[27] J. C. D. Milton and J. S. Fraser, Can. J. Phys. 40, 1626 (1962).

[28] J. H. Neiler, F. J. Walter, and H. W. Schmitt, Phys. Rev. 149, 894 (1966).

[29] Results of computations for ^{233}U are not plotted in the symmetric region because of the uncertainty of fragment yields of Ref. 27 in the region.

[30] V. P. Eismont and V. A. Yurgenson, Yadern. Fiz. 1, 185 (1965) [transl.: Soviet J. Nucl. Phys. 1, 129 (1965)].

[31] V. M. Strutinsky, Nucl. Phys. A95, 420 (1967).

[32] J. Terrell, Phys. Rev. 127, 880 (1962).

PHYSICAL REVIEW C VOLUME 3, NUMBER 2 FEBRUARY 1971

Coulomb Excitation of Levels in Pd^{105}[†]

H. H. Bolotin and D. A. McClure[*]
Argonne National Laboratory, Argonne, Illinois 60439

(Received 25 February 1970)

The low-lying excited states of Pd^{105} were investigated by means of Coulomb excitation using 4.4–8.0-MeV α-particle projectiles. The γ-ray spectrum resulting from the deexcitation of these levels was recorded at each bombarding energy with the aid of a large-volume high-resolution Ge(Li) detector. Thirteen transitions were observed that result from direct $E2$ excitation of 10 excited states up to an excitation energy of 782 keV. The $B(E2\uparrow)$ values from the ground state to each of these 10 levels was determined. Several $E2$ transitions were found to be strongly enhanced over estimates of single-particle speed, a pattern suggestive of collective behavior. The measured $B(E2)$ values, together with some inferred $M1$ transition speeds, are compared with predictions of a weak-coupling core-excitation model.

I. INTRODUCTION

The level scheme of Pd^{105} displays considerable complexity. Thirteen excited states up to an energy of ~1100 keV have been reported[1-3] from a number of studies of the decay of Ag^{105}. Although the experimental information previously available on the level structure of this nuclide is not sufficient to describe the characteristics of the low-lying excited states in detail, it appears that a simple shell-model description of these levels will not be totally adequate. Previous[4-9] Coulomb-excitation studies of Pd^{105}, conducted with NaI(Tl) detectors, observed only three excited states at 280, 442, and 780 keV but showed the $E2$ excitation of the latter two levels to be considerably enhanced over single-particle estimates. Other information suggestive of the presence of possible collective behavior comes from the measured $B(E2)$ values of the first excited state of the even-mass Pd isotopes. When the values of the quadrupole-deformation parameter β_2 derived[10] from these reduced transition probabilities are expressed as ratios to the corresponding single-particle estimates, these ratios increase monotonically from Pd^{104} to Pd^{110} and are among the largest known outside the deformed rare-earth region. A similar behavior has already been noted[11] in the even Ru isotopes. Thus, a static ground-state deformation might be anticipated for nuclei in this mass region.

Recent radioactivity studies[1-3] of Pd^{105} have shown its level scheme to be much more complex than had been suggested by the older Coulomb-excitation investigations. This observation of numerous low-lying states not observed in the poor-resolution Coulomb-excitation work conducted with NaI(Tl) detectors raises the possibility that these earlier excitation data may have been incorrectly interpreted. The $E2$ excitation strengths to the more recently observed levels could be useful in establishing the level structure of this nuclide. To this end, the Coulomb excitation of Pd^{105} was reexamined by use of a high-resolution large-volume Ge(Li) detector.

Thirteen deexcitation transitions, representing the excitation of 10 excited states up to an energy of 782 keV in Pd^{105}, were observed and the $B(E2\uparrow)$ value of each of these states was determined.

II. EXPERIMENTAL METHODS AND PROCEDURES

Thick targets of both isotopically enriched[12] (77.2% Pd^{105}) and naturally abundant Pd (22.23% Pd^{105}) were bombarded with α particles from the Argonne tandem Van de Graaff accelerator. The targets were in the form of self-supporting metallic rolled foils ~65 mg/cm^2 thick. The deexcitation γ rays were viewed with an ~30-cm^3 Ge(Li) spectrometer that displayed a linewidth of 2.9 keV at a deposited γ-ray energy of 1.33 MeV. The spectra were recorded up to a γ-ray energy of ~2600 keV and stored in a 4096-channel pulse-height analyzer. To prevent possible line shift and broadening during the runs, digital zero and gain stabilization were employed at the analog-to-digital converter of the analyzer with the aid of pulses from an extremely stable dual-pulse generator.[13] Spectra were recorded at seven α-particle energies from 4.4 to 8.0 MeV.

The determination of the relative excitation probabilities as a function of incident projectile energy not only provides valuable information on the complicated γ-ray branching and feeding of the levels populated, but also provides a means whereby the character and multipole order of the Coulomb excitation of each state may be established. From the measurement of the absolute yield, the reduced transition probability for the excitation of each level can be inferred.

The absolute yields of the γ rays were determined from the Ge(Li) data. The absolute γ-ray detection efficiency of the detector was determined with the use of well-calibrated single γ-ray intensity standards run in the identical geometric configuration used in the Coulomb-excitation studies and with the target in position in the target chamber. Thus, all attenuation effects due to absorption in the target, target-chamber walls, etc. were automatically taken into account.

In addition, since absolute yields were to be determined, a new and accurate method was employed to measure and correct for the fractional counting losses suffered in the entire electronic system for each spectrum recorded in both the efficiency-calibration and Coulomb-excitation runs. This technique[14] automatically took account of all the counting losses incurred, despite time-dependent variations in counting rate due to unreproducible and at times severe fluctuations of the beam current of the accelerator.

To obviate effects of anisotropic γ-ray emission, the Ge(Li) detector was placed approximately 3 cm from the target and at an angle of 55° to the beam direction – the angle at which $P_2(\cos\theta)$ vanishes. Since the coefficient of $P_4(\cos\theta)$ is negligibly small for the Coulomb-excitation process (especially for target nuclei with spin $\frac{5}{2}$, the spin of the Pd^{105} ground state), this detector placement leads to the confident expectation that effects of the γ-ray angular distribution may be ignored, as was done in analyzing the present data.

