RDM lifetime measurements in ^{107}Cd

K Andgren¹, S F Ashley², P H Regan², E A McCutchan³, N V Zamfir³,
L Amon⁴, R B Cakirli⁴, R F Casten³, R M Clark⁵, G Gürdal^{3,6},
K L Keyes⁷, D A Meyer³, M N Erduran⁴, A Papenberg⁷, N Pietralla⁸,
C Plettner³, G Rainovski⁸, R V Ribas⁹, N J Thomas^{2,3}, J Vinson³,
D D Warner¹⁰, V Werner³ and E Williams³

¹ Department of Physics, Royal Institute of Technology, S-104 05 Stockholm, Sweden

² Department of Physics, University of Surrey, Guildford GU2 7XH, UK

³ WNSL, Yale University, New Haven, CT 06520, USA

⁴ Department of Physics, Istanbul University, Istanbul, Turkey

⁵ Lawrence Berkeley National Lab, Berkeley, CA 94720, USA

⁶ Clark University, Worcester, MA, 01610-1477, USA

⁷ Institute of Physical Research, University of Paisley, Paisley PA1 2BE, UK

⁸ Department of Physics and Astronomy, SUNY, Stony Brook, NY 11794, USA

⁹ Instituto de Física, Uni. de Sao Paulo, SP, Caixa Postal 05315-970, Brazil

¹⁰ CCLRC, Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, UK

Received 18 March 2005

Published 12 September 2005

Online at stacks.iop.org/JPhysG/31/S1563

Abstract

Lifetimes for decays linking near-yrast states in ^{107}Cd have been measured using the recoil distance method (RDM). The nucleus of interest was populated via the $^{98}\text{Mo}(^{12}\text{C}, 3n)^{107}\text{Cd}$ fusion–evaporation reaction at an incident beam energy of 60 MeV. From the measured lifetimes, transition probabilities have been deduced and compared with the theoretical $B(E2)$ values for limiting cases of harmonic vibrational and axially deformed rotational systems. Our initial results suggest a rotor-like behaviour for the structure based on the unnatural-parity, $h_{\frac{11}{2}}$ orbital in ^{107}Cd , providing further evidence for the role of this ‘shape-polarizing’ orbital in stabilizing the nuclear deformation in the $A \sim 100$ transitional region.

1. Introduction

Collective behaviour in nuclei can often be approximated to either a near-harmonic quadrupole vibration [1] or the rotation of a symmetrically deformed object [2]. The even–even cadmium isotopes are considered to be amongst the best examples of nuclei which exhibit the $U(5)$ dynamical symmetry, corresponding to collective quadrupole-vibrational excitations in nuclei [3–5]. However, as pointed out in [6–8] the yrast sequences of such nuclei appear to show a change in collective excitation from vibrational to rotational which is associated with the population of low- Ω , unnatural parity $h_{\frac{11}{2}}$ orbitals. The decay schemes of the odd- N ,

Cd isotopes from $A = 105$ – 123 all show collective band structures built on this negative parity orbital [9–14] and magnetic moment measurements in these nuclei have demonstrated an almost pure $h_{11/2}$ neutron character for the bandhead of these structures [15]. However, in contrast to the vibrational-like behaviour deduced for the even–even cores, the structures in the odd- A Cd isotopes have been interpreted using cranked–shell model (CSM) arguments to be rotational in nature [8–14], with the $h_{11/2}$ neutron orbital weakly-coupled in a rotation-aligned [16] manner to a statically (weakly) deformed core.

The concept of E-GOS (E_γ over spin) plots has been introduced [6, 7] to provide a simple, empirical method with which to identify vibrator-to-rotor transitions as a function of increasing angular momentum. Such plots for the near-stable $A \sim 100$ – 110 region allude to the shape-polarizing role of one or two unpaired $h_{11/2}$ neutron orbitals in altering the yrast mode of excitation from a quasi-vibrational structure to a rotational, statically deformed sequence. A complementary test for such a change of excitation mode can be obtained from the measurement of transition rates from decays of the excited levels [4, 17]. In the simplest approximation, the reduced transition probability, $B(E2)$, between yrast states in a perfect, axially symmetric rotor approaches a constant value with increasing spin, while for a perfect harmonic vibrator it is proportional to the phonon number, n , of the initial state [18]. Note that the behaviour of the intra-yrast $B(E2)$ values is modified in the quadrupole vibrational limit ($U(5)$) of the interacting boson approximation (IBA) to take into account finite valence space arguments [5] (see section 4).

