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γ-γ Directional Correlation Measurements in ^{106}Pd

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11 directional correlations of γ-ray cascades in ^{106}Pd were measured after the decay of 30-sec ^{106g}Rh. The following correlation coefficients were measured: $A_{22}(873\text{-}616) = -0.103 \pm 0.010$, $A_{44}(873\text{-}616) = 0.350 \pm 0.025$; $A_{22}(1192\text{-}512) = 0.360 \pm 0.012$, $A_{44}(1192\text{-}512) = 1.230 \pm 0.022$; $A_{22}(1061\text{-}1128) = 0.46 \pm 0.07$, $A_{44}(1061\text{-}1128) = 0.30 \pm 0.13$; $A_{22}(1113\text{-}1128) = -0.37 \pm 0.06$, $A_{44}(1113\text{-}1128) = 0.19 \pm 0.05$; $A_{22}(1150\text{-}1128) = 0.20 \pm 0.05$, $A_{44}(1150\text{-}1128) = 1.33 \pm 0.20$; $A_{22}(1178\text{-}1128) = 0.24 \pm 0.03$, $A_{44}(1178\text{-}1128) = 1.00 \pm 0.15$; $A_{22}(1766\text{-}512) = 0.28 \pm 0.07$, $A_{44}(1766\text{-}512) = 1.90 \pm 0.50$; $A_{22}(1796\text{-}512) = 0.20 \pm 0.03$, $A_{44}(1796\text{-}512) = -0.01 \pm 0.14$; $A_{22}(1925\text{-}512) = 0.22 \pm 0.08$, $A_{44}(1925\text{-}512) = 0.24 \pm 0.08$; $A_{22}(1988\text{-}512) = 0.24 \pm 0.13$, $A_{44}(1988\text{-}512) = 0.30 \pm 0.13$; $A_{22}(2112\text{-}512) = 0.44 \pm 0.15$, $A_{44}(2112\text{-}512) = 1.60 \pm 0.50$; where the directional-correlation function is given by $W(\theta) = 1 + A_{22}P_2(\cos\theta) + A_{44}P_4(\cos\theta)$. The following $E2/M1$ multipole mixing ratios were determined: $-53 \le \delta(616) \le -15$, $\delta(1061) = 1.20 \pm 0.15$, $\delta(1113) \sim -1.5$, $1.9 \le \delta(1925) \le 3.5$, and $1.5 \le \delta(1988) \le 4$. The levels at 2189, 2241, 2437, and 2500 keV are each assigned a spin of 2 on the grounds of four observed $2 \to 2 \to 0$ correlations, and levels at 1704, 2278, 2306, and 2624 keV are each assigned a spin of 0 on the grounds of five observed $0 \to 2 \to 0$ correlations. The levels from this and previous work are compared with those calculated with the vibrational model of Ferreira and his co-workers up through the four-phonon energy region.

I. INTRODUCTION

Many workers have investigated the level structure of ^{106}Pd because this nucleus has been cited as one of the best examples of the high-phonon quadrupole vibrations in spherical nuclei.[1,2] Early level scheme investigations, involving mainly γ-ray studies, established much of the low-energy level structure.[3-10] The spin of ^{106}Rh was determined from Alburger's[11] investigation of the β-ray spectra. Internal-conversion electron intensities have been investigated by Smith,[12,13] Alburger and Toppel,[14] Scheuer *et al.*,[15] and de Aisenberg and Suarez.[16] More recent high-resolution γ-ray and coincidence studies[17-27] coupled with the internal-conversion and earlier γ-ray studies mentioned above have led to many spin and parity assignments to the levels of ^{106}Pd. Earlier γ-γ directional-correlation studies[24,28-34] have mainly involved the lower-lying levels; however, the coincidence studies of Strutz and his co-workers[26] were performed by counting for long periods of time with the detectors at 180 and at 90°, and the results imply the existence of several 0^+ levels not reported earlier which are very important for the identification of the states belonging to the three- and four-phonon vibrations. While this work has been valuable as a guide, one cannot draw strong conclusions without measuring actual directional correlations. In addition the identification of γ-ray cascades with the spin sequence $0 \to 2 \to 0$ requires the measurement of the coincidence rate at an angle intermediate to 90 and 180°. In order to obtain reliable data one should also change angles frequently to avoid systematic errors.