The energies of all γ rays observed were determined by comparison with γ-ray transitions at 121.970 ± 0.030 keV in Co^{57} and at 1173.226 ± 0.040 keV in Co^{60}, both of which are known to high accuracy.[15] This comparison was made with the aid of an extremely linear ramp generator and a chopper, which in combination accurately defined the local differential nonlinearity of the electronic system over the entire energy range of interest.[16] This information, coupled with the pulse-height positions of the calibration γ rays, yielded the energies of the γ rays observed in the Coulomb-excitation study to accuracies limited principally by the errors in the determination of the centroid positions of the peaks representing individual transitions. The centroids and peak areas of both the calibration γ rays and Pd^{105} deexcitation lines were determined by a computer program which employed a Gaussian line shape in a variable-metric minimization procedure.[17]

III. RESULTS

A. γ-Ray Spectra and Level Scheme

The spectra of deexcitation γ rays from the enriched Pd^{105} target were recorded with the Ge(Li) spectrometer at α-particle energies of 4.4, 5.2, 5.6, 6.0, 6.4, 7.2, and 8.0 MeV. Each spectrum was accumulated over a period of 1–4 h, depending upon the α-particle beam current available at each specific bombarding energy. A representative spectrum, taken with the enriched Pd^{105} target at 7.2-MeV α-particle energy, is shown in Fig. 1. The γ-ray energies and intensities observed at each bombarding energy are listed in Table I.

From previously reported studies of the decay of Ag^{105}, it was evident that a few transitions depopulating some of the states excited in the present work would be either too weak to be observed or not seen strongly enough to establish the γ-ray branching ratios of these levels with sufficient accuracy. Fortunately, those states weakly excited in the Coulomb-excitation study are fed strongly in the β decay of Ag^{105}. Therefore, a source of Ag^{105} was prepared by means of the $\mathrm{Rh}^{103}(\alpha, 2n)\mathrm{Ag}^{105}$ reaction, and the γ-ray spectrum was recorded with the Ge(Li) spectrometer. The 63.9-keV γ ray was too weak to be observed in the Coulomb excitation of the 344.6-keV state, and the 370.0-keV γ ray depopulating the 650.7-keV level was partially obscured in the deexcitation spectrum by the presence of the stronger 373.8-keV line from the Pd^{110} impurity in the target. Hence, their intensities relative to other γ rays depopulating the same states were adopted from the relative intensities determined from the Ag^{105} spectrum.

From the above information, a level scheme that includes only those states observed in the Coulomb-excitation study of Pd^{105} has been constructed. Figure 2 compares this with the Pd^{105} level scheme proposed by Pierson and Rengan[2] from their study of the decay of Ag^{105}. The spin and parity assignments are mostly taken from the radioactivity investigations, which covered the

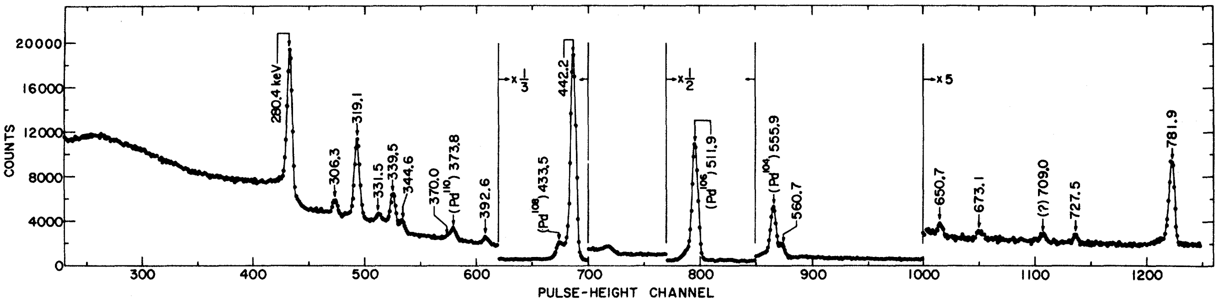

FIG. 1. Representative γ-ray spectrum resulting from Coulomb excitation of Pd^{105} with 7.2-MeV α particles. A thick metallic target enriched to 77.2% in Pd^{105} was employed. The deexcitation γ rays were viewed with a large-volume Ge(Li) detector. The energies of the transitions are in keV. Transitions resulting from Coulomb excitation of the first excited states of some even-mass Pd isotopes present in the target are appropriately labeled. All other transitions, with the single exception of that at 709.0 keV, whose origin is not certain, are assigned to Pd^{105}. No deexcitation γ rays were observed outside the energy range displayed.

same range of excitation energy. The schemes are in excellent agreement on the states common to the two studies. It is also worth noting that all levels previously assigned positive parity were found to be Coulomb-excited, and that the 781.9-keV state had not been observed in studies of the Ag^{105} decay.

B. Determinations of $B(E2\uparrow)$

The theoretical Coulomb-excitation cross sections were computed from the tables, formulas, and calculational aids presented in the comprehensive review article of Alder *et al.*[18] The α-particle bombarding energies employed were all low enough to allow the excitation-function graphs and tables in this article to be utilized directly. The stopping power $(dE/\rho dx)$ for α particles in the target material is required in order to calculate the thick-target yields from the graphs and formulas of Ref. 18 that relate these yields to the cross section. The stopping power of Pd for α particles was obtained by quadratic interpolation with respect to atomic number by use of Bischel's[19] tabulation of the stopping powers of Kr, Ag, and Sn for protons. It was assumed that the stopping power for α particles is 4 times that of protons at $\frac{1}{4}$ the α-particle energy. (To avoid additional interpolation, the α-particle energies employed were those corresponding to proton energies listed by Bischel.[19])

In order to ascertain the absolute probability of direct excitation of each level, it is necessary to correct the observed absolute γ-ray intensities for internal conversion, the branching ratios of all transitions depopulating individual levels, and the feeding of each state by transitions originating

TABLE I. γ-ray energies and intensities in Pd^{105}. The excitation energies E_i of the initial and E_f of the final levels are given in the last column.

