2$ strengths of decays from the non-yrast states considered here.



^{106}Cd

Figure 3. Low-lying portion of the ^{106}Cd level scheme. Levels represented in this figure have been interpreted as vibrational phonon states, with the 6^+(2491), 4^+(2105), 3^+(2252), and 0^+(2144) states forming part of the three-phonon quintuplet. The $B(E2)$s from the 2^+_1 and 4^+_1 levels in the figure are from the NDS [9], because the lifetimes of these low-lying levels are too long to be determined by the present Doppler-shift attenuation method. The $E2$ strengths for the decays from the two-phonon levels and upper limits for the 4^+(2105), 3^+(2252), and 0^+(2144) states were determined using the angular distributions at 2.6 and 3.3 MeV.

4 Acknowledgments

The authors sincerely thank H.E. Baber for his contributions in maintaining the Van de Graaff accelerator. This material is based upon work supported by the U.S. National Science Foundation under Grant No. PHY-0956310.

References

[1] P.E. Garrett et al., Phys. Rev. C **78**, 044307 (2008).
[2] K. L. Green et al., Phys. Rev. C **80**, 032502 (2009).
[3] P.E. Garrett and J.L .Wood, J. Phys. G: Nucl. Part. Phys. **37**, 064028 (2010).
[4] P.E. Garrett et al., Phys. Rev. C **75**, 054310 (2007).
[5] D. Bandyopadhyay et al., Phys. Rev. C **76**, 054308 (2007).
[6] M. Kadi et al., Phys. Rev. C **68**, 031306(R) (2003).
[7] L.E. Svensson et al., Nucl. Phys. **A584**, 547 (1995).
[8] L.E. Svensson, Ph.D. thesis, University of Uppsala (1989).
[9] D. De Frenne and A. Negret, Nuclear Data Sheets **109**, 943 (2008).
[10] E. Sheldon and V.C. Rogers, Comput. Phys. Commun. **6**, 99 (1973); P.A. Moldauer, Phys. Rev. C **14**, 764 (1976).
[11] T. Belgya, G. Molnár, and S.W. Yates, Nucl. Phys. **A607**, 43 (1996).
[12] K.B. Winterbon, Nucl. Phys. **A246**, 293 (1975).
[13] C.A. McGrath, P.E. Garrett, M.F. Villani, and S.W. Yates, Nucl. Instrum. Methods Phys. Res. A **421**, 458 (1999).
[14] D.C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).
[15] A. Giannatiempo, A. Nannini, and P. Sona, Phys. Rev. C **58**, 3316 (1998).