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$E0$ transitions in ^{106}Pd: Implications for shape coexistence

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Level lifetimes in ^{106}Pd were measured with the Doppler-shift attenuation method following inelastic neutron scattering, and electric monopole transition strengths between low-lying 2^+ states were deduced. This result represents the first determination of $E0$ transitions in the Pd nuclei for levels with $J_i = J_f \neq 0$. The large $\rho^2(E0)$ values obtained provide evidence for shape coexistence, extending observation of such structures in the N = 60 isotones.

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I. INTRODUCTION

The presence of electronic monopole ($E0$) transitions has been established as a model-independent signature of shape coexistence in nuclei [1]. When configurations with different mean-squared charge radii mix, large $\rho^2(E0)$ values emerge. $E0$ transitions thus provide evidence of shape coexistence, and $\rho^2(E0)$ values quantify the extent of mixing between coexisting shapes. As noted in the survey of $E0$ transitions by Wood *et al.*, [1], surprisingly few $\rho^2(E0)$ values are known, generally because the lifetimes of the levels have not been determined.

Shape coexistence has been established previously in many regions of the chart of the nuclides, including the N = 60 isotones [2]. Large $\rho^2(E0)$ values have been measured in ^{98}Sr, ^{100}Zr, and ^{102}Mo between the ground and first excited 0^+ states, and are interpreted as coexisting $K = 0$ structures [2]. The presence of shape coexistence has not been extended further.

Colvin *et al.* [3] have studied $E0$ transitions between low-lying 0^+ states (four excited 0^+ states are known below 2.5 MeV in ^{106}Pd) with the ^{105}Pd(n,γ) and ^{105}Pd(n,e^-) reactions. In addition to reporting the properties of 0^+ excitations, they provide experimental energies and intensities in ^{106}Pd from both γ-ray and internal conversion electron measurements following thermal neutron capture. In the present work, we have taken advantage of the existing conversion electron data and combined these data with γ-ray intensities, multipole mixing ratios, and level lifetimes of states populated by the $(n,n'\gamma)$ reaction to extract $\rho^2(E0)$ values for ^{106}Pd. These represent the first $\rho^2(E0)$ values determined in the Pd nuclei for transitions between levels with $J_i = J_f \neq 0$.

II. EXPERIMENTAL PROCEDURES

A study of the low-lying structure of ^{106}Pd was performed via γ-ray spectroscopy following inelastic neutron scattering with the methods described in Ref. [4]. Nearly monoenergetic neutrons ($\Delta E_n < 100$ keV at $E_n = 2$ MeV) were provided through the ^{3}H$(p,n)^3$He reaction at the 7-MV Van de Graaff accelerator at the University of Kentucky. The scattering sample consisted of 19.98 g of ^{106}Pd metal powder, 98.53% enriched, in a cylindrical polyethylene container 1.8 cm in diameter and 3.5 cm in height, which was suspended at a distance of 5 cm from the end of a tritium gas cell used for neutron production. The γ rays from the $(n,n'\gamma)$ reaction were detected with a high-purity germanium (HPGe) detector with a relative efficiency of 55% and energy resolution of 2.1 keV full-width-at-half-maximum (FWHM) at 1332 keV. For the γ-ray singles measurements, an annular BGO detector was utilized for Compton suppression and as an active shield. The HPGe detector was at a distance of 115 cm from the scattering sample. Both detectors were shielded by boron-loaded polyethylene, copper, and tungsten, and time-of-flight gating was also employed to suppress background radiation and improve the spectral quality. The neutrons were monitored with a BF_3 long counter at 90°

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relative to the beam axis and at a distance of 3.78 m from the gas cell. The flux of neutrons was also monitored by observing the time-of-flight spectrum of neutrons in a fast liquid scintillator (NE218) at an angle of 43° with respect to the beam axis and 5.9 m from the gas cell. Spectra from γ-ray calibration sources such as ^{24}Na, ^{60}Co and ^{137}Cs acquired concurrently with the in-beam spectra were used to monitor the energy calibration. The detector efficiencies and small energy non-linearity corrections were obtained using ^{226}Ra and ^{152}Eu radioactive sources.

