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Coulomb excitation of ^{105}Pd with protons

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Twelve known low-lying positive parity levels in ^{105}Pd up to 962 keV excitation energy were investigated by measuring, in singles mode, with a high resolution 57 cm^{3}Ge(Li) detector, the yields and angular anisotropies of the deexcitation γ rays following Coulomb excitation with 2 to 4 MeV protons. Out of the seven of these levels which have been populated for the first time through Coulomb excitation with protons, the 696.2 keV level is proposed to be Coulomb excited for the first time. Level energies, the branching ratios, the multipole mixing ratios, $B(E2)$ and $B(M1)$ transition probabilities, and half-lives were deduced. The angular distributions support $\frac{5}{2}^+$, $\frac{3}{2}^+$, $\frac{7}{2}^+$, $\frac{5}{2}^+$, and $\frac{3}{2}^+$ spin-parity assignments, for the 560.6, 673.2, 696.2, 781.8, and 961.9 keV levels, respectively. The present results have been discussed in view of the existing experimental data, as well as in terms of various core-particle coupling models.

I. INTRODUCTION

The ^{105}Pd nucleus has been subjected to a number of investigations, both theoretical[1,2] and experimental.[3–15] Based on the data of nuclear reactions and radioactivity, Abukhov *et al.*[7] established the level scheme for ^{105}Pd up to about 2 MeV excitation energy. The heavy ion reactions[8,9] have helped to propose the structure of the quasirotational bands in ^{105}Pd. Previous Coulomb excitation studies of ^{105}Pd with heavy ions have been carried out by several workers.[10–15] The lifetimes of some of the levels were determined through the Doppler shift attenuation method using Coulomb excitation with 35 MeV ^{12}C and 100 MeV ^{35}C ions.[14,15] Gal'Perin *et al.*[11] observed levels in ^{105}Pd up to 962 keV excitation energy with 46.1 MeV $^{14}N^{5+}$ ions, while Geiger *et al.*[12] as well as Bolotin and McClure[13] observed ten levels up to 782 keV with 5—10 MeV and 4.4—8.0 MeV α projectiles, respectively. Each of these three groups deduced $B(E2)\uparrow$ values, while Bolotin and McClure[13] as well Geiger *et al.*[12] also discussed the limitations of the weak coupling core excitation model[16] in describing the experimental data.

Coulomb excitation with protons, which involves a direct one-step process and thereby yields more reliable nuclear information, has been carried out so far only incompletely by two groups,[6,17] Mark *et al.*[17] using a 5.1×5.1 cm NaI detector could only identify two levels at 270 and 430 keV, and Chatterjee *et al.*[6] using a natural thick Pd target and a 32.2 cm^3 Ge(Li) detector observed (because of the poor statistics of their data) only five low-lying levels and computed their $B(E2)$ values. The corresponding $B(E2)$ values reported by the earlier workers[11–13] are quite discrepant for some cases and may carry different unestimated uncertainties because of feeding and deexcitation of various levels by the unobserved intermediate transitions.[3] Very little information is available on the magnetic dipole transitions in ^{105}Pd. No results on the multipole mixing ratios (δ values) had been reported earlier through Coulomb excitation, while the corresponding results obtained through nuclear reaction and radioactivity[3] differ from each other for most of the cases. Moreover, in the literature whereas J^π values for the 696.2 keV level have been tentatively assigned[3] as $\frac{7}{2}^+$, for the 673.2 keV level it is ambiguous between $\frac{1}{2}^+$ and $\frac{3}{2}^+$ values,[3,4] and for the 781.9 keV level the suggested possible values[3,10,15] are $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{9}{2}^+$. The possibility of the $\frac{3}{2}^+$ value for the 560.6 keV level[11] had been supported earlier.[7,15] The 961.9 keV level had been earlier assigned a J^π value[3,4,7] of $\frac{1}{2}^+$ or $\frac{3}{2}^+$. These drawbacks of the existing experimental data prompted us to reinvestigate the Coulomb excitation of ^{105}Pd with low energy protons through the measurements of γ-ray yields and to measure angular anisotropies using an enriched target, and a high resolution and high efficiency Ge(Li) detector. The results have been compared with the reported theoretical as well as experimental values.