Transition energy (keV)	Observed γ-ray intensity (γ-rays per 10^{10} incident α particles) for the following E_α (MeV): 4.4	5.2	5.6	6.0	6.4	7.2	8.0	Assigned $E_i \to E_f$ (keV)
280.37 ± 0.06	9.50	27.4	39.9	58.4	69.1	128	217	280.4 → 0
306.25 ± 0.08	0.57	1.73	3.68	6.05	6.47	12.0	27.6	306.3 → 0
319.08 ± 0.05	4.67	13.0	24.2	34.8	43.0	78.3	136	319.1 → 0
331.48 ± 0.10	···	···	0.55	2.14	2.36	6.68	13.6	650.7 → 319.1
339.49 ± 0.06	···	···	2.43	6.31	9.94	31.8	76.9	781.9 → 442.2
344.55 ± 0.10	····	1.27	3.18	4.31	4.73	8.71	12.6	344.6 → 0
369.98 ± 0.48	···	···	···	···	···	2.74	4.24	650.7 → 280.4
392.56 ± 0.10	···	···	···	1.26	2.91	6.80	12.4	673.1 → 280.4
442.24 ± 0.08	25.7	109	194	316	436	892	1630	442.2 → 0
560.74 ± 0.20	0.22	1.91	3.74	6.57	10.1	23.1	45.3	560.7 → 0
650.65 ± 0.20	···	···	···	1.85	2.19	3.74	12.5	650.7 → 0
673.12 ± 0.26	···	···	···	···	1.91	3.73	9.3	673.1 → 0
727.54 ± 0.19	···	···	···	···	1.18	3.10	7.92	727.5 → 0
781.90 ± 0.19	···	1.80	3.69	7.99	17.2	48.0	122	781.9 → 0

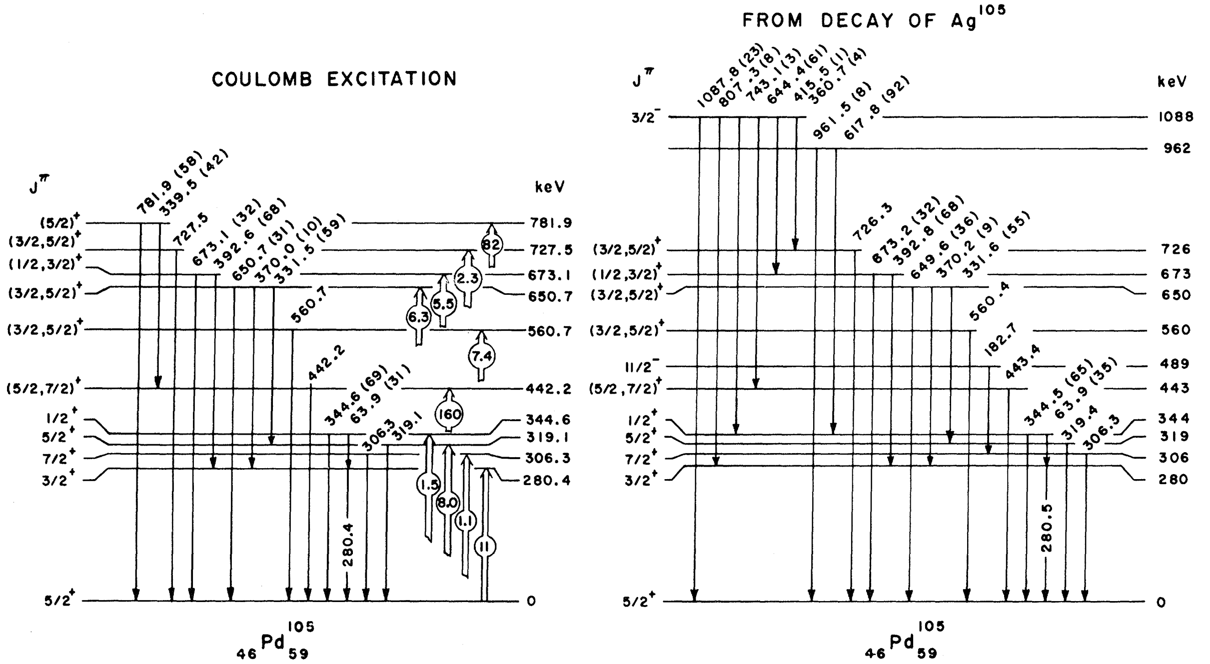

FIG. 2. Level schemes of Pd^{105} Shown on the right is the decay scheme proposed by Pierson and Rengan (Ref. 2) from their study of the radioactive decay of Ag^{105}. (Only those transitions whose placements are considered certain and whose relative intensities were determined by those authors have been included.) The level scheme presented on the left is that derived solely from the present Coulomb-excitation investigation. The $B(E2\uparrow)$ values (in units of $10^{-51}\ e^2\,\mathrm{cm}^4$) determined in the present study are contained in the upward pointing pot-bellied arrows which schematically represent the direct $E2$ excitation of the indicated states. The branching ratios of the transitions are indicated in parentheses following the energies (in keV) of the appropriate transitions and are given as percentages of the total decay of a given level. All energies are in keV. The spin and parity assignments are inferred principally from the radioactive-decay studies. Those spins assigned with less certainty are enclosed in parentheses. The positive-parity assignments of all levels in the left-hand scheme reflect the $E2$ excitation of these states and are seen to be consistent with those proposed by the authors of Ref. 2.

from levels at higher excitation energy. For each transition observed in both the present Coulomb-excitation study and in the decay of Ag^{105}, the relative internal-conversion coefficient was calculated from the relative γ-ray intensities in our Ag^{105} investigation and the relative intensities of internal-conversion-electron lines measured in a study of the same decay by Suter *et al.*[1] These ratios were normalized to the theoretical conversion coefficient[20] of the 442.2-keV ($M1+E2$) transition (for which the theoretical $M1$ and $E2$ conversion coefficients are virtually identical) to yield the total internal-conversion coefficients of these transitions. With the exception of the 63.9-keV transition for which a sizable total internal-conversion coefficient ($\alpha_T = 1.6 \pm 0.2$) was determined, corrections for internal conversion were small ($\leq 2\%$).