The γ-ray excitation functions of the levels in ^{106}Pd were measured at 90° with respect to the incident neutrons over a range of neutron energies from 2.0 to 3.8 MeV in 0.1-MeV steps. The γ-ray thresholds and shapes of the excitation functions were used to identify new levels and to place transitions in the level scheme, supporting the coincidence analysis discussed in the final paragraph of this section. Along with the angular distribution data, the excitation functions also contributed to the determination of spins. The excitation function yields, corrected for γ-ray detection efficiency and normalized, were compared to statistical model calculations using the code CINDY [5, 6], which predicts the change in the cross sections as a function of bombarding energy. Angular distribution measurements were performed at neutron energies of 2.2, 2.7, and 3.5 MeV, where the detector was located at angles between 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 [5, 6]. Gamma-ray intensities were also obtained from the angular distribution data. The data analysis was performed using the TV software package [7].

Level lifetimes were extracted from each of the three angular distribution measurements using the Doppler-shift attenuation method (DSAM) with the methodology described in Refs. [8, 9]. While the recoil velocity imparted (v/c $\approx$ 0.001) in neutron scattering reactions on heavy nuclei is small, it is sufficient to produce measurable Doppler shifts, and lifetimes from a few femtoseconds to greater than a picosecond can be determined. The Doppler-shifted γ-ray energy, $E_\gamma(\theta)$, measured at a detector angle of θ with respect to the incident neutrons can be related to E_0, the energy of the γ ray emitted by a nucleus at rest, by the expression,

$$E_\gamma(\theta) = E_0\left[1 + F_{\rm exp}(\tau)\frac{v_{\rm cm}}{c} cos\ \theta\right], \qquad (1)$$

where $v_{\rm cm}$ is the velocity of the center-of-mass in the inelastic neutron scattering collision with the nucleus, and c is the speed of light. $F_{\rm exp}(\tau)$ is the experimental attenuation factor determined from the measured Doppler shift and is compared with calculated attenuation factors to determine the lifetime [8]. The data used for determining the lifetime of the 2242.5-keV 2^+ state of ^{106}Pd are illustrated in Fig. 1. The techniques for measuring nuclear lifetimes using the DSAM with the $(n, n'\gamma)$ reaction have been developed to a high degree of precision in our laboratory in recent years. In many cases, the relative uncertainties of γ-ray energies can be determined to <10 eV, so the largest source of uncertainty now resides in our incomplete knowledge of the stopping powers of the residual nuclei recoiling at low velocities.

A γ-γ coincidence measurement (see Ref. [10] for details of the setup) was carried out at a neutron energy of 3.3 MeV with four HPGe detectors placed approximately 6 cm from the center of the sample in a co-planar arrangement. Events were recorded when at least two detectors registered γ-ray events 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, and the off-line coincidence data analyses were performed using the RADWARE software package [11]. The γ-γ coincidence data were used to build the level scheme of ^{106}Pd, and also to determine the relative γ-ray intensities if complex multiplets appeared in the singles spectra. The extensive level scheme will be reported separately [12].

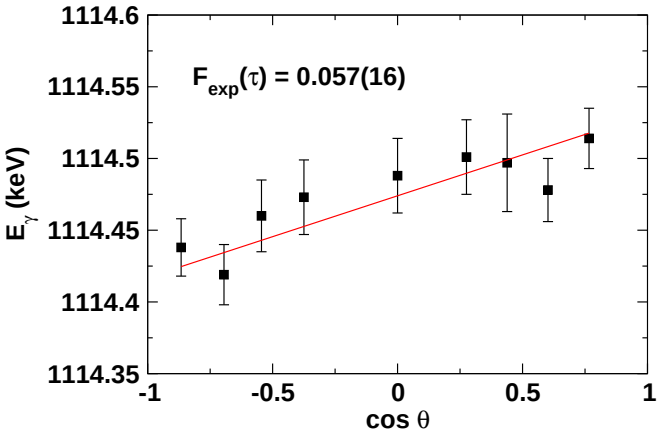

FIG. 1. (Color online) $E_\gamma(\theta)$ vs. *cos* θ for the 1114.5-keV γ ray from the 2242.5-keV 2^+ level of ^{106}Pd. The experimental attenuation factor, $F_{\rm exp}(\tau) = 0.057(16)$, is extracted from the slope of the linear fit to the data.

III. RESULTS

To determine $\rho^2(E0)$ values, several quantities must be known with small uncertainties – namely, the internal conversion electron and γ-ray intensities, the multipole mixing ratio for the transition, and the level lifetime. For consistency, the internal conversion electron intensities and γ-ray intensities were taken from the work of Colvin *et al.* [3] for the determination of the internal conversion coefficient, α_K. The γ-ray intensities from the current data were used to determine the γ-ray branching ratios, B.R., particularly when branches not identified in Ref.