II. EXPERIMENTAL PROCEDURE

The details of the experimental procedure followed have been described in our recent publications.[18,19] A 2—4 MeV proton beam, generated with the variable energy cyclotron at Panjab University, Chandigarh, was employed to induce Coulomb excitation on a target foil of enriched (91.4%) ^{105}Pd. The deexcitation γ-ray yields were measured at an angle of 55° to the beam direction with a 57 cm^3 Ge(Li) detector having an energy resolution of 1.7 keV at the 1.33 MeV line of ^{60}Co. A typical singles γ-ray spectrum recorded with 3.35 MeV protons and displaying the well-resolved peaks, each marked with the source of origin, is shown in Fig. 1. It is seen that besides

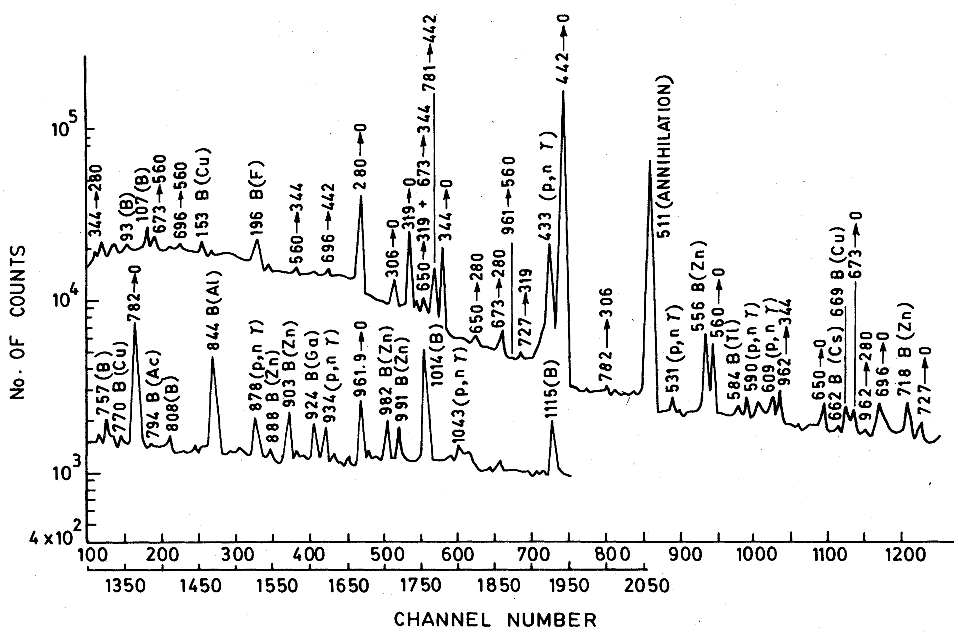

FIG. 1. The relevant portion of the gamma-ray spectrum from a thick target of ^{105}Pd bombarded with 3.35 MeV protons observed with a 57 cm^3 Ge(Li) detector placed at 55° to the beam direction. The peaks marked (B) correspond to background gamma rays.

Coulomb excited gamma rays, there are some gamma rays from (p,nγ) reactions. Though the compound contribution, as calculated using computer code CINDY,[25] is less than 1% of the Coulomb excitation in the total (p,p$'\gamma$) cross section at 3.35 MeV proton energy, the (p,nγ) cross section seems to be still significant, giving rise to many gamma rays through this reaction. With 3.35 MeV protons, the measurements were also carried out at 0°, 30°, 45°, 60°, and 90° with the beam direction to provide data for anisotropy treatment. The analysis procedure to ascertain the underlying Coulomb reaction mechanism, to deduce $B(E2)\uparrow$ values from the measured γ-ray yields, to deduce the mixing ratio for a given spin sequence from the angular distributions as well as to assign definite spins to the levels using the χ^2 test at 0.1% level of significance, has been described earlier.[18,19]

TABLE I. The $B(E2)\uparrow$ values (in units of $e^2cm^4\times10^{-50}$) and their comparison with the previous results for the ^{105}Pd levels.