Since the excitation cross section (and thus the resulting feeding from above) of all states is a sensitive function of the bombarding energy and the level excitation energy, the measured intensities of all transitions observed at each projectile energy were used to correct for feeding to obtain the absolute intensity of each transition originating from a directly excited level. [This procedure required only a rudimentary *a priori* knowledge of the level scheme, since the accurate transition energies obtained from the Ge(Li) spectra served to define the level scheme virtually independent of prior information.] The resultant measured net yield for each observed transition is plotted as a function of α-particle energy in Fig. 3. The solid lines in this figure represent the normalized theoretical $E2$ thick-target yield[18] for each level. The net yield dependence of each transition is seen to be consistent with $E2$ excitation of the depopulated level.

The higher the excitation energy of the state, the more sensitive the net yield is to projectile energy. From this dependence (Fig. 3) it is evident that (a) the 331.5-, 392.6-, and 339.5-keV transitions are not ground-state transitions but rather result from excitation of the 650.7-, 673.1-, and 781.9-keV states, respectively, and (b) all other transitions proceed directly to the ground state. These findings are in accord with the place-

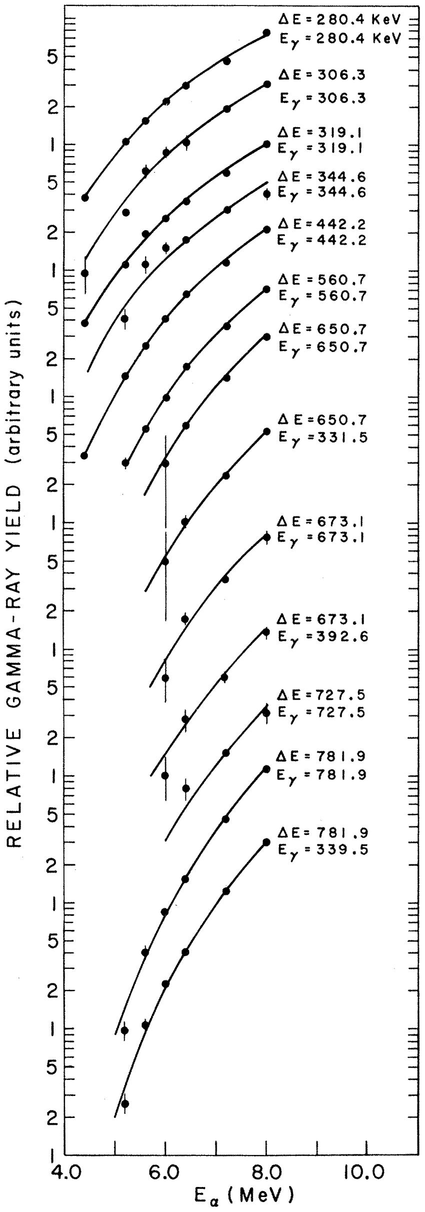

FIG. 3. Relative thick-target yield obtained for each γ ray observed in the present Coulomb-excitation study. The points represent the data obtained at each α-particle bombarding energy. The solid curve represents the theoretically predicted $E2$ excitation thick-target yield for each γ ray depopulating a particular level. The theoretical curves have been normalized to the data by the weighted average of the $B(E2\uparrow)$ determined at each α energy. ΔE and E_γ denote, respectively, the excitation energy of the state and the γ-ray energy, in keV. For clarity of presentation, the data corresponding to individual transitions have been arbitrarily displaced along the ordinate in the order of the excitation energy of the level of origin. Table I lists the absolute thick-target yield of each γ ray observed at the various α-particle energies employed.

ment of these transitions in the level scheme of Fig. 2.

The absolute thick-target yield due to direct excitation of each state was then obtained from the measured branching ratios, and was compared with the theoretical value to determine the $B(E2\uparrow)$ value at each α-particle bombarding energy. The $B(E2\uparrow)$ value adopted for each state (Table II) was obtained from a weighted average of these values. Although the statistical errors are negligible, estimates of other systematic errors associated with efficiency determinations, thick-target theoretical-yield calculations (including uncertainties in stopping power), background subtraction, isotopic composition of the target, and beam-current integration lead to the errors specified in Table II.

A similar Coulomb-excitation study with a target of natural isotopic abundance bombarded by 8.0-MeV α particles was undertaken to confirm these results obtained with the enriched Pd^{105} target. The $B(E2\uparrow)$ values obtained with the two targets agreed within the assigned errors. In addition, the presence of Pd^{104,106,108,110} in both targets enabled us to determine the $B(E2\uparrow; 0^+ \to 2^+)$ values for the first excited state of each isotope and are presented in Table III. In every case, these measured values agree with the most recently reported[10,21] $B(E2\uparrow)$ values for these even-A isotopes to well within the quoted errors. This accord is convincing evidence that efficiency determinations, isotopic abundances, etc. were properly evaluated and that the Pd^{105} $B(E2\uparrow)$ values determined in the present work do not suffer from other significant, but unspecified, systematic uncertainties.

The only Pd^{105} levels for which $B(E2\uparrow)$ values have been reported[4,5] in the literature are those at 280.4, 442.2, and 781.9 keV. These earlier results, obtained from Coulomb-excitation studies with NaI(Tl) detectors, are presented for comparison in Table II. It is apparent that the previously reported $B(E2\uparrow)$ values are in strong disagreement with each other. However, in an older report by Temmer and Heydenberg,[6] noted as superseded (with no explanation) in their later paper,[4] the $B(E2\uparrow)$ values quoted for these two states are in good agreement with those determined in the present investigation.

The 709.0-keV transition, indicated by (?) in the spectrum of Fig. 1, was observed only at the three highest α-particle energies. This transition has not been reported in any earlier studies of Pd^{105} and cannot be fitted between any two known levels of this nuclide. The yield of this transition as a function of projectile energy is too steep to be consistent with $E2$ excitation of a possible new state at 709 keV. However, if indeed this transition does result from Coulomb excitation of Pd^{105}

TABLE II. $B(E2)$ values for levels in Pd^{105}.