In order to shed more light on the role of the $h_{11/2}$ orbital in driving the proposed $U(5)$ -like vibrational even–even cadmium cores to statically deformed, rotational-aligned configurations [8], we have extended the lifetime measurements in the $h_{11/2}$ band in ^{107}Cd and neighbouring nuclei. The preliminary results of this analysis are presented in this paper. The evaluated nuclear data for the lifetime of the first transition ($\frac{15}{2}^- \rightarrow \frac{11}{2}^-$) in the negative parity sequence in ^{107}Cd [17] have been interpreted as evidence for a vibrational-like coupling [19] rather than a rotational-aligned configuration as might be expected from the CSM-like analysis described in [9–14]. (There has also been an unevaluated report on the lifetimes in the $\nu h_{11/2}$ band in this nucleus [20].)

2. Experimental details and data analysis

The nucleus of interest was populated via the fusion–evaporation reaction $^{98}\text{Mo}(^{12}\text{C}, 3n)^{107}\text{Cd}$ at an incident beam energy of 60 MeV delivered by the WNSL Yale tandem accelerator. The self-supporting target had a thickness of $1.05(5) \text{ mg cm}^{-2}$. The beam was estimated to lose less than 1.5 MeV through the target [21], with the beam energy in the centre of the target estimated to be 59.3 MeV. Reaction γ -rays were detected using the SPEEDY Ge detector array [22], which consisted of eight, four-element germanium clover detectors. The hardware electronic master-gate condition was set such that at least two separate clover units had to register Compton-suppressed energy events in prompt, mutual coincidence ($\Delta t \sim 50 \text{ ns}$) for the event to be recorded for subsequent off-line analysis. The Ge detectors were arranged in two separate angular rings centred at average of 41.5° and 138.5° relative to the beam axis. A gold stopper was inserted behind the target position and measurements were taken at ten different target–stopper distances (11, 14, 18, 23, 28, 41, 56, 127, 330 and $2008 \mu\text{m}$) which were determined and kept constant using the piezo-electric feedback capacitance system of the New Yale Plunger Device (NYPD) [23, 24].

The data were sorted into γ – γ coincidence matrices for the different angle–angle combinations and evaluated for the ten different target–stopper distances. The average value of

Figure 1. (Upper): γ -ray spectra obtained from a gate on the Doppler shifted component of the 798 keV transition $\frac{19}{2}^- \rightarrow \frac{15}{2}^-$ in the $h_{11/2}$ band of ^{107}Cd . The decaying 515 keV transition is labelled and the change in the intensities of the unshifted and shifted parts with respect to the distance can be clearly seen. The regions from which the background is calculated are also shown. The ring–ring combination is 41° – 41° and the target–stopper distances from left to right are 11 μm , 56 μm and 2008 μm respectively. (Centre) and (Lower): gates on the shifted component of the 956 keV $\frac{23}{2}^- \rightarrow \frac{19}{2}^-$ transition showing the 798 keV transition at forward and backward (lower) angles.

the recoil velocity of the reaction products leaving the ^{98}Mo target was deduced by measuring the centroids of stopped and shifted peaks associated with the strongest transitions in ^{107}Cd [10] to be 0.81(4)% of the speed of light. The state mean lifetimes were then deduced following analysis using the differential decay curve method (DDCM) as outlined in [26–28].