Level energy (keV)	J^π	Present	Coulomb excitation: Chatterjee and Baliga (Ref. 6)	Geiger *et al.* (Ref. 12)	Bolotin and McClure (Ref. 13)	Galperin *et al.* (Ref. 11)	Theory de Takacsy and Das Gupta (Ref. 2)
280.4	$\frac{3}{2}^+$	0.85±0.07	0.73±0.16	0.97±0.06	1.10±0.10	0.2±0.1	1.2
306.2	$\frac{7}{2}^+$	0.12±0.01		0.11±0.01	0.12±0.02	0.4±0.1	0.95
319.2	$\frac{5}{2}^+$	0.73±0.08	0.95±0.20	0.87±0.05	0.81±0.10	0.8±0.2	3.6
344.6	$\frac{1}{2}^+$	0.23±0.03		0.27±0.03	0.15±0.03	2.0±0.4	0.24
442.2	$\frac{7}{2}^+$	19.0 ±1.6	16.2 ±2.7	19.7 ±1.2	16.5 ±1.3	18±4	21.6
560.6	$\frac{5}{2}^+$	0.92±0.14	1.11±0.38	1.10±0.08	0.75±0.10	0.6±0.2	0.74
650.6	$\frac{3}{2}^+$	0.86±0.17		0.79±0.05	0.66±0.13	1.7±0.5	1.05
673.2	$\frac{3}{2}^+$	0.89±0.16		0.90±0.06	0.57±0.11	0.5±0.3	
696.2	$\frac{7}{2}^+$	0.20±0.10					
727.3	$\frac{5}{2}^+$	0.43±0.09		1.21±0.09	0.24±0.06	1.0±0.3	
781.8	$\frac{5}{2}^+$	9.66±0.80	11.9 ±3.0	11.4 ±0.7	8.27±0.83	5±1	10.4
961.9	$\frac{3}{2}^+$	1.6 ±0.3				0.5±0.2	

