COULOMB EXCITATION OF THE PALLADIUM ISOTOPES

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The B(E2) values and lifetimes of the first 2^+ states of the even palladium isotopes and the 279.9, 319.3, 442.1, 561.7 and 781.7 keV states of ^{105}Pd have been measured from the Coulomb excitation with 3.2 MeV protons by observing the de-excitedgamma-rays with a high resolution Ge(Li) detector. The 319.3, 561.7 and 781.7 keV states have been observed for the first time in the Coulomb excitation with low-energy protons. The change in collective behaviour of the first 2^+ states with the change in neutron number has been noticed in even palladium nuclei. The properties of the excited states of ^{105}Pd have been discussed in the light of core particle coupling models.

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1. *Introduction*

Coulomb excitation studies have been proved to be an efficient method to look into the collective aspect of the excited states of the nuclei. The most important feature of the Coulomb excitation process is that, the information on electromagnetic transition rates between the nuclear states can be obtained very easily. It was pointed out by Scharff-Goldhaber and Weneser [1] that the low-lying states of medium weight nuclei might result from the harmonic vibrations of the nucleus about an average spherical shape. The collective nature of the low-lying states in Pd isotopes are expected from this point of view. Hence the Coulomb excitation study of the Pd isotopes would be of interest to observe the collective behaviour of the low-lying states with increase in neutron number. The low-lying states of ^{105}Pd would be of interest from the point of view of weak coupling model which showed considerable success in explaining the low-lying Coulomb excited states of ^{107,109}Ag [2].

The excited states of even mass Pd nuclei were studied earlier from the Coulomb excitation by Stelson and Grodzins [3], Robinson et al. [4] and Bolotin and McClure [5]. The Coulomb excitation of the states of ^{105}Pd with alpha particles were studied earlier by Geiger et al. [6] and Bolotin and McClure [5] using the Ge(Li) detectors. It may be worth-

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while to reinvestigate the Coulomb excitation of Pd nuclei with low-energy protons by using the high resolution Ge(Li) detector for detecting the de-excited gamma-rays. With the protons of energies much below the Coulomb barrier, the possibility of nuclear scattering or multiple Coulomb excitation is small. Hence the $B(E2)\uparrow$ values of the excited states can be extracted from the first order perturbation theory of Alder et al. [7].

It has been noted from the earlier Coulomb excitation studies, while the reported $B(E2)\uparrow$ values of the first 2^+ states of even Pd nuclei are in reasonably good agreement, the reported $B(E2)\uparrow$ values of the 782 keV state and a few other states of ^{105}Pd have shown considerable discrepancies. The present study of Coulomb excitation with 3.2 MeV protons have excited the first 2^+ states of the even Pd nuclei and a number of low-lying states of ^{105}Pd. The $B(E2)\uparrow$ values of these states have been measured and compared with other published results.

2. *Experiment*

A thick target of natural palladium (99.99%) was bombarded with the external proton beam of energy 3.2 MeV and the current ~15 nA from the Cyclotron at Saha Institute of Nuclear Physics, Calcutta. The de-excited gamma-rays were observed with a 32.2 cm^3 Ge(Li) detector (2.1 keV resolution at 1332 keV) at an angle of 55° with respect to the beam direction to minimize the angular distribution effect. The single gamma spectrum was taken in bins of 0.66 keV/ch and stored in a 4096 channel LABEN analyser. The computer analysis of the spectrum was carried out with the computer code SPAN [8]. Standard calibrating sources were used for the energy calibration of the gamma-rays and the efficiency calibration of the Ge(Li) detector.