Level energy (keV)	$B(E2\uparrow)$ ($e^2\,\mathrm{cm}^4\times10^{-48}$) Present work	Ref. 4	Ref. 5	Ref. 7	J [a]	$B(E2\downarrow)$ [b] ($e^2\,\mathrm{cm}^4\times10^{-48}$)
280.4	0.0110 ± 0.0010	0.040	0.0084	≤0.013	$\frac{3}{2}$	0.017
306.3	0.0012 ± 0.0002	⋯	⋯	⋯	$\frac{7}{2}$	0.0009
319.1	0.0081 ± 0.0010	⋯	⋯	⋯	$\frac{5}{2}$	0.0081
344.6	0.0015 ± 0.0003	⋯	⋯	≤0.026	$\frac{1}{2}$	0.0045
442.2	$0.165\ \pm0.013$	0.17	0.057	0.21	$(\frac{5}{2},\frac{7}{2})$	(0.165, 0.127)
560.7	0.0075 ± 0.0010	⋯	⋯	⋯	$(\frac{3}{2},\frac{5}{2})$	(0.0113, 0.0075)
650.7	0.0066 ± 0.0013	⋯	⋯	⋯	$(\frac{3}{2},\frac{5}{2})$	(0.0099, 0.0066)
673.1	0.0057 ± 0.0011	⋯	⋯	⋯	$(\frac{1}{2},\frac{3}{2})$	(0.0171, 0.0086)
727.5	0.0024 ± 0.0006	⋯	⋯	⋯	$(\frac{3}{2},\frac{5}{2})$	(0.0036, 0.0024)
781.9	0.0827 ± 0.0083	⋯	⋯	0.059	$(\frac{5}{2})$	(0.0827)

[a] These spin values for all levels, with the exception of that at 781.9 keV, are those proposed by Kawakami, private communication and were derived principally on the basis of internal-conversion-electron studies (including determinations of the ratios for the L subshells) of the transitions observed in the decay of Ag^{105}. The 781.9-keV level is not observed in the decay of Ag^{105} and the listed spin of this level is that favored by the authors of Ref. 9.

[b] These $B(E2\downarrow)$ values were derived from the $B(E2\uparrow)$ values of the present work and the spin assignments of the levels. Where the spin is uncertain, the two $B(E2\downarrow)$ values corresponding to the alternative spin choices are listed.

(and there is no strong evidence that it does), its yield would not be inconsistent with $E2$ excitation of a level at ~1.2 MeV. Since no observed γ ray could represent a ground-state transition from a level at this approximate energy, the 709-keV transition (if attributed to Pd^{105}) might presumably be dipole in character in order to allow for its successful competition with the more energetic ground-state transition. On the assumption that no other significant branching from this state has been missed, a value $B(E2\uparrow)\approx0.01\ e^2\,\mathrm{cm}^4\times10^{-48}$ can be inferred for excitation of this possible level at ~1.2 MeV. (It should be pointed out that we make no claim for the existence of such a state, and do not even propose that the 709-keV transition be assigned to Pd^{105}.) However, the inferred $B(E2\uparrow)$ value of such a state can be used to estimate a reasonable upper limit on the excitation probability of any unobserved level in Pd^{105} up to an energy of ~1.2 MeV.

TABLE III. Comparison of $B(E2;\ 0\rightarrow2)$ values for even Pd isotopes (natural Pd target) obtained in the present work with previously reported values.

Pd isotope	Level energy (keV)	Isotopic abundance (%) (natural sample)	Measured $B(E2\uparrow)$ ($e^2\,\mathrm{cm}^4\times10^{-50}$) Present work	Previous value
104	555.9	10.97	53.1 ± 4.0	55.0 ± 3.8 [a]
106	511.9	27.33	68.9 ± 3.7	$71\ \pm4$ [b]
108	433.5	26.71	79.2 ± 5.0	$76\ \pm5$ [b]
110	373.8	11.81	88.0 ± 6.0	$91\ \pm6$ [b]

[a] See Ref. 10. [b] See Ref. 21.

IV. TRANSITION PROBABILITIES

The reduced $E2$ excitation probabilities from the ground state to each of the 10 observed excited levels in Pd^{105} are presented in Table II. The $B(E2\downarrow)$ values corresponding to deexcitation of these levels to the ground state are related to the upward excitation by the relation

$$B(E2\downarrow)=B(E2\uparrow)(2I_0+1)/(2I^*+1)\,,$$

where I_0 and I^* are the respective spins of the ground state and excited state. The $B(E2\downarrow)$ values of these ground-state transitions are also listed in Table II.[22]

The reduced $E2$ excitation probability to each of the levels is compared with single-particle and one-phonon transition speeds in Table IV. The single-particle excitation probabilities are taken from Moszkowski[23] and include the spin statistical factors. The one-phonon speeds are derived from the measured[21] $B(E2\uparrow;\ 0^+\rightarrow2^+)$ values for the neighboring Pd^{104} even-even nuclide.

It would also be of considerable interest to determine the partial $M1$ transition probabilities of all the deexcitation transitions. Unfortunately, the $E2/M1$ multipole mixing ratios of most transitions are not available. The results of previously

TABLE IV. Enhancement of $E2$ excitations in Pd^{105}.

Level energy (keV)	J [a]	Favor factors F_M [b]	 F_{ph} [c]
280.4	$\frac{3}{2}$	13	0.15
306.3	$\frac{7}{2}$	2.1	0.08
319.1	$\frac{5}{2}$	2.4	0.07
344.6	$\frac{1}{2}$	0.5	0.04
442.2	$(\frac{5}{2},\frac{7}{2})$	(49, 294)	(1.5, 1.1)
560.7	$(\frac{3}{2},\frac{5}{2})$	(8.9, 2.2)	(0.10, 0.07)
650.7	$(\frac{3}{2},\frac{5}{2})$	(7.8, 1.9)	(0.09, 0.06)
673.1	$(\frac{1}{2},\frac{3}{2})$	(1.9, 6.8)	(0.16, 0.08)
727.5	$(\frac{3}{2},\frac{5}{2})$	(2.9, 0.7)	(0.03, 0.02)
781.9	$(\frac{5}{2})$	(25)	(0.75)

[a] See footnote a of Table II.

[b] $F_M = B(E2\uparrow)/B_{sp}(E2\uparrow)$, where B_{sp} is taken as the Moszkowski (Ref. 20) single-particle estimate and includes the spin statistical factor. For those levels whose spins are uncertain, F_M values are presented for each listed spin choice.