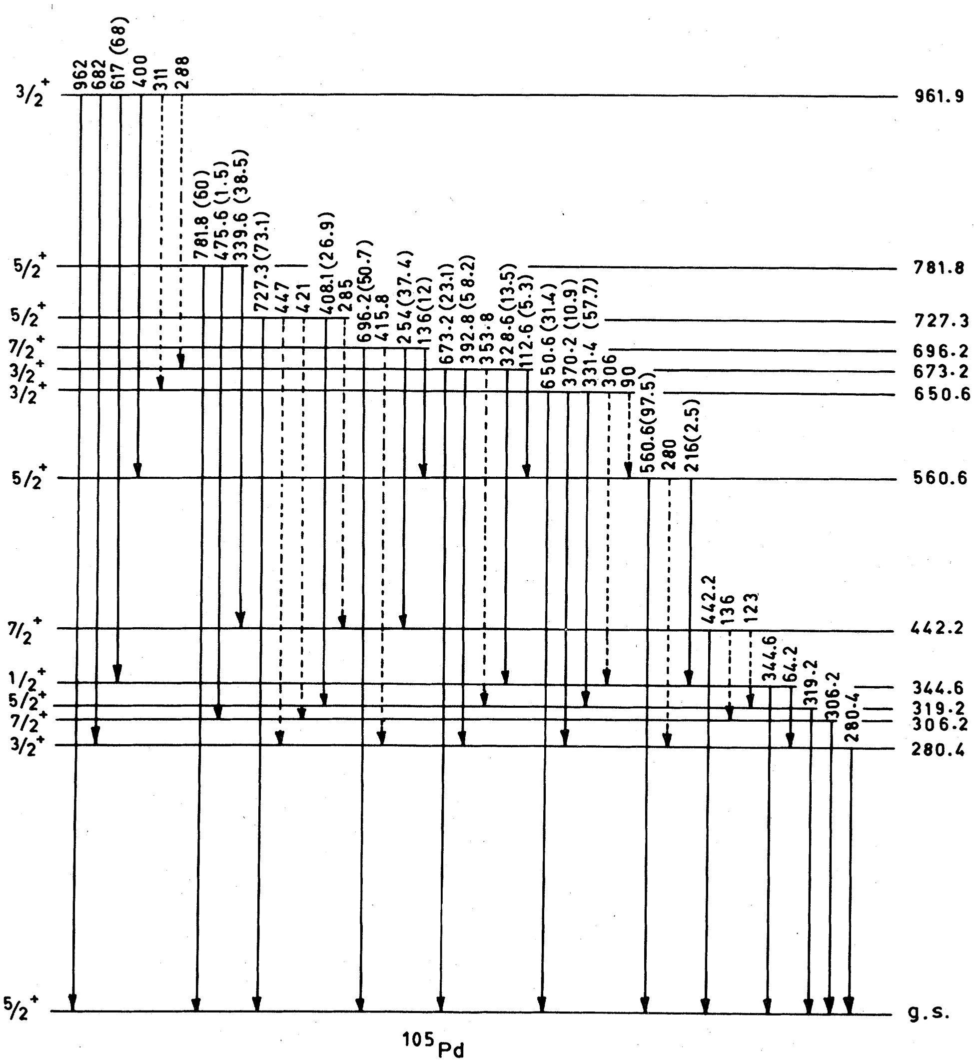

FIG. 2. Level scheme of ^{105}Pd. The γ-ray relative intensities are the average of their values measured at different proton energies.

III. RESULTS AND DISCUSSION OF LEVEL PROPERTIES

The proposed decay scheme for the Coulomb excited levels of ^{105}Pd is displayed in Fig. 2. The observed deexcitation transitions are indicated by solid arrows. Besides the 696.2 keV level, which has been observed earlier only through stripping as well as heavy ion reactions,[3,8] the 306.2, 344.6, 650.6, 673.2, 727.3, and 961.9 keV levels are Coulomb excited for the first time with protons. In calculations for $B(E2)$, we took into account the feeding as well as the deexcitation of each level through the observed intermediate transitions.

The 696.2 keV gamma ray has a contribution from the (p,nγ) reaction also, because of the deexcitation of the 1043 keV level in ^{105}Ag. The existence of the 254 keV line from the 696$\rightarrow$442 keV transition, however, indicates the excitation of the 696 keV level through Coulomb excitation. It may be pointed out that the 254 keV γ ray cannot arise from the (p,nγ) reaction or from any other transition of ^{105}Pd or ^{105}Ag. The net Coulomb yield for the 696.2 keV γ ray was calculated by subtracting the contribution of the (p,nγ) reaction, by taking $I_\gamma(1043)/I_\gamma(696)$ as 2.8 from the literature.[3] The intensity of the 1043 keV gamma ray is taken from our gamma-ray spectrum (Fig. 1). The average value of $B(E2)$ was obtained from the various experimental points in the excitation function of the net Coulomb yield of the 696 keV γ ray.

Excitation functions were drawn for other observed Coulomb excited levels (Fig. 3) to ascertain the mode of excitation and to find the average values of $B(E2)\uparrow$. The averages of $B(E2)\uparrow$ values are displayed in the third column of Table I. The assigned errors for $B(E2)$ values result from uncertainties in peak areas, in the efficiency of the Ge(Li) detector, in the current integrator, and in the stopping power of protons in ^{105}Pd.

Our $B(E2)$ values for many levels are in reasonable agreement with the earlier work.[6,12,14] However, the re-

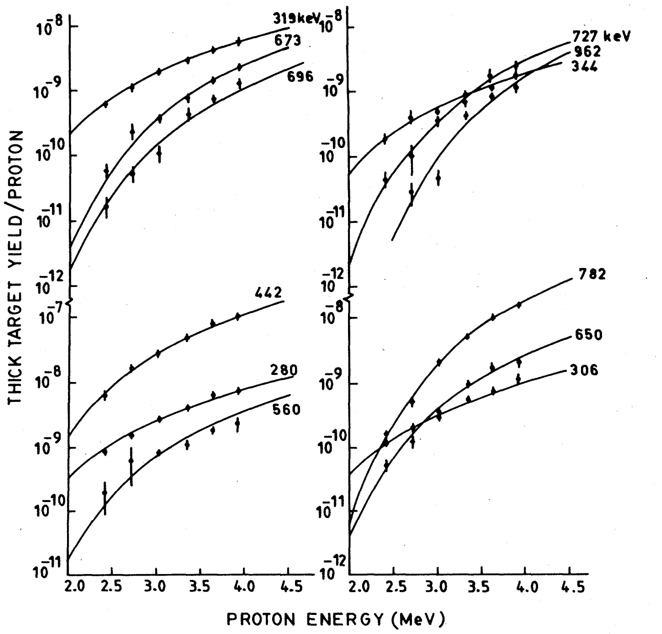

FIG. 3. The thick target gamma ray yields as a function of proton energy for the excited levels in ^{105}Pd. The solid curves show the theoretical yields predicted from the $E2$ mode of excitation.