3. *Results*

Natural palladium contains several even mass isotopes of palladium and one odd mass isotope, ^{105}Pd (22.2% in natural palladium). From the Coulomb excitation with protons, the de-excited gamma-rays from the first 2^+ states of even Pd isotopes have been identified except that of ^{102}Pd, the abundance of which is small (0.96%) in natural sample. The gamma-rays at energies 555.8 (^{104}Pd), 511.6 (^{106}Pd), 434.6 (^{108}Pd) and 373.6 keV (^{110}Pd) are shown in Fig. 1a and 1b. The gamma-rays having energies 279.9, 319.3, 339.3, 442.1, 561.7 and 781.7 keV are identified as belonging to ^{105}Pd. On the basis of these gamma-rays observed in the present work a level scheme has been proposed for ^{105}Pd (Fig. 2). The energies of the gamma-rays measured by us agree quite well with the published values. The branching ratio of the two transitions from the 781.7 keV level of ^{105}Pd is exactly equal to that measured by Bolotin and McClure.

No attempt was made in our experiment to measure the absolute cross-section directly. The relative cross-sections have been measured from the gamma-ray yield by considering the internal conversion coefficient and the cascade transitions from the higher lying levels. The $B(E2)$ values of the excited states have been calculated from the first order perturbation theory of Alder et al. [7]. To calculate the thick-target integral, the stopping power