The main purpose of the present investigation was to measure the directional correlations of γ-ray cascades which originate from energy levels which might be identified as levels of the three- and four-phonon excitations, for the purpose of fixing the spins of these levels. Another important goal was to extend the comparison of experimentally observed energy levels to those predicted with the model of Ferreira and his co-workers.[35] This comparison had been made earlier in Ref. 24 up through the three-phonon levels; however, until now the 0^+ level of the three-phonon quintet had not been identified. In fact the 1704-keV level which is identified as the quintet 0^+ level, on the grounds of directional-correlation data of the present work, had been previously assigned $J^\pi = 1^+$ by Rao and Fink.[19] In addition it seemed necessary to verify, through directional-correlation measurements, the 0^+ spin assignment made to the 2278-keV level by Strutz and his co-workers. Such assignments cannot be firmly made on the grounds of coincidence data taken during long runs at only two angles. This assignment is important, however, since the existence of a 0^+ state at this energy could very well correspond to the four-phonon 0^+ level. We also felt that it was important to fix as many spins as possible in the three- and four-phonon energy region before attempting to search among the levels for those predicted by the theory.

The choice of ^{106}Ru as parent of ^{106}Pd, rather than one of the ^{106}Ag isomers, was made because no 0^+ levels above the ground state had been previously found in the decay of either 8.5-day ^{106m}Ag or 24-min ^{106}Ag. At least two 0^+ levels had been firmly established earlier in the decay of 30-sec ^{106g}Rh, which is the daughter of 1-yr ^{106}Ru. The very weak β branches (~10^{-2}%) to most of the levels above the two-phonon energy region result in very weak γ-ray cascades. As a consequence, more than one year was required to collect the data for the present investigation. A partial decay scheme of ^{106g}Rh is shown in Fig. 1.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The correlation data were collected using an automated directional-correlation table with a 33-cm^3 true-coaxial Ge(Li) detector as the fixed detector and a 3-in. by 3-in. NaI(Tl) detector as the moving detector whose position was changed

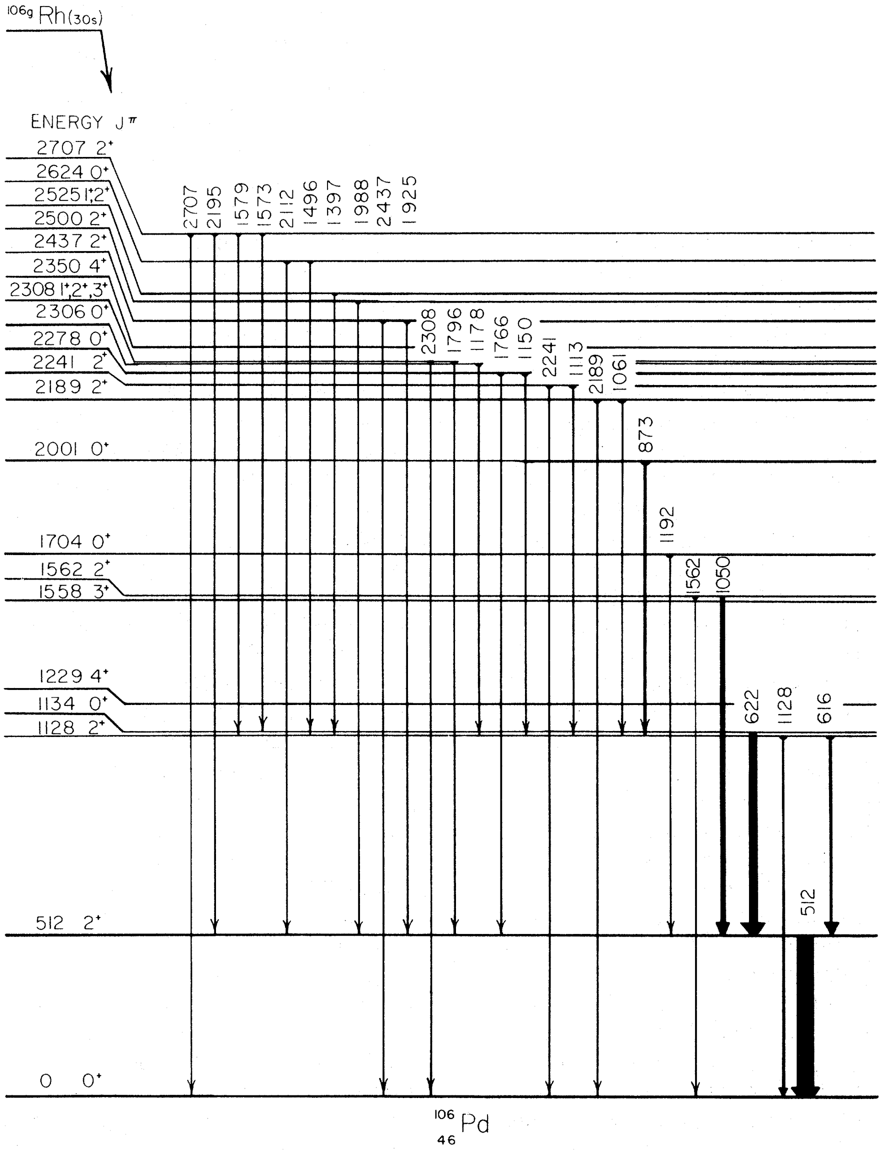

FIG. 1. Partial decay scheme of ^{106g}Rh. This scheme was construcuted from the results given in Refs. 19 and 26 and the present investigation. All known levels up to 2707 keV and all γ rays connecting these levels are given; however, the very weak γ rays from higher levels reported in Ref. 26 are omitted for simplicity.