sults by Gal'Perin *et al.*[11] are significantly lower for the 280.4, 781.8, and 961.9 keV levels and higher for the 306.2, 344.6, 650.6, and 727.3 keV levels. The reported $B(E2)$ value by Geiger *et al.*[12] for the 727.3 keV level is much higher than the present value, which is in good agreement with the value by Bolotin and McClure.[13] It is interesting to note that the present values agree reasonably with the theoretical results obtained from deformed Hartree-Fock-plus-BCS calculations,[2] except for the 306.2 and 319.2 keV levels. The large theoretical $B(E2)$ value of 0.95 e^2b^2 for the 306.2 keV level seems to be unreasonable with strong single particle coupling as this level has been assigned single particle configuration $g_{7/2}$ with a c^2S value[2] of 2.52.

The angular distribution results obtained at five angles for most of the gamma rays were subjected to the χ^2 test, and the values of coefficients A_2 and the mixing ratios δ were obtained as summarized in Table III. Three typical specimen χ^2 tests for 673.2→0, 696.2→0, and 781.→0 transitions are displayed in Fig. 4. We have also shown in Table III the values of δ, as available in the literature. It is pertinent to point out that our values of δ are, in general, in agreement with those found in the literature. It is evident from this table that many mixing ratios have been obtained for the first time in the present work. The data on the deexcitation transitions and half-lives of the levels are summarized in Table II. From χ^2 tests, we have been

TABLE II. Summary of information obtained from the Coulomb excitation of ^{105}Pd.

E_γ (keV)	$J_i^\pi \to J_f^\pi$	$B(E2)\downarrow$ (e^2cm$^4\times10^{-50}$)	δ	$B(M1)\downarrow$ (10^{-2} μ_n^2)	Half-life of the level ($T_{1/2}$) Present work	Ref. 3
280.4	$\frac{3}{2}^+\to\frac{5}{2}^+$	1.28±0.11	$0.13^{+0.02}_{-0.03}$	7.01	25.4 ps	67±14 ps
306.2	$\frac{7}{2}^+\to\frac{5}{2}^+$	0.09±0.11	$-0.81^{+0.28}_{-0.16}$	1.95	9.2 ns	
319.2	$\frac{5}{2}^+\to\frac{5}{2}^+$	0.73±0.08	$-0.14^{+0.05}_{-0.07}$	2.64	45 ps	40±10 ps
344.6	$\frac{1}{2}^+\to\frac{5}{2}^+$	0.69±0.09	$E2$		<1.7 ns	0.88±0.05 ns
442.2	$\frac{7}{2}^+\to\frac{5}{2}^+$	14.25±1.2	$-1.73^{+0.42}_{-0.45}$	0.65	17.9 ps	3.7±1.0 ps
560.6	$\frac{5}{2}^+\to\frac{5}{2}^+$	0.92±0.14	$-1.80^{+0.54}_{-0.36}$	0.06	<84.5 ps	1.9±0.5 ps
650.6	$\frac{3}{2}^+\to\frac{5}{2}^+$	1.29±0.14	$-0.38^{+0.05}_{-0.04}$	2.58	<1.7 ps	
331.5	$\frac{3}{2}^+\to\frac{5}{2}^+$	0.66±0.13	$-0.035^{+0.012}_{-0.008}$	41.5		
673.3	$\frac{3}{2}^+\to\frac{5}{2}^+$	1.34±0.24	$-0.78^{+0.14}_{-0.21}$	0.23	<11.5 ps	>2 ps
696.3	$\frac{7}{2}^+\to\frac{5}{2}^+$	0.15±0.07	$-0.81^{+0.34}_{-0.27}$	0.08	<91.4 ps	
254.0	$\frac{7}{2}^+\to\frac{7}{2}^+$	9.5±1.0	$-1.22^{+0.37}_{-0.28}$	0.3		
727.3	$\frac{5}{2}^+\to\frac{5}{2}^+$	0.43±0.09	$-0.14^{+0.06}_{-0.04}$	8.04	<2.3 ps	
408.3	$\frac{5}{2}^+\to\frac{5}{2}^+$	1.37±0.15	$0.55^{+0.14}_{-0.21}$	51.9		
781.8	$\frac{5}{2}^+\to\frac{5}{2}^+$	9.66±0.80	$0.57^{+0.26}_{-0.21}$	12.7	<0.5 ps	1.5±0.5 ps
475.7	$\frac{5}{2}^+\to\frac{7}{2}^+$	0.13±0.03	$-0.22^{+0.10}_{-0.08}$	0.44		
339.6	$\frac{5}{2}^+\to\frac{7}{2}^+$	2.7 ±1.1	$-0.08^{+0.04}_{-0.03}$	30.8		
617.3	$\frac{3}{2}^+\to\frac{1}{2}^+$		$-0.97^{+0.60}_{-0.26}$ or $0.28^{+0.12}_{-0.13}$			