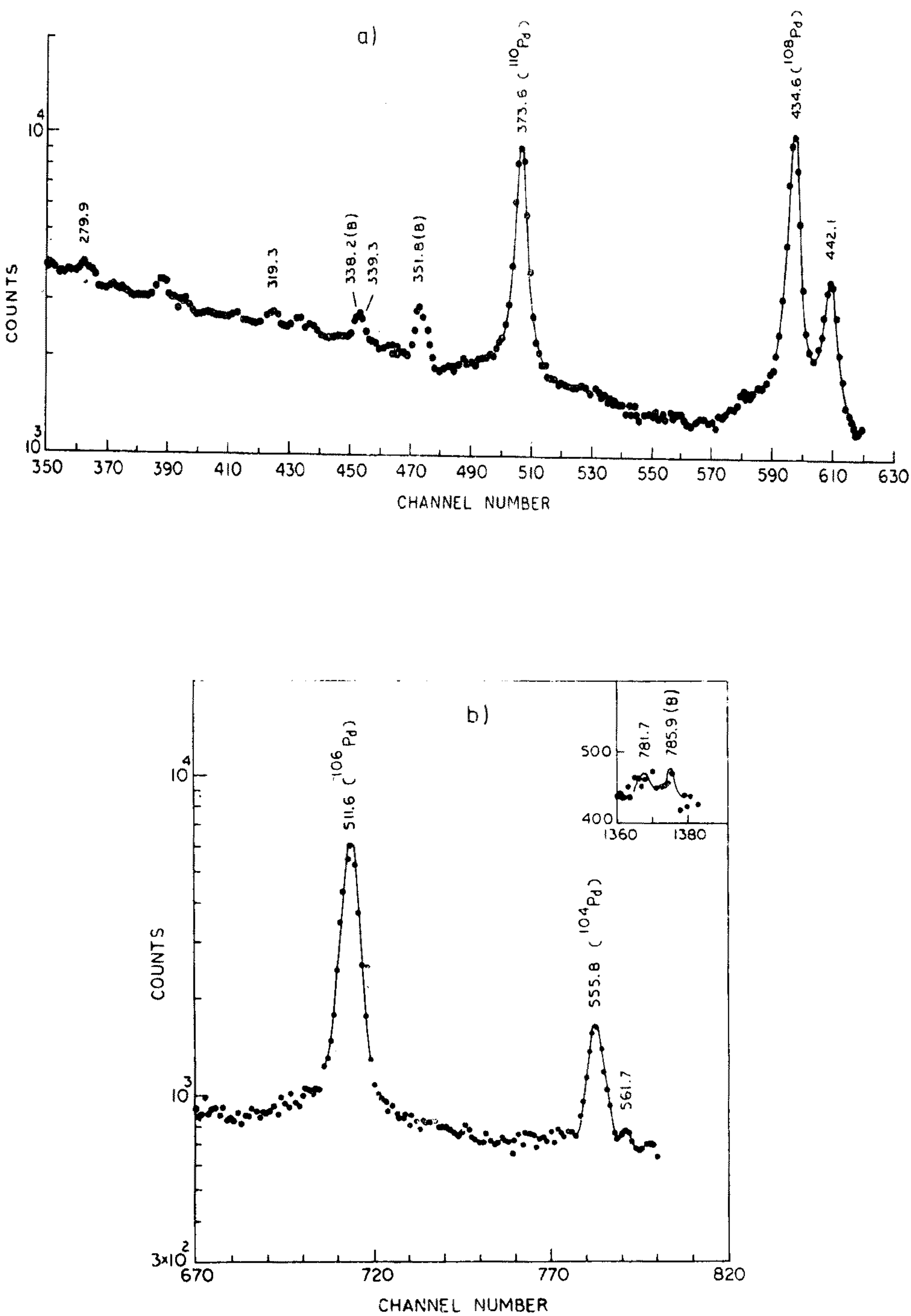

Fig. 1a, b. Relevant portions of the gamma-ray spectrum observed from the bombardment of natural palladium target with 3.2 MeV protons. The peaks marked (B) correspond to background gamma-rays of protons has been taken from the Nuclear Data Tables [9], and the f_{E2} values for E2 excitation have been taken from the work of Alder et al. [7].

The B(E2)↑ values of the excited states of the Pd nuclei have been calculated by normalising them to the measured B(E2)↑ of the first 2^+ state of ^{108}Pd taken from the work of Robinson et al. [4]. The errors of the B(E2)↑ values are greater in the present work

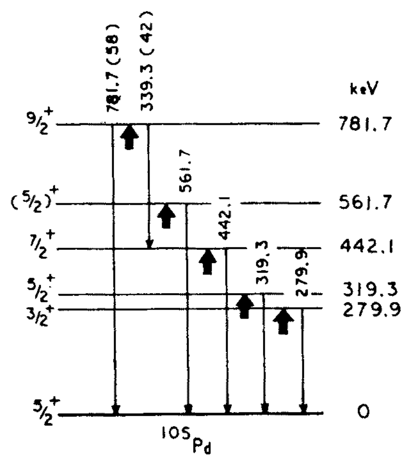

Fig. 2. Levels of ^{105}Pd excited in Coulomb excitation with 3.2 MeV protons

because of the coupling of errors in relative B(E2)↑ measurement and further increase due to normalisation. The measured B(E2) values of the first 2^+ states of the even Pd nuclei are in very good agreement with the reported values (Table I) except for that of ^{104}Pd. The B(E2)↑ value for the first 2^+ state of ^{104}Pd measured by us is slightly smaller than the reported values [3, 4], although they are within the errors. The B(E2)↑ values measured by us for the ^{105}Pd states are compared with the other reported results (Table II). It is observed that the measured B(E2)↑ value of the 442.1 keV state of ^{105}Pd is close to that observed by Bolotin and McClure and that of 781.7 keV state is close to that observed

TABLE I

B(E2)↑ values of the first 2^+ states of even Pd nuclei

Pd isotope	Isotopic abundance in natural sample (%)	Level energy (keV)	Measured B(E2)↑ in e^2 cm$^4 \times 10^{-50}$		
			Previous values	Bolotin, McClure [5]	Present work
104	10.97	555.8	44 ± 3.8^a	53.1 ± 4.0	44 ± 7
106	27.3	511.6	71 ± 4^b	68.9 ± 3.7	73 ± 11
108	26.7	434.6	76 ± 5^b	79.2 ± 5.0	76 ± 9
110	11.8	373.6	91 ± 6^b	88.0 ± 6.0	89 ± 14

^{a} Ref. [3]. ^{b} Ref. [4].