Figure 1 shows selected examples of angle-projected spectra obtained by gating on Doppler shifted γ -ray transitions from gates set on the shifted components of the 798 keV and 956 keV transitions in the $\Delta I = 2$ sequence built on the yrast $I^\pi = \frac{11}{2}^-$ state in ^{107}Cd . Due to the finite thickness of the target and the relatively small initial recoil velocity, a small fraction ($\sim 10\%$) of the recoiling nuclei were observed to stop in the target. This effect can be inferred by the incidence of unshifted peaks in the total projection spectra taken for the longest target–stopper distance (2008 μm). Since the lifetimes of the higher-spin states in ^{107}Cd are expected to be less than 1 ps [4, 20], these states would be expected to decay in flight and only shifted peaks should appear in the spectra. Since both shifted and unshifted components are observed at the longest distance, some of the recoils must have stopped (and

Figure 2. Mean lifetime determination of the $I^\pi = 15/2^-$ level (left) and the $I^\pi = 19/2^-$ (right) yrast levels in ^{107}Cd . The γ - γ matrices were gated on the shifted components of the feeding transitions 798 keV and 956 keV, respectively. The intensities of the shifted and unshifted peaks of the decaying 515 keV and 798 keV transitions, are shown in the lower panels.

therefore decayed) within the target. Any problems in the analysis associated with this effect can be avoided by selectively gating only on the *shifted* component of the feeding transitions.

3. Results

The lifetimes of the yrast $\frac{15}{2}^-$ and $\frac{19}{2}^-$ states in ^{107}Cd were extracted from the current data. Figure 2 shows the intensity curves, from which the lifetimes were obtained.

The decay mean life for the $\frac{15}{2}^-$ state in ^{107}Cd has been measured previously by Häusser *et al* [17] to be 23.5(15) ps. Our initial analysis gives a value of $\tau = 26.5(9)$ ps for this state, consistent at the 2σ level with the evaluated value. Our value of $\tau = 3.4(6)$ ps for the $\frac{19}{2}^-$ state is also consistent with the unevaluated value reported by Vishnevsky *et al* [20]. The lifetimes of higher spin states in the negative-parity sequence in ^{107}Cd are comparable to or shorter than the slowing down time in the stopper (<1 ps) and therefore the DDCM analysis was not used for these states.

4. Discussion and conclusions

A series of simple relations allow a comparison of the measured ratios of the $B(E2 : I \rightarrow I - 2)$ values between yrast states in the Cd isotopes and the lowest-lying (collective) decay in the same nucleus for different mechanisms of collective nuclear excitation. These are plotted for the yrast bands in $^{106,8}\text{Cd}$ [29] and the negative parity bands in $^{107,9}\text{Cd}$ [4, 20] in figure 3.

Assuming axially symmetric ($\gamma = 0^\circ$) quadrupole deformed shapes, the $B(E2 : I \rightarrow I - 2)$ value for a stretched E2 transition between two successive states in a rotational band,

Figure 3. Ratio of measured $B(E2)$ values for the low-lying yrast states in $^{106,8}\text{Cd}$ and the negative parity bands in $^{107,9}\text{Cd}$. The solid lines represent the limiting cases for a perfect axially deformed rotor, a perfect harmonic vibrator and the $U(5)$ limit of the interacting boson model. The solid data point for ^{107}Cd corresponds to the measurement obtained in the current work. The other data points are from [4, 20, 29].

characterized by a constant K value and a transition quadrupole moment, Q_0 , is given by [18],

$$\begin{aligned} B(E2 : I, K \rightarrow I - 2, K) &= \frac{5}{16\pi} Q_0^2 |\langle IK20 | I - 2K \rangle|^2 \\ &= \frac{5}{16\pi} Q_0^2 \frac{3(I - K)(I - K - 1)(I + K)(I + K - 1)}{(2I - 2)I(2I - 1)(2I + 1)}. \end{aligned} \quad (1)$$

Thus, for constant values of K and Q_0 in an axially symmetric rotational band, the ratio of $B(E2)$ values for the band members is simply given by the square of the ratio of Clebsch–Gordan coefficients [30, 31].

In the $U(5)$ vibrational limit of the interacting boson model [5], the ratio of $B(E2)$ value between successive yrast, $\Delta I = 2$ states can be reduced to [32]

$$\frac{B(E2 : I \rightarrow I - 2)}{B(E2 : 2^+ \rightarrow 0^+)} = \frac{1}{4} \frac{I(2N - I + 2)}{N} \quad (2)$$

where N is the number of valence bosons ($N = 5, 6$ for $^{106,8}\text{Cd}$ respectively) and I is the spin of the upper yrast level which decays via a stretched electric quadrupole transition to an yrast state of spin $I - 2$.