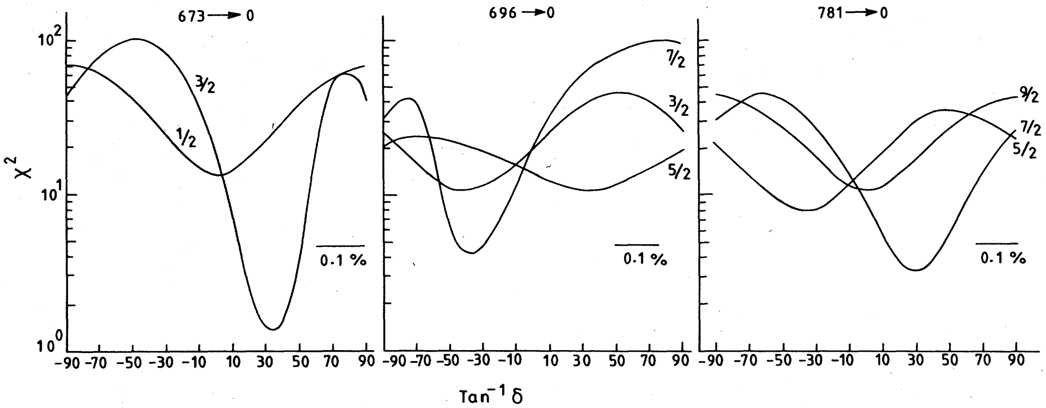

FIG. 4. The χ^2 vs $\tan^{-1}\delta$ curves for the 673.2, 696.2, and 781.8 keV gamma rays of ^{105}Pd.

able to make definite assignments of J^π as $\frac{5}{2}^+$, $\frac{3}{2}^+$, $\frac{7}{2}^+$, and $\frac{3}{2}^+$ for 560.6, 673.2, 696.2, and 781.8 keV levels, respectively.

The present work assigns a unique value of J^π as $\frac{5}{2}^+$ for the 560.6 keV level and discards the possibility of the value $\frac{3}{2}^+$ suggested earlier.[11,15] For the 673.2 keV level, our data support an earlier[3] J^π assignment of $\frac{3}{2}^+$. The present investigations disagree, on the basis of the χ^2 test, with the $\frac{1}{2}^+$ value proposed for the 673.2 keV level in the β-decay study.[4] The assignment of a $\frac{1}{2}^+$ value to this level[4] on the basis of the δ value seems to be faulty, because of large errors (80%) involved. Further, the δ value obtained from the poorly determined internal conversion coefficients[24] cannot be safely used for comparison as has been done by these authors.[4] The 961.9 keV level has been assigned a J^π value of $\frac{3}{2}^+$ on the basis of angular distributions of the 617.3 keV transition from this level. The spin value $\frac{1}{2}^+$ is discarded since we have found an anisotropy with $A_2 = -0.11 \pm 0.04$ for the angular distributions of 617.3 keV transitions. The reduced quadrupole transition probability for the 961.9 keV level was also obtained using the thick target yield of the 617.3 keV (961.9→344 keV) gamma ray. The 961.9 keV γ ray has not been used for this purpose because of the expected contribution from the (p,nγ) reaction to this gamma ray. The branching ratios were used from the literature.[3]

It had been pointed out earlier[12,13] that most of the low-lying levels cannot be interpreted in terms of the simple shell model as well as the weak coupling model. The presence of appreciable $B(M1)$ components in the 442.2→0 and 781.8→0 keV transitions suggests that the 442.2 and 781.8 keV levels cannot be treated as members

TABLE III. Comparison of mixing ratios for the transitions in ^{105}Pd.