[3] were observed in our data. Multipole mixing ratios, $\delta(E2/M1)$, were determined from our angular distribution measurements, as were the level lifetimes. The $E0$ component for $2_i^+ \rightarrow 2_f^+$ transitions was determined by subtracting the theoretical $\alpha_K(M1)$ and $\alpha_K(E2)$ contributions, taken from `BrIcc` [13] and scaled by the measured value of δ, from the measured α_K. The $\rho^2(E0)$ values were calculated from the experimental quantities using Eqn. 2, where the electronic factors, $\Omega_K(E0)$, were also taken from `BrIcc` [13], and $\tau^{E0}_{partial}$ is the partial lifetime of the $E0$ transition. The results are given in Table I.

$$\rho^2(E0) \times 10^3 = \frac{10^3}{\tau^{E0}_{partial} \times \Omega_K(E0)} \qquad (2)$$

Some comments on the 1562.2-keV 2_3^+ level are in order. The lifetime determined in our measurements, 2.5^{+42}_{-10} ps, is near the limit for the DSAM and exhibits a large uncertainty. Fortunately, the lifetime of this level, 2.0(3) ps, could be deduced from $B(E2; 2_3^+ \rightarrow 0_1^+) = 0.14(2)$ W.u. determined in Coulomb-excitation measurements [16, 17]. This latter value, which is in agreement with our measurement, but has a smaller uncertainty, was used in the calculations. Similarly, the mixing ratio for the $2_3^+ \rightarrow 2_1^+$, 1050.4-keV transition was determined in our measurements to be $\delta = 0.22(4)$. This value is in good agreement with the adopted value from the Nuclear Data Sheets (NDS), 0.24(1) [14], but the NDS value is the average of several measurements and was used in the calculations because of its smaller uncertainty.

In addition to the conversion electron data of Colvin *et al.* [3], another determination of the internal conversion coefficient for the $2_3^+ \rightarrow 2_1^+$, 1050.4-keV transition has been reported [18]. This value is larger than that reported by Colvin *et al.* and does not agree within the uncertainties reported. For completeness, this value, which leads to an even larger $\rho^2(E0)$ value, is included in Table I.

IV. DISCUSSION

Figure 2 presents the $\rho^2(E0) \times 10^3$ values deduced in the present work. The ground, 1134-keV 0_2^+, and 1706-keV 0_3^+ states are taken to be bandheads of $K = 0$ structures, while the 1128-keV 2_2^+ and 2243-keV 2_5^+ states are taken to be bandheads for $K = 2$ structures. Two states with spin-parity 3^+ (at 2591 and 2714 keV) are observed in the energy range expected for a 3^+, $K = 2$ band member for the 2_5^+ bandhead; but we do not choose between them at present. The pattern of large interband $E0$ strengths supports shape coexistence for the $K = 0$ structures and for the $K = 2$ structures. The coexistence of $K = 0$ bands is widely established [2] and a few examples of $K = 2$ bands coexisting are now known (see, *e.g.*, Refs. [1, 19, 20]). The present results provide strong evidence for shape coexistence in ^{106}Pd and extend the observation of shape coexistence in the $N = 60$ isotones, which is well-established in ^{98}Sr, ^{100}Zr, and ^{102}Mo [2].

Both ^{106}Pd and ^{104}Ru, have been studied by Coulomb excitation with heavy ions, and an extensive set of E2 matrix elements is available for each nucleus [16, 17, 21]. From these matrix elements, the expectation values of the E2 moments in the intrinsic frame, which are directly related to the collective behavior of the nucleus, can be deduced, and the nuclear charge deformation and the triaxiality can be determined. The low-lying states characterized in ^{104}Ru and ^{106}Pd appear to be amazingly similar. Unfortunately, to our knowledge, there have been no studies of internal conversion electrons in ^{104}Ru. Therefore, the evidence of shape coexistence observed in the lighter N = 60 isotones, i.e., ^{98}Sr, ^{100}Zr, and ^{102}Mo, and now in ^{106}Pd, cannot yet be extended to ^{104}Ru.

V. SUMMARY

By combining previously measured internal conversion electron data in ^{106}Pd with level lifetimes determined with the DSAM following inelastic neutron scattering, $\rho^2(E0)$ values were determined, thus extending the region of observed shape coexistence to the Pd nuclei.

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TABLE I. Data for $E0$ transitions in ^{106}Pd.