every 15 min. The Ge(Li) detector has a photopeak-to-Compton ratio of 20 : 1 and an energy resolution of 2.2 keV at 1.33 MeV. The γ-ray spectrum from the Ge(Li) detector was collected in a 512-channel pulse-height analyzer, the memory of which was split into four groups using a dc routing system. The routing dc voltage levels are supplied from position switches on the correlation table so that each of the memory sections corresponds to one of four angular positions of the movable detector. The analyzer is gated by coincidence pulses from a standard two-detector coincidence system. Resolving times of approximately 1 μsec were used in all the experiments in which the 512-keV γ ray was in the cascade and all of these correlations were measured simultaneously. The long resolving time guarded against the usual limited dynamic range of simple coincidence counting systems. This effect can result in a strong energy dependence of the time alignment which can in turn lead to serious errors in the data. The γ rays feeding the 512-keV level are weak enough to allow the use of a long resolving time, while accidental to total coincidence rates range between 10 and 15%. For all the other cascades, resolving times of 100 nsec were used, and each cascade was time aligned separately, while only the correlations of those γ rays very close in energy were run together. The radioactive source was approximately 100 μC of ^{106}RuCl$_3$ in a dilute solution of HCl. The liquid source was contained in a glass capillary tube of 1-mm inside diameter and 5 mm long. The source strength was limited by the detection rate of the intense low-energy γ rays in the NaI(Tl) detector. Source-to-detector distances ranged from 3 to 3.9 cm for the Ge(Li) detector and from 5.7 to 6 cm for the NaI(Tl) detector for the various experiments, and the corrections to the data for the finite angle subtended by the detectors was made using the results of Avignone and Frey[36] and Yates[37] for the Ge(Li) and NaI(Tl) detectors, respectively. Typical corrections ranged from 15 to 18% for A_{22} and 40 to 55% for A_{44}.

A. 873-γ-616-γ Directional Correlation

The γ-γ directional correlation of this cascade has been measured earlier with a variety of results.[7, 24] In addition $\delta(616)$ has been determined from measurements of the 616-γ-512-γ directional correlation.[29, 32] The values of $|\delta|$ reported are 7 ± 2, 4.35 ± 0.80, ≥ 8, and 30 in Refs. 24, 29, 32, and 7, respectively. The question of this mixing ratio is important because the vibrational model predicts that transitions between low-lying 2^+ levels will be almost pure $E2$. According to the theoretical work of Greiner,[38] small $M1$ admixtures are allowed in these $2^+ \rightarrow 2^+$ transitions.

In this experiment the single-channel pulse-height analyzer (SCA) associated with the NaI(Tl) detector was set to accept the entire 873-keV full-energy peak, while that associated with the Ge(Li) detector was set to accept a wide energy region including the 616- and 622-keV full-energy peaks. The data were collected at angles of 90, $112\frac{1}{2}$, 135, $157\frac{1}{2}$, 180, $202\frac{1}{2}$, 225, $247\frac{1}{2}$, and 270° between the detectors. A typical coincidence spectrum is shown in Fig. 2. A chance coincidence spectrum was taken by throwing the coincidence system completely out of time and collecting coincidence data for a long enough period to re-

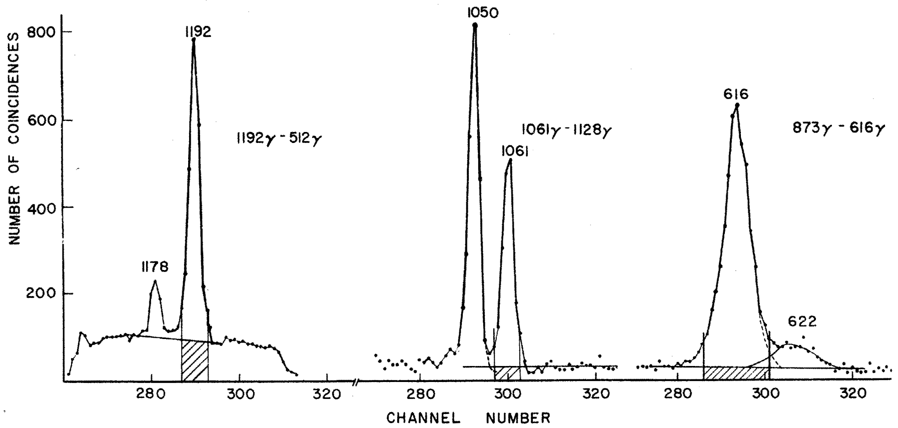

FIG. 2. Typical coincidence spectra collected during the 1192-γ–512-γ, 1061-γ–1128-γ, and 873-γ–616-γ directional-correlation experiments. These spectra were taken under varied conditions of biased amplifier gain and bias level. The analyses of the data and background corrections are indicated by the lines and cross-hatched areas.