TABLE II

$B(E2)\uparrow$ values for levels in ^{105}Pd

Level energy (keV)	Spin-parity[a] J^{π}	Measured $B(E2)\uparrow$ in $e^2\,cm^4 \times 10^{-50}$		
		Geiger et al. [6]	Bolotin, McClure [5]	Present work
279.9	3/2+	0.97±0.06	1.10±0.10	0.73±0.16
306.3	7/2+	0.11±0.02	0.12±0.02	
319.3	5/2+	0.88±0.07	0.81±0.10	0.95±0.20
344.6	(1/2+)	0.28±0.03	0.15±0.03	
442.1	7/2+	19	16.5±1.3	16.2 ±2.7
561.7	(5/2+)	1.11±0.07	0.75±0.10	1.11±0.38
650.7	3/2+	0.79±0.07	0.66±0.13	
673.1	(1/2+)	0.92±0.07	0.57±0.11	
727.5	(5/2+)	1.23±0.08	0.24±0.06	
781.7	9/2+	11.3 ±0.06	8.27±0.83	11.9 ±3.0

[a] J^{π} for ^{105}Pd states are taken from Refs. [19] and [20].

by Geiger et al. It may be noted that the $B(E2)\uparrow$ value measured by Geiger et al. for the 727 keV state is $1.23 \pm 0.08\ e^2\,cm^4 \times 10^{-40}$. This is almost five times of that measured by Bolotin and McClure. This level was not excited in our experiment. Hence this ambiguity remains unresolved. It is not surprising that some of the states observed in earlier experiments with alpha particles have not been observed in the present work. The $B(E2)\uparrow$ values of these states are very small and hence it is difficult to excite these states by Coulomb excitation with protons.

4. *Discussion*

The E2 enhancement factors and half-lives of the first 2^+ states of even Pd nuclei measured in our work is shown in Table III. The collective nature of the first 2^+ states of the even Pd nuclei is evident from the E2 enhancement of these states compared to the single particle estimate. It is observed that the collective nature of the first 2^+ states increases with the increase in neutron number. This may be understood on the basis of the deviation

TABLE III

Properties of the first 2^+ states of even Pd nuclei

Nucleus	Level energy (keV)	J^{π}	$B(E2)\downarrow$ $(e^2 \cdot b^2)$	$\frac{B(E2)\downarrow}{B(E2)_{s.p.}}$	$T_{1/2}$ (ps)
^{104}Pd	555.8	2+	0.088±0.014	30.4	12.1±1.9
^{106}Pd	511.6	2+	0.146±0.022	49.1	11.0±1.7
^{108}Pd	434.5	2+	0.152±0.018	49.9	24.2±2.9
^{110}Pd	373.6	2+	0.177±0.028	56.6	43.7±6.9

of the neutron number from the nearest shell closure. A similar effect has also been noticed in case of Cd and Sn nuclei in this region [10, 11]. However, it is interesting to note that the $B(E2)\downarrow/B(E2)_{s.p}$ of the first 2^+ states of ^{106}Pd and ^{108}Pd are almost equal and hence the collectivity of the first 2^+ states of these two isotopes is almost the same.

The complex structure of the low-lying states of ^{105}Pd may be understood from the coupling of the odd neutron to the ^{104}Pd core. From the shell model description, the $5/2^+$ ground state of ^{105}Pd is described as the single odd neutron in $d_{5/2}$ orbital. The other available single particle states will be $s_{1/2}$, $g_{7/2}$, $d_{3/2}$ and $h_{11/2}$ above the $d_{5/2}$ ground state. According to de-Shalit [12] the $d_{5/2}$ neutron is coupled to the one phonon or two-phonon vibration of the neighbouring even core. Due to the coupling of $d_{5/2}$ to the first 2^+ state of the ^{104}Pd nucleus a multiplet of states having spins $1/2^+$, $3/2^+$, $5/2^+$, $7/2^+$ and $9/2^+$ would arise. In the weak coupling model each member of this multiplet would have the same $B(E2)\downarrow$ and equal to the $B(E2)\downarrow$ of the core state considered. The E2 enhancement and half-lives of the states of ^{105}Pd measured in the present investigation are shown in Table IV. It is observed from the present investigation that the prediction of weak coupling model is satisfied to some extent only by the 442.1 keV ($7/2^+$) and 781.7 keV ($9/2^+$) states (Table IV). The $B(E2)\downarrow$ of the other observed states are small. It is also observed that the $B(E2)\downarrow$ of the 442.1 keV and 781.7 keV states are considerably enhanced over the single particle