E_γ (keV)	A_2	Mixing ratio (δ) Present	Ref. 26	Ref. 27	Ref. 9	Ref. 4	Ref. 3	Ref. 28	Ref. 1
254	-0.027 ± 0.007	$1.22^{+0.37}_{-0.28}$							
280	0.091 ± 0.011	$0.13^{+0.02}_{-0.03}$	0.132 (8)	0.07 (7)		0.178 (14)	0.10 (10)		
306	-0.085 ± 0.011	$-0.81^{+0.28}_{-0.16}$	0.06 (1)	0.055 (2)	0.02 (4)	0.02 (4)	0.055 (2)	$-0.39^{+0.13}_{-0.06}$	
319	-0.053 ± 0.013	$-0.14^{+0.05}_{-0.07}$	0.11 (1)	0.091 (13)	-0.07 (± 10.0)	-0.007 (20)	0.10 (2)	-0.16 (3)	
331	0.021 ± 0.004	$-0.035^{+0.012}_{-0.008}$							-0.062 (9)
339	-0.198 ± 0.097	$-0.08^{+0.04}_{-0.03}$			-0.04 ± 0.04				
408.3	-0.136 ± 0.006	$0.55^{+0.14}_{-0.21}$							
442	-0.066 ± 0.011	$-1.73^{+0.42}_{-0.45}$		0.8 ± 0.5	-0.33 (13)		0.8 (7)		
476	-0.292 ± 0.130	$-0.22^{+0.01}_{-0.08}$							
560	0.091 ± 0.011	$-1.80^{+0.54}_{-0.36}$							
650	-0.094 ± 0.012	$-0.38^{+0.05}_{-0.04}$							
673	-0.134 ± 0.012	$-0.78^{+0.14}_{-0.21}$							
696	-0.085 ± 0.009	$-0.81^{+0.34}_{-0.27}$							
782	-0.136 ± 0.006	$0.57^{+0.26}_{-0.21}$							

of the $\nu d^{1}_{5/2}\otimes 2^{+}_{1}$ (^{104}Pd) multiplet. The total observed $E2$ strength, i.e., $\sum B(E2;g\to f)=0.355\ e^{2}b^{2}$, is smaller than the $B(E2;0\to 2^{+}_{1})=0.55\ e^{2}b^{2}$ value of the ^{104}Pd core.[13] To explain the missing fraction of the $B(E2)\uparrow$ sum, the weak coupling model suggests that the members of the $\nu d^{1}_{5/2}\otimes 2^{+}_{1}$ (^{104}Pd) multiplet are strongly admixed in the ground state wave function;[13] however, the presence of a strongly retarded $M1$ component in the 442.2→0 keV transition is inconsistent with this proposition.

The theoretical calculations with the vibration-particle[20,21] and the rotation-particle[22] coupling models have also not been very successful. The success of the variable moment-of-inertia model[23] and the rotation aligned coupling model[1] in reproducing the decoupled $\Delta I=2$ bands and of the deformed Hartree-Fock-plus-BCS (Ref. 2) calculations to reproduce satisfactorily, in addition, the spin sequence, the spectroscopic factors, and $B(E2)$ values of most of the low lying levels, indicate that the explicit incorporation of deformation in the even-even core provides a good explanation of many features of the experimental spectra. The $\frac{5}{2}^{+}$ spin-parity assignment to the 781.8 keV level in the present work and earlier Coulomb excitation studies[15] is, however, inconsistent with the suggestion[1] that the 442.2 ($\frac{7}{2}^{+}$) and the 781.8 keV levels belong to the rotationlike ground state band.

IV. CONCLUSION

Our results complete and update the data on Coulomb excitation of ^{105}Pd. We could identify many intermediate transitions not observed previously through Coulomb excitation.[13] The existing discrepancies in the reported $B(E2)\uparrow$ values have been resolved and the 696.2 keV level has been assigned a new $B(E2)\uparrow$ value. The 560.6, 673.2, 696.2, 781.8, and 961.9 keV levels have been uniquely assigned J^{π} values of $\frac{5}{2}^{+}$, $\frac{3}{2}^{+}$, $\frac{1}{2}^{+}$, $\frac{5}{2}^{+}$, and $\frac{3}{2}^{+}$, respectively. Many of the δ values have been deduced for the first time through Coulomb excitation. The values of $B(M1)$ obtained in this work have complemented the data on the deexcitation transitions. The results have helped us to bring out the limitations of the weak core-particle coupling model more clearly.

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