sult in peaks with statistics comparable to those of the in-time correlation experiments.

The energy range accepted by the NaI(Tl) detector was large enough to allow interference between the cascade of interest and pulses due to the Compton-scattering distributions of higher-energy γ rays. Data to correct the correlation data for this effect were taken by setting the energy window of the SCA, associated with the Ge(Li) detector, to accept only pulses associated with the 616-keV γ ray. The SCA associated with the NaI(Tl) detector was widened to accept more than the entire full-energy peak of the 873-keV γ ray. The pulses from the NaI(Tl) detector, gated by the two-detector coincidence pulses, were collect- in the multichannel analyzer at all angles at which correlation data were collected. A sharp, clean full-energy peak was observed sitting on a small continuum due to the interference cascades. These data were also corrected for chance coincidences, and the portion of the remaining continuum which fell in the window range of correlation experiments, was used as a first-order correction to the correlation data. The correction turned out to be less than 5%.

The results of the corrected correlation are given in Table I and imply $15 < |\delta| < 53$ which corresponds to an $M1$ admixture of less than 0.5%. The result is smaller than the $M1$ admixture predicted with the theory of Greiner[38] and is in good agreement with the early results of Robinson *et al.*[17]

B. 1192-γ-512-γ Directional Correlation

The 1192-γ–512-γ directional correlation was run by setting the energy window of the SCA associated with the NaI(Tl) detector to accept only the 512-keV γ-ray full-energy peak and by setting the energy window associated with the Ge(Li) detector to accept the entire 1178 and 1192 peaks and some of the continuum near the peaks. The coincidence system was time aligned by measuring the 1192 peak intensity as a function of delay introduced between the timing pulses. The correlation was measured at angles of 90, 135, 180, 225, and 270° between the detector axes. The appearance of the 1178-keV γ ray in coincidence with the 512-keV γ ray, as shown in Fig. 2, as well as with the 1128-keV γ ray, as seen later, verifies its position in the decay scheme assigned by Fink and Rao.[19] (See Fig. 1.) The results of this correlation given in Table I very strongly show the typical characteristics of a $0 \rightarrow 2 \rightarrow 0$ cascade thereby fixing the spin of the 1704-keV level as having spin and parity $J^{\pi} = 0^{+}$.

C. 1061-γ-1128-γ Directional Correlation

In this measurement the energy window associated with the NaI(Tl) detector was set to accept the full-energy peak of the 1128-keV γ ray, while that associated with the Ge(Li) detector was set to accept a broad region about the 1061 line. This window included the 1050-keV γ ray which is almost 60 times stronger than the 1061-keV γ ray and consequently appears in the spectrum as a chance coincidence peak. The correlation data were collected at angles of 90, 135, 180, 225, and 270° between the detector axes. The results, corrected for chance coincidences and detector geometry, are given in Table I.

In the interpretation of these results, one can rule out $J = 6$ for the 2189-keV level on the grounds that the only A_{22} and A_{44} values in agreement with experiment require the 1061-keV γ ray to be pure $L = 5$, which would be unobservably weak. An assignment of $5 \rightarrow 2 \rightarrow 0$ for this cascade can be ruled out on the grounds of the positive values measured for A_{22} and A_{44}. The cascade $4 \rightarrow 2 \rightarrow 0$ has a theoretical value of $A_{44} = 0.0091$ which is also in conflict with the present data. In addition,

TABLE I. Directional-correlation results.