TABLE IV

Properties of the excited states of ^{105}Pd

Level energy (keV)	J^π	$B(E2)\downarrow$ $(e^2 \cdot b^2)$	$\frac{B(E2)\downarrow}{B(E2)_{s.p.}}$	Mixing ratio δ	$B(M1)\times 10^2$ $(e\hbar/2\,MC)^2$	$T_{1/2}$ (ps)
279.9	$3/2^+$	0.0110 ± 0.0024	3.7	$+0.132\pm0.008$[a]	3.5	51
319.3	$5/2^+$	0.0095 ± 0.0020	3.2	$+0.091\pm0.013$[b]	8.3	15
442.1	$7/2^+$	0.1215 ± 0.0202	41.5	$-0.33\ \pm0.13$[c]	15.4	2.7
561.7	$(5/2^+)$	0.0111 ± 0.0038	3.8			
781.7	$9/2^+$	0.0714 ± 0.0180	24.3			1.6

[a] Ref. [19]. [b] Ref. [21]. [c] Ref. [20].

estimate and the values are close to that of the first 2^+ states of the neighbouring even nuclei of Pd. The 279.9 keV, 319.3 keV and 561.7 keV states show only slight E2 enhancement over the single particle estimate. It is also observed that only 70% of the core state $B(E2)$ is distributed among these excited states of ^{105}Pd majority of which is fragmented into two states, 442.1 and 781.7 keV respectively. Bolotin and McClure have given the argument about the missing $B(E2)\uparrow$; according to them the missing $B(E2)\uparrow$ may be attributed to the ground state, considering a transition $J_0 \to j_0$. As a result of this, the ground state will have a quadrupole moment. If in the present work the missing $B(E2)\uparrow$ strength is attributed to the ground state, the ground state will have the static quadrupole moment 0.76, very close to the measured value 0.86 [13]. The missing $B(E2)\uparrow$ strength could entirely be accounted for by an admixture of $(2^+\otimes d_{5/2})$ coupling in the ground state. Such an admixture of configuration would lead to M1 transitions from the core coupled states to the ground state. The calculated B(M1) of the ^{105}Pd states are quite consistent with this simple picture of admixture. The small E2 enhancement of a few states of ^{105}Pd may also be understood from the admixture of the single particle states to the core coupled states. It may be concluded that these states contain large admixture of single particle components. The states which were weakly excited or not excited at all in the present work were excited with appreciable strength in (p, d) reaction [14]. This also proves the large single particle admixture to these states.

Attempts were made earlier by several authors to explain the structure of ^{105}Pd from vibration particle coupling and rotation particle coupling [15, 16]. Neither of these calculations could reproduce the level structure satisfactorily. However, the theoretical calculation by Takacsy and Das Gupta [17] on the basis of Hartree-Fock plus BCS calculation achieved considerable success in reproducing the spectroscopic factors as well as the B(E2) values of a number of states of ^{105}Pd. Recently Chatterjee and Bhattacharya [18] made an attempt to explain the low-lying structures of ^{105}Pd, ^{107,109}Cd nuclei on the basis of phonon quasiparticle coupling calculation. The properties of the low-lying levels of ^{107,109}Cd in this calculation have been explained successfully. For ^{105}Pd nucleus, calculations were carried out considering a single neutron (or hole) coupled to the ^{104}Pd and ^{106}Pd cores. These calculations although achieved success in reproducing the spectroscopic factors of a number of states and the B(E2) of a few excited states, yet it would not explain the B(E2) of a number of other states. It seems from the above calculations that the ^{105}Pd nucleus is more complex in nature than the ^{107}Cd and ^{109}Cd, the properties of the low--lying levels of which were reproduced very satisfactorily from the pure particle harmonic vibrator core coupling calculations. As a natural consequence of this, calculations with pure harmonic vibrator cores could not explain the properties of a number of low-lying states of ^{105}Pd. However, it is realised that improvement in the present calculation may be achieved if the anharmonic effects in the Pd cores vibrations can be taken into account. The success of the calculation of Takacsy and Das Gupta may be understood from the fact that in this calculation deformation in the core was considered.

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