[c] $F_{ph} = B(E2\downarrow)/B(E2;\ 2 \rightarrow 0)$, where $B(E2;\ 2\rightarrow 0)$ is the value for the next lowest even isotope Pd^{104} and was measured to be $0.110\ e^2 cm^4 \times 10^{-48}$ (Ref. 10). For those levels whose spins are uncertain, F_{ph} is presented for each of the spin choices listed.

reported[24] γ-γ angular-correlation studies of cascade transitions observed in the Ag^{105} decay are conflicting and are therefore felt to be inconclusive in their determinations of the multipole mixing of the transitions investigated. Although the internal-conversion work of Suter *et al.*[1] has provided the K conversion coefficients and K/L conversion ratios of most transitions (except those of lowest energy) in the decay of Ag^{105}, the theoretical $E2$ and $M1$ conversion coefficients are too close in value to allow a meaningful multipole decomposition of these transitions.

However, the internal-conversion ratios for the L subshell are more sensitive to multipole mixing and have recently been measured[3] for the 64-, 280-, and 344-keV transitions. These resultant multipole ratios have been combined with the present results to obtain the partial lifetimes of the $M1$ components of these transitions. These results are compared with the corresponding single-particle $M1$ lifetimes in Table V. An *upper limit* to the lifetime of all other states may be obtained from the measured $B(E2\uparrow)$ values and branching ratios for each state by assuming a pure $E2$ character for the ground-state transitions. These upper-limit estimates are of little interest except that the value $t_{1/2} < 2.3\times10^{-12}$ sec obtained for the 782-keV state leads to an upper limit $t_{1/2}(339\ \text{keV}) < 5.4\times10^{-12}$ sec for the partial half-life of the 339.5-keV branch. This lifetime, listed in Table V, is fairly short and will be discussed in Sec V.

V. DISCUSSION

The $\frac{5}{2}^+$ spin and parity of the ground states of virtually all even-odd nuclides in the $A = 105$ mass region suggests that the dominant character of these levels is due to the $d_{5/2}$ neutron orbital. In ${}_{40}Zr^{91}_{51}$ the unperturbed single-particle energies of the $s_{1/2}$, $g_{7/2}$, $d_{3/2}$, and $h_{11/2}$ neutron orbitals are all more than 1.5 MeV above that of the $d_{5/2}$ orbital; but as the number of neutrons increases beyond the $N = 50$ closed shell, the short-range residual pairing interaction can lead to a single-quasiparticle level scheme in which these orbitals become significantly closer to the ground state. There is ample evidence that this is the case for ${}_{46}Pd^{105}_{59}$. The $h_{11/2}$ orbital, which in Zr^{91} possesses the highest unperturbed single-particle energy in this major shell, is undoubtedly the origin of the $\frac{11}{2}^-$ low-lying excited state at 489.0 keV. On a larger scale, the (d,p) and (d,t) reaction studies of Čujec[25] have convincingly shown that the single-

TABLE V. $M1$ transition probabilities.

Transition energy (keV)	Assigned to $E_i \rightarrow E_f$ (keV)	Multipole assignment	Partial half-life [a] (sec)	Enhancement factor [b]
63.9	344.4 → 280.4	$M1$ [c]	5.8×10^{-9}	6×10^{-3}
280.4	280.4 → 0	$M1$ part (97.7%) [c]	4.7×10^{-11}	2×10^{-2}
339.5	781.9 → 442.2	$M1$ [d]	$<5.4\times10^{-12}$	$>1\times10^{-1}$

[a] These partial half-lives are those of the *transitions.*

[b] This column lists the ratio of the Weisskopf $M1$ single-particle half-life estimate of the transition (internal-conversion correction included) to the partial half-life of the transition presented in column 4 of this table.

[c] The sizes of the $M1$ components of the transitions (100 and 97.7% for the 63.9- and 280.4-keV transitions, respectively) are those assigned by Kawakami, private communication and were derived from his L-subshell internal-conversion studies of the decay of the Ag^{105}.

[d] Taken as pure $M1$ (see text, Sec. V) for the purpose of estimating its single-particle lifetime.

quasiparticle energies of *all* of the orbitals in this major shell are within ~650 keV of the $d_{5/2}$ ground state in Pd^{105}.

In addition, the long-range part of the residual interaction gives rise to vibrational (phonon) states in the even-even nuclei, and the coupling of these phonons with the single quasiparticles can lead to low-energy core-coupled excited-state multiplets. Thus, the experimentally observed complexity of the level structure of Pd^{105} below an excitation energy of ~1 MeV is not unexpected.

There exist, however, certain definitive differences between the properties of the excited single-quasiparticle levels and those of the excited core-coupled multiplet states. The former should display relatively large (d,p) strengths (i.e., spectroscopic factors) and $B(E2\uparrow)$ values that are reasonably close to single-particle estimates. The core-excited multiplets are expected to be weakly excited in stripping reactions, and the ones arising from one-phonon coupling to the ground-state orbital should possess highly enhanced $E2\uparrow$ strengths derived from that of the one-phonon excitation of the even-even core. In the case of configuration mixing, these differences may become less distinct. However, the observation of some highly enhanced $E2$ transitions in Pd^{105} indicates that the collective features of at least some of these levels are still salient.

Much additional information on the level structure of Pd^{105}, including definitive orbital-angular-momentum and spin assignments, lifetime determinations of many of the excited states, etc., will be required before detailed shell-model calculations can profitably be compared with experimental findings. Even then, the shell-model description of the states in Pd^{105} would be complicated and might be of dubious reliability. In default of such calculations, the results of the present investigation are a valuable complement to the previously available information on the levels in Pd^{105} and can provide some insight into the collective components of these excited states.