Level (keV)	Transition	E_γ (keV)	γ-ray B.R.	Lifetime (τ) (ps)	δ	$\alpha_K(\times 10^3)$	$\rho^2(E0)\times 10^3$
1133.9	$0_2^+ \to 0_1^+$			8.4(1.9) [a]			14(4) [b]
1562.2	$2_3^+ \to 2_1^+$	1050.4	0.847(17)	2.0(3) [c]	+0.24(1) [a]	1.12(13) [d]	34(19)
						1.56(24) [e]	97(39)
1706.4	$0_3^+ \to 0_1^+$			4.0(7) [a]			< 3
1909.5	$2_4^+ \to 2_1^+$	1397.6	0.597(25)	1.6^{+15}_{-5} [f]	$+1.32^{+11}_{-25}$ [f,g]	0.68(9) [d]	20^{+11}_{-20}
					$+0.25^{+6}_{-5}$ [f,g]		18^{+10}_{-18}
2242.5	$2_5^+ \to 2_2^+$	1114.5	0.314(6)	0.70^{+36}_{-18} [f]	$+0.66^{+48}_{-33}$ [f,h]	1.46(26) [d]	100^{+45}_{-63}

[a] From Ref. [14]
[b] From Ref. [15]
[c] From Ref. [16, 17]
[d] From Ref. [3]
[e] From Ref. [18]
[f] From the present measurements
[g] It was not possible to choose between the two values of δ, so both are listed.
[h] Ref. [14] lists a value of $+1.5^{+3}_{-2}$, but the origin of this value could not be determined.

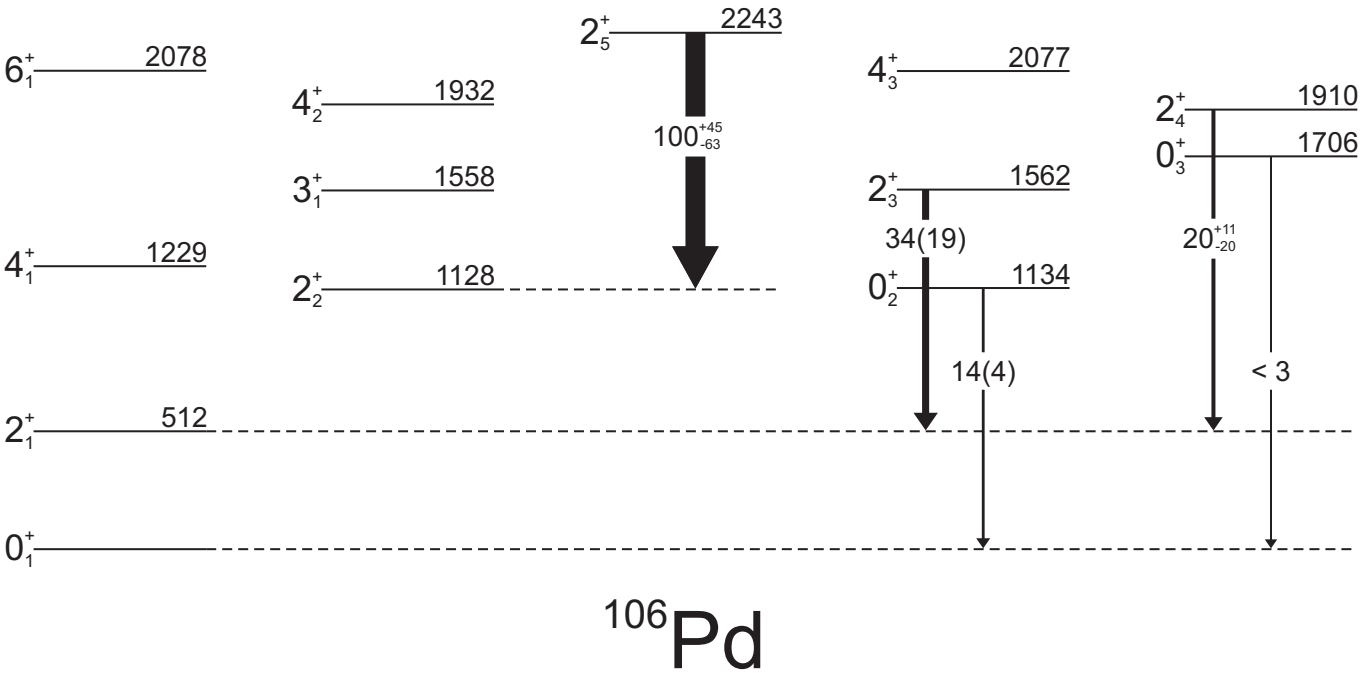

FIG. 2. (Color online) Low-lying positive-parity levels of ^{106}Pd [14] shown as $K = 0$ and $K = 2$ bands. $E0$ transitions are shown by arrows and the corresponding $\rho^2(E0)\times 10^3$ values are given on the arrows.

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