Cascade	A_{22}	A_{44}	Assigned spin sequence
873-616	-0.103 ± 0.010	0.350 ± 0.025	$0 \rightarrow 2 \rightarrow 2$
1192-512	0.360 ± 0.012	1.230 ± 0.022	$0 \rightarrow 2 \rightarrow 0$
1061-1128	0.46 ± 0.07	0.30 ± 0.13	$2 \rightarrow 2 \rightarrow 0$
1113-1128	-0.37 ± 0.06	0.19 ± 0.05	$2 \rightarrow 2 \rightarrow 0$
1150-1128	0.20 ± 0.05	1.33 ± 0.20	$0 \rightarrow 2 \rightarrow 0$
1178-1128	0.24 ± 0.03	1.00 ± 0.15	$0 \rightarrow 2 \rightarrow 0$
1766-512	0.28 ± 0.07	1.90 ± 0.50	$0 \rightarrow 2 \rightarrow 0$
1796-512	0.20 ± 0.03	-0.01 ± 0.14	$(1, 2, 3) \rightarrow 2 \rightarrow 0$
1925-512	0.22 ± 0.08	0.24 ± 0.08	$2 \rightarrow 2 \rightarrow 0$
1988-512	0.24 ± 0.13	0.30 ± 0.13	$2 \rightarrow 2 \rightarrow 0$
2112-512	0.44 ± 0.15	1.60 ± 0.50	$0 \rightarrow 2 \rightarrow 0$

the positive experimental A_{44} for this cascade rules out spin sequences of $1\rightarrow 2\rightarrow 0$ and $3\rightarrow 2\rightarrow 0$ for all values of $\delta(2/1)$. The only cascade which fits the data is a $2\rightarrow 2\rightarrow 0$ cascade which requires the 1061-keV transition to be multipole mixed with the $L=2$ to $L=1$ multipole mixing ratio $\delta=1.20\pm0.15$. The phase convention used throughout this work is that of Krane and Steffen.[39]

D. 1113-γ-, 1150-γ-, and 1178-γ-1128-γ Directional Correlations

The directional correlations of the 1113-γ–1128-γ, 1150-γ–1128-γ, and 1178-γ–1128-γ cascades were run simultaneously. The energy window of the SCA associated with the NaI(Tl) detector was set to accept the 1128-keV full-energy peak, while that associated with the Ge(Li) detector was set to accept a broad energy region which included the 1113-, 1150-, and 1178-keV γ rays. The system was time aligned with a resolving time of 100 nsec and it was experimentally determined that all three γ-ray cascades were simultaneously in proper time alignment. The data were collected at angles of 90, 135, 180, and 270° between the detector axes and again at angles of 90, 135, $157\frac{1}{2}$, 180, $202\frac{1}{2}$, and 270°. The results were in good agreement; however, much more data were collected using just the four angles. The resulting directional-correlation coefficients, corrected for chance coincidences and detector geometry are given in Table I. Typical coincidence spectra taken during the correlation experiments are shown in Fig. 3.

The 1113-γ–1128-γ directional-correlation results are rather interesting, since the A_{22} is large and is the only negative A_{22} coefficient with the exception of that of the 873-γ–616-γ correlation. The data fitted the $2\rightarrow 2\rightarrow 0$ cascade with $\delta\sim -1.5$. A spin assignment of 6, 4, or 3 for the 2241-keV level can be ruled out on the grounds of these results; however, a spin assignment of 5 to this level cannot be ruled out on the grounds of these data alone. The theoretical values of the correlation coefficients for a 5(4)2(2)0 cascade are $A_{22}=-0.2759$ and $A_{44}=+0.1168$ and are not absolutely ruled out by the present data. In order to investigate the possibility that the 1113-keV transition may be an $E4$ transition in a $5\rightarrow 2\rightarrow 0$ cascade, a very rough determination of the conversion coefficient was made. The K-shell internal-conversion line intensities of the 1113- and 1192-keV transitions were measured in a combination magnetic-lens–Si(Li) spectrometer. The intensity ratio was found to be $I(1113K)/I(1192K)\simeq 0.5$, while the relative γ-ray intensity ratio from the data given in Ref. 19 is $I(1192\gamma)/I(1113\gamma)\simeq 2.33$. The 1192-keV transition is assumed to be pure $E2$, since the 1192-γ–512-γ directional correlation of the present work has established the spin of the 1704 level as 0 and the spin and parity of the 512-keV level are well known to be 2^+. The rough conversion ratio of the two transitions taken with the γ-ray intensity ratio implies that $\alpha_k(1113)$ is approximately the same as $\alpha_k(1192)$ which is almost a factor of 4 smaller than $\alpha_k(E4)$ for this energy. A more accurate conversion measurement will be possible at some later time when the energy resolution of the Si(Li) detector is sufficiently good so that these weak lines can be more clearly lifted from the large β background; however, we feel that the present rough result is suf-