Within this framework, it is interesting to compare the present data with the weak-coupling core-excitation model of Lawson and Uretsky.[26] In this model the $d_{5/2}$ neutron orbital would be expected to couple to the ground state and first excited state of the neighboring even-even Pd^{104} core to yield a Pd^{105} level scheme in which there is a $\frac{5}{2}^+$ ground state and a quintet of excited states with spins of $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{9}{2}^+$. In the case of a pure vibrational core, transitions from each member of the excited multiplet to ground represent the $2^+ \rightarrow 0^+$ Pd^{104} core deexcitation. Thus, $M1$ ground-state transitions from the multiplet states would be forbidden, while the corresponding $B(E2\downarrow)$ of each transition should be equal to the $B(E2\downarrow; 2^+ \rightarrow 0^+)$ of Pd^{104}. However, $M1$ transitions between multiplet states with $\Delta J = 1$ would be allowed. In addition, the center of gravity of the excitation energies of the multiplet members should coincide with the excitation energy of the 2^+ state of the Pd^{104} core. To the extent that configuration mixing is present, these simple prescriptions may be considerably altered. Nevertheless, the gross features of this weak-coupling model may be used as a guide in assessing the core-excitation contributions to the low-lying levels in Pd^{105}.

As is evident from the data of Table IV, the $E2$ excitation probabilities of most of the observed states are considerably smaller than are expected from the prescription based on the simple core-excitation model. Indeed, only for the 442.2- and 781.9-keV levels are the $B(E2\uparrow)$ values consistent with that of the excitation of the 2^+ core state in Pd^{104} (i.e., $F_{ph} \approx 1$). The 280.4-keV level, and possibly the 560.7-, 650.7-, and 673.1-keV states (depending on their spins) display $B(E2\uparrow)$ values that are somewhat enhanced over single-particle estimates (column 3, Table IV), but still fall well below pure core-excitation expectations (i.e., $F_{ph} \ll 1$). The $E2$ transitions from the ground state to all other excited states proceed with approximately single-particle speed and show little, if any, core-excitation strength.

Thus, on the basis of the $B(E2\uparrow)$ values, only the 442.2- and 781.9-keV levels qualify as prime candidates for membership in a possible core-excitation multiplet. Despite competition from potential deexcitation transitions to other states of similar spin and like parity, the 781.9-keV level decays only to the ground state and to the other strongly excited state at 442.2 keV. This behavior further supports a similar constitutional makeup for these levels and is wholly consistent with a core-excitation interpretation for these states. The estimated upper limit for the $B(E2\uparrow)$ of any unobserved state up to an excitation energy of ~1.2 MeV (Sec. III) strongly suggests that no unobserved individual state below this energy possesses any appreciable $E2$ strength. It can therefore be concluded that the core-excitation strength of the "missing" multiplet members must be shared over many other levels whose wave functions contain significant single-quasiparticle components.

It is of little value to discuss the center of gravity of a multiplet whose members cannot be identified and enumerated. However, the center of gravity of the multiplet in Pd^{105} would be expected at ~554 keV (the excitation energy of the 2^+ state in Pd^{104}).

The (d,p) and/or (d,t) cross sections determined[25] for the 442.2- and 781.9-keV levels are the smallest observed for states below ~1 MeV. The findings are consistent with the collective core-excitation interpretation of these levels as inferred from the present Coulomb-excitation work. With the exception of the 442.2- and 673.1-keV states, Čujec[25] has proposed angular momentum assignments for all levels observed in the present study. Unfortunately, the relatively poor proton and triton resolution in that experiment did not allow the clear separation of all levels of interest, and it is possible that some of these angular momentum assignments are doubtful. For example, the ground state and 781.9-keV level have been assigned $l_n = 2$ and 0, respectively. However, the latter assignment is inconsistent with the strong enhancement of the $E2$ excitation of the 781.9-keV state, since this enhancement favors an $l_n = 2$ assignment for this level.

Unfortunately, little definitive information is available on the magnetic-dipole transitions in Pd^{105}. However, the 63.9- and 280.4-keV transitions have been shown to be almost pure $M1$ radiation, while the successful competition of the 339.5-keV transition with the enhanced $E2$ 781.9-keV transition suggests that it too is dominantly $M1$. Table V summarizes the information concerning these transitions. The 63.9- and 280.4-keV $M1$ transitions are retarded, while the 339.5-keV transition between the two possible multiplet members is rather strong (more than a tenth of the single-particle speed). Beyond the statement that these results are not inconsistent with the predictions from the model, little can be said. Knowledge (not now available) of the speeds of the $M1$ components of the ground-state transitions from the 442.2- and 781.9-keV "multiplet" could allow a more critical assessment of predictions from the weak-coupling model and thus might lead to a clearer evaluation of the structure of the levels concerned.

In the absence of polarization of the nucleus by the odd nucleon, the $E2$ excitation of the multiplet should exhaust the $E2$ strength of the $0^+ \rightarrow 2^+$ excitation of the even-even core. Thus, the $\sum B(E2\uparrow)$ in the odd-A nucleus should be equal to the $B(E2\uparrow; 0^+ \rightarrow 2^+)$ of the core. Although the complete set of multiplet members is not delineated and the $E2\uparrow$ strength appears to be shared among many predominantly single-quasipartical states, the above sum rule should still be applicable under the assumption that virtually all the $E2$ excitation strength is derived from core excitation. The $\sum B(E2\uparrow)$ over the 10 observed states falls far short of such expectations and accounts for only 53% of the $B(E2\uparrow; 0^+ \rightarrow 2^+)$ value for the core. This result is quite similar to the value Kistner and Schwarzschild[11] report from their Coulomb-excitation studies of Ru^{99} and Ru^{101}. These authors found that $\sum B(E2\uparrow)$ over all observed levels was only ~65% of the corresponding core values of the neighboring even-even nuclides.