From the E-GOS energy parametrization, the $\nu h_{11/2}$ band in ^{107}Cd appears to have a rotational, rather than vibrational-like character [7], which is consistent with the obtained lifetimes for this band as shown in figure 3. The corresponding E-GOS plot for the even–even nucleus ^{106}Cd indicates a more vibrational-like sequence at low-spins, leading to the conclusion that the $h_{11/2}$ neutron in ^{107}Cd polarizes the nucleus towards a stable prolate deformation.

Acknowledgments

This work was supported by the US Department of Energy under the contracts DE-FG02-91ER-40609, DE-FG02-88ER-40417 and the Yale University Flint and Science Development Fund, and the Engineering and Physical Sciences Research Council (UK).

References

- [1] Scharff-Goldhaber G and Weneser J 1955 *Phys. Rev.* **98** 212
- [2] Bohr A 1952 *Mat.-Fys. Medd. K. Dan. Vidensk. Selsk.* **26** 14
- [3] Kern J *et al* 1995 *Nucl. Phys. A* **593** 21
- [4] Harissopulos S *et al* 2001 *Nucl. Phys. A* **683** 157
- [5] Arima A and Iachello F 1976 *Ann. Phys.* **99** 253
- [6] Regan P H *et al* 2003 *Phys. Rev. Lett.* **90** 152502
- [7] Regan P H *et al* 2005 *Acta Phys. Polon. B* **36** 1313
- [8] Thorslund I *et al* 1993 *Nucl. Phys. A* **564** 285
- [9] Regan P H *et al* 1993 *J. Phys. G: Nucl. Part. Phys.* **19** L157
- [10] Jerrestam D *et al* 1992 *Nucl. Phys. A* **545** 835
- [11] Juutinen S *et al* 1994 *Nucl. Phys. A* **577** 727
- [12] Regan P H *et al* 1994 *Phys. Rev. C* **49** 1885
- [13] Fotiades N *et al* 2000 *Phys. Rev. C* **61** 064326
- [14] Hwang J K *et al* 2002 *J. Phys. G: Nucl. Part. Phys.* **28** L9
- [15] Riegel D *et al* 1973 *Phys. Lett. B* **46** 170
- [16] Stephens F S *et al* 1973 *Phys. Lett. B* **44** 429
- [17] Häusser O *et al* 1974 *Phys. Lett. B* **52** 329
- [18] Bohr A and Mottelson B 1998 *Nuclear Structure Vol II* (Singapore: World Scientific)
- [19] Alaga G *et al* 1973 *Phys. Lett. B* **43** 459
- [20] Vishnevsky I N *et al* 1991 *Sov. J. Nucl. Phys.* **54** 191
- [21] Ziegler J F, Biersack J P and Littmark U 1985 *The Stopping and Ranges of Ions in Solids* vol 1 (London: Pergamon)
- [22] Krücken R 2000 *Proc. Int. Symp. on Advances in Nuclear Physics (Bucharest, Romania, Dec. 1999)* ed D Poenaru and S Stoica (Singapore: World Scientific) p 336
- [23] Krücken R 2000 *J. Res. Natl. Inst. Stand. Technol.* **105** 53
- [24] Dewald A *et al* 1992 *Nucl. Phys. A* **545** 822
- [25] Regan P H *et al* 1995 *Nucl. Phys. A* **586** 351
- [26] Andgren K *et al* 2005 *Phys. Rev. C* **71** 014312
- [27] Dewald A *et al* 1989 *Z. Phys. A* **334** 163
- [28] Böhm G *et al* 1993 *Nucl. Instrum. Methods Phys. Res. A* **329** 248
- [29] Firestone R B and Shirley V S 1996 *Table of Isotopes* 8th edn (Singapore: Wiley)
- [30] Alaga G, Alder K, Bohr A and Mottelson B R 1955 *Mat.-Fys. Medd. K. Dan. Vidensk. Selsk.* **29** 9
- [31] Stevenson P D 2002 *Comput. Phys. Commun.* **147** 853
- [32] Casten R F and Warner D 1988 *Rev. Mod. Phys.* **60** 389