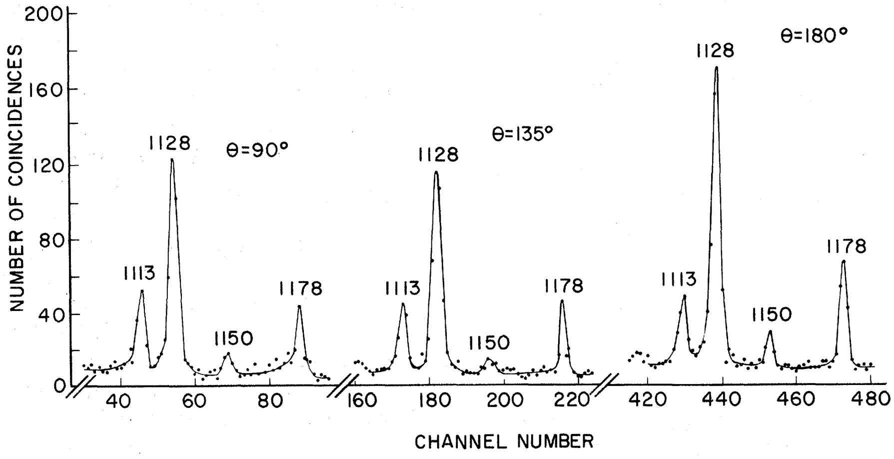

FIG. 3. Typical coincidence data collected during the 1113-γ–, 1150-γ–, and 1178-γ–1128-γ directional correlations. The energy window associated with the NaI(Tl) detector was wide enough to accept a significant part of the Compton continuum of the 1178 γ ray to give rise to the large 1128-γ full-energy peak in the Ge(Li) coincidence spectrum.

ficiently accurate to give strong support to the assignment $J^\pi = 2^+$ to the 2241-keV level.

The 1150-γ–1128-γ and 1178-γ–1128-γ directional-correlation coefficients listed in Table I strongly imply that these cascades are $0 \rightarrow 2 \rightarrow 0$ cascades even though the measured A_{22} coefficients and the theoretical coefficient $A_{22} = 0.357$ are somewhat outside of the quoted error bars. The A_{44} coefficients are far too large to fit any other reasonable cascade. In addition these cascased are far too weak to perform the careful interference checks performed in the case of the 873-γ–616-γ correlation discussed in Sec. II A and it is conceivable that a small undetected interference could contribute a source of systematic error not accounted for in the quoted error bars. On the grounds of the above correlation coefficients we assign the 2278- and 2306-keV levels spins and parities $J^\pi = 0^+$.

E. 1766-γ-, 1796-γ-, 1925-γ-, 1988-γ-, and 2112-γ-512-γ Directional Correlations

These five directional correlations were measured in order to investigate the spins of the levels at 2278, 2308, 2437, 2500, and 2624 keV which span the upper portion of the four-phonon energy region. The energy window of the SCA associated with the NaI(Tl) detector was set to accept pulses due to the 512-keV full-energy peak, while that associated with the Ge(Li) detector was set to accept the broad energy region which included all five of the full-energy peaks of interest. The correlations were run simultaneously with a coincidence resolving time of 1 μsec in order to avoid energy dependence of the time alignment. In this case, chance coincidence correction data were taken with two separate sources. The Ge(Li) detector was rotated away from the correlation table and a second source was placed at just the correct distance so as to give the same number of singles event, under the 512-keV γ-ray full-energy peak, as during the correlation experiment. The fraction of the full-energy peaks in the correlation data which was attributable to chance coincidences was approximately 15%. The correlation data were collected at angles of 90, 135, 180, 225, and 270° between the detector axes. The resulting correlation coefficients are presented in Table I, while coincidence spectra of a typical run are shown in Fig. 4.

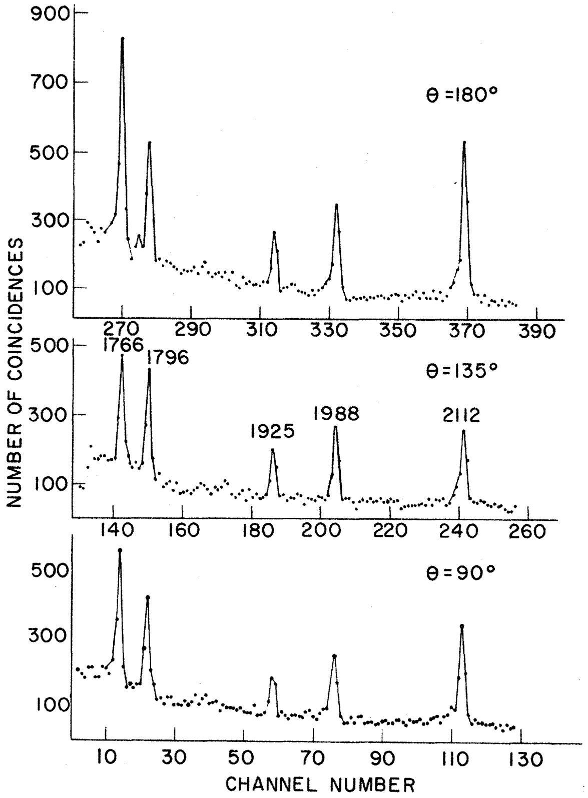

FIG. 4. Typical coincidence data collected during the 1766-γ–, 1796-γ–, 1925-γ–, 1988-γ–, and 2112-γ–512-γ directional-correlation measurements.