Polarization of the nucleus by the odd particle can give rise to a static quadrupole moment Q for the ground state of the odd-A nucleus. Attributing the "missing" fraction of the $\sum B(E2\uparrow)$ to the ground-state quadrupole strength $B(E2; I_0 \rightarrow I_0)$ leads[15] to a ground-state quadrupole moment (~0.95 b) that is almost identical to the value (~0.9 b) similarly inferred for the ground states of Ru^{99} and Ru^{101}. Although this result is independent of the structure of the nuclear state, within the framework of weak coupling it would imply that a considerable contribution from various collective core-coupled components is admixed into the wave function of the ground states of these nuclides. For example, in this context, the "missing" $B(E2\uparrow)$ strength in Pd^{105} could be entirely accounted for by an ~36% admixture of the $(2^+ d_{5/2})$ coupling in the ground state. Such a simply constituted admixed configuration would imply that the $M1$ components of the ground-state transitions from multiplet members would no longer be forbidden and could proceed with speeds approaching single-particle estimates. Although information on the strengths of the possible $M1$ components of these ground-state transitions from the "multiplet" levels in Pd^{105} is not presently available, the analogous 89.4-keV transition from the strongly excited $\frac{3}{2}^+$ first excited state in Ru^{99} is reported[11] to have an $M1$ component that is retarded by a factor of ~10^4 relative to the single-particle speed. This large retardation is inconsistent with a similarly large amplitude for a $(2^+ d_{5/2})$ coupling component in the Ru^{99} ground-state wave function that could be invoked to explain the "missing" $E2$ excitation strength in that nuclide. At the same time, $M1$ components of some of the transitions between members of a multiplet are found to be fairly fast in Ru^{99}, Ru^{101}, and Pd^{105}. These two facets of the $M1$ depopulation of the "multiplet" states are not readily reconciled without invoking still additional configuration components arising from core coupling to other available orbitals. Such components would favor enhanced $E2$ excitation and, at the same time, would cause some of the $M1$ ground-state transitions to be, say, l forbidden, and therefore highly hindered.

ACKNOWLEDGMENTS

One of us (D.A.M.) appreciates the support provided by an Argonne Universities Association – Argonne National Laboratory predoctoral fellowship. The authors are indebted to Dr. R. D. Lawson for helpful and illuminating discussions.

†Work performed under the auspices of the U. S. Atomic Energy Commission.

*Present address: School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332.

[1] T. Suter, P. Reyes-Suter, W. Scheuer, E. Aasa, and G. Bäckström, Arkiv Fysik 20, 431 (1961).

[2] W. R. Pierson and K. Rengan, Phys. Rev. 159, 939 (1967).

[3] H. Kawakami and K. Hisatake, J. Phys. Soc. Japan 26, 849 (1969); H. Kawakami, private communication.

[4] G. M. Temmer and N. P. Heydenburg, Phys. Rev. 104, 967 (1956).

[5] H. Mark, C. McClelland, and C. Goodman, Phys. Rev. 98, 1245 (1955).

[6] G. M. Temmer and N. P. Heydenburg, Phys. Rev. 98, 1308 (1955).

[7] V. D. Vasil'ev, K. I. Erokhina, and I. Kh. Lemberg, Izv. Akad. Nauk SSSR, Ser. Fiz. 26, 992 (1962) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 26, 1000 (1962)].

[8] D. G. Alkhazov, V. D. Vasil'ev, G. M. Gusinskii, I. Kh. Lemberg, and V. A. Nakichvriskvili, Izv. Akad. Nauk SSSR, Ser. Fiz. 28, 1683 (1964) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 28, 1575 (1964)].

[9] G. M. Gusinskii and I. Kh. Lemberg, Izv. Akad. Nauk SSSR, Ser. Fiz. 30, 449 (1966) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 30, 456 (1966)].

[10] P. H. Stelson and L. Grodzins, Nucl. Data A1, 21 (1965).

[11] O. C. Kistner and A. Schwarzschild, Phys. Rev. 154, 1182 (1967).

[12] Obtained from Oak Ridge National Laboratory.

[13] M. G. Strauss, L. L. Sifter, F. R. Lenkszus, and R. Brenner, IEEE Trans. Nucl. Sci. 15, No. 3, 518 (1968).

[14] H. H. Bolotin, M. G. Strauss, and D. A. McClure, Nucl. Instr. Methods 83, 1 (1970).

[15] J. B. Marion, Nucl. Data A4, 301 (1968).

[16] M. G. Strauss, F. R. Lenkszus, and J. J. Eichholz, Nucl. Instr. Methods 76, 285 (1969); M. G. Strauss and F. R. Lenkszus, Nucl. Phys. A132, 195 (1969).

[17] H. H. Bolotin, in *Proceedings of the Conference on Slow-Neutron-Capture Gamma-Ray Spectroscopy, Argonne National Laboratory, Argonne, Illinois, 2–4 November 1966,* edited by F. E. Throw (Argonne National Laboratory, Argonne, Illinois, 1966), p. 255; W. C. Davidon, Argonne National Laboratory Report No. ANL-5990 (revised), 1966 (unpublished).

[18] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. 28, 432 (1956).

[19] H. Bischel, in *American Institute of Physics Handbook,* edited by D. E. Gray (McGraw-Hill Book Company, Inc., New York, 1963), pp. 8–20. The values of the stopping power listed for Ag in this reference differ by ≤1% from the values reported by P. H. Stelson and F. K. McGowan, Phys. Rev. 110, 489 (1958).

[20] R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

[21] R. L. Robinson, F. K. McGowan, P. H. Stelson, W. T. Milner, and R. O. Sayer, Nucl. Phys. A124, 553 (1969).

[22] It should be noted that the half-life of the 344.6-keV level has been measured by Kawakami and Hisatake (Ref. 3) to be $(8.01 \pm 0.64) \times 10^{-10}$ sec. Used with the measured relative intensities of the 344.6- and 63.9-keV transitions depopulating this $\frac{1}{2}^+$ state, this lifetime implies a $B(E2\uparrow)$ value for the 344.6-keV $E2$ transition that is approximately twice that obtained in the present work. No ready explanation can be offered for this discrepancy, since a reevaluation of the present data confirms the $B(E2)$ value that Table II lists for this transition.

[23] S. A. Moszkowski, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy,* edited by K. Seigbahn (North-Holland Publishing Company, Amsterdam, The Netherlands, 1965), Vol. II, p. 863.

[24] R. K. Golden, Ph. D. thesis, University of Pennsylvania, 1957 (unpublished); Diss. Abstr. B 17, 1575 (1957); M. Raether, Z. Physik 150, 38 (1958).

[25] B. Čujec, Phys. Rev. 131, 735 (1963).

[26] R. D. Lawson and J. L. Uretsky, Phys. Rev. 108, 1300 (1957); A. de-Shalit, *ibid.* 122, 1530 (1961).