The 1766-γ–512-γ and 2112-γ–512-γ directional correlations both very strongly exhibit the characteristic behavior of $0 \rightarrow 2 \rightarrow 0$ cascades. Although there is little doubt that the 1766-γ–512-γ correlation is that of a $0 \rightarrow 2 \rightarrow 0$ cascade it is disturbing that such a clean, large γ-ray peak leads to a correlation with such a large error. The reason is the large, angle-dependent background due to the Compton distributions of the interfering cascades. The background, however, does not have the proper shape necessary to artificially generate the characteristic $0 \rightarrow 2 \rightarrow 0$ correlation shape, hence we conclude that this cascade must have the spin sequence $0 \rightarrow 2 \rightarrow 0$.

The 1796-γ–512-γ directional-correlation results can be used to rule out a spin assignment of 0 or 4 to the 2308-keV level. The elimination of the spin assignment of 0 indicates that this level is really a different level than the 2306-keV level for which we assigned spin 0 on the grounds of the results of the 1178-γ–1128-γ directional correlation discussed above. Spin assignments of 5 and 6 are allowed by the above correlation data with multipolarities of $L = 3$ and $L = 4$ for 1796-keV transition, respectively. We have estimated the expected K-shell internal-conversion electron intensities of the 1796-keV transition for $L = 3$ and $L = 4$ based on the relative γ-ray intensities given in Ref. 19. It was determined that for these high multipoles the conversion lines should have been easily observed above the β continuum in our combination magnetic-Si(Li) spectrometer. We have successfully used this technique earlier to measure the K-shell intensities of some very weak conversion lines in the presence of a large β continuum.[40] The results of this search showed some small peaks more in line with intensities expected from transitions of $M1$ or $E2$ character rather than those expected for $L=3$ or $L=4$ transitions. This work also should be repeated when better resolution than the present 15 keV is available; however, we feel that these data certainly indicate that a spin of 5 or 6 for the 2308-keV level is very doubtful. Unfortunately, we are not able to eliminate any of the spins 1, 2, or 3 for this level on the grounds of these and earlier measurements.

The 1925-γ–512-γ directional-correlation coefficients given in Table I fit only the $2 \rightarrow 2 \rightarrow 0$ cascade and all other spins from 1 through 6 can be eliminated as possible assignments to the 2437-keV level. We find that the data are consistent with the assignment of spin 2 to this level and a multipole mixing ratio of $1.9 \leq \delta \leq 3.5$ for the 1925-keV transition. The 1988-γ–512-γ directional correlation results are also incompatible with any spin assignment from 1 to 6 to the 2500-keV level except for a spin of 2. The data are consistent with that predicted for a $2 \rightarrow 2 \rightarrow 0$ cascade with a multipole mixing ratio of $1.5 \leq \delta \leq 4$, for the 1988-keV transition.

III. DISCUSSION AND CONCLUSIONS

In this section we integrate our results into a level scheme based on these and results summarized in Refs. 19, 26, and 41. In addition we have calculated the vibrational structure up through the four-phonon ($\nu = 4$) levels, using the results of the model proposed by Ferreira, Castilho, and Aguilera Navarro,[35] and we shall attempt to identify key levels in the vibrational spectrum up through $\nu = 4$. (See Fig. 5.)

The main contribution of the present work was the discovery of the 0^+ levels in the energy region of the three- and four-phonon levels by γ-γ directional correlation techniques. Some of the

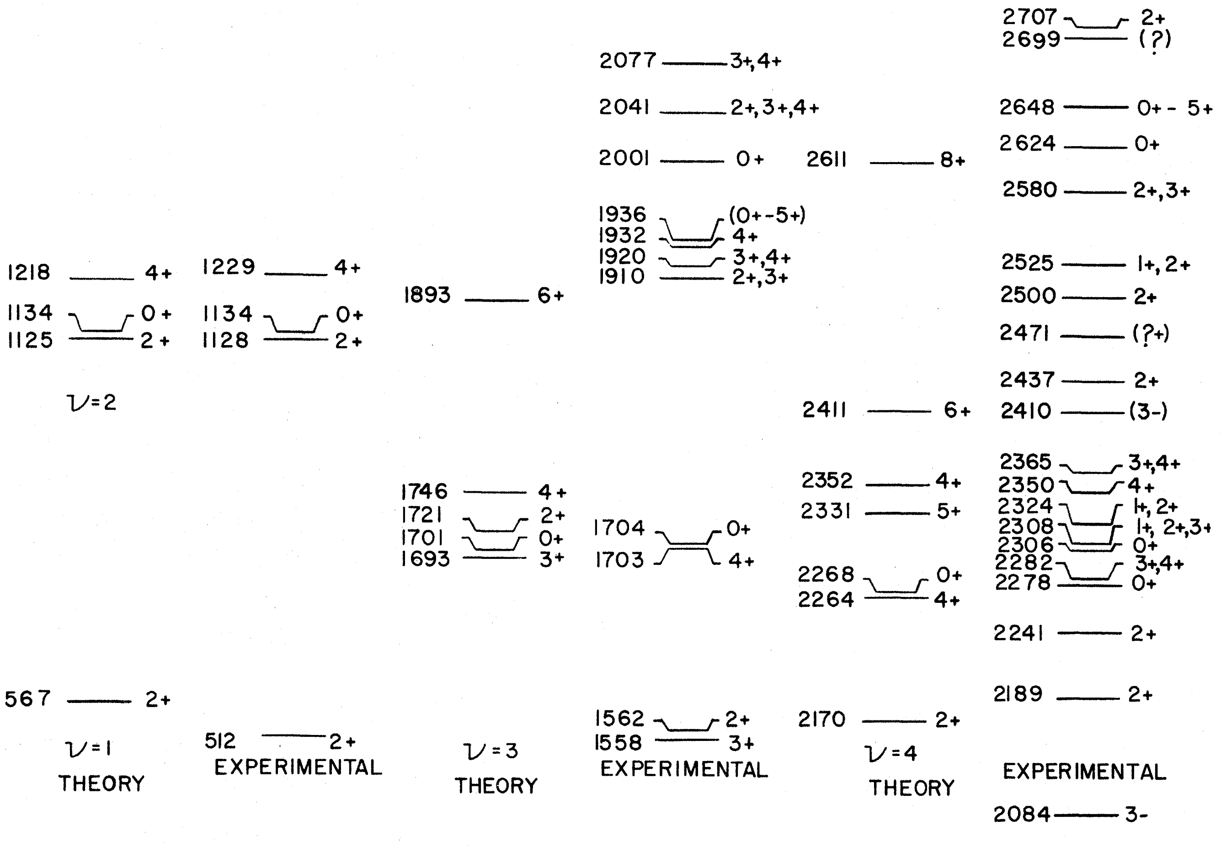

FIG. 5. Experimentally established energy levels of ^{106}Pd and those predicted by the vibrational model of Ferreira, Castilho, and Aguilera Navarro (Ref. 35).

spins of these levels had been inferred from the results of the coincidence measurements of Strutz and his co-workers; however, the characteristics of $0 \rightarrow 2 \rightarrow 0$ cascades are difficult to distinguish from other cascades unless actual directional correlations are measured. At present, levels with $J^{\pi} = 0^+$ are known to exist at 512, 1134, 1704, 2001, 2278, 2624, 2830, and 2878 keV. If we search among these levels for those which are almost equally spaced we find the 0^+ levels of the $\nu = 1$, 2, 3, 4, and 5 multiplets and we obtain spacings of 512, 567, 569, and 566 keV between these levels, respectively. This almost equal level spacing implies rather strong vibrational characteristics for this nucleus, all the way up through the energy region where $\nu = 4$ levels are predicted to be.

Another very strong characteristic of vibrational nuclei is the almost pure $E2$ character of the transitions between low-lying 2^+ levels. The 616-keV transition has been investigated several times and had been found by early investigators[7] to have an $M1$ component in line with that predicted by the vibrational model, while more recently $M1$ components much larger than those allowed by current theory have been reported.[24, 29, 32] Our values of A_{22} and A_{44} parameters for the 873-γ–616-γ directional correlation imply an $M1$ admixture of less than 0.14% (or $|\delta| > 15$) which strongly supports the pure vibrational character of the 1128- and 512-keV levels.

Earlier investigators have reported levels at 2306 and 2308 with different spins. We conclude from our measurements of the directional correlations of both the 1796-γ–512-γ and 1178-γ–1128-γ cascades that the 1178-keV γ ray originates from a level whose spin is 0, while 1796-keV γ ray originates at a level very nearby whose spin is either 1, 2, or 3. The order of these levels was chosen by reference to the precision energy measurements of Rao and Fink[19] and those of Strutz[26] and his co-workers. During the 1178-γ–1128-γ directional-correlation experiment, a γ-ray line at 1150 keV was discovered in the data. This γ ray is very likely that reported by Strutz and his co-workers, on which they based the existence of a level at 2278 keV with spin 0. The 1150-γ–1128-γ directional correlation of the present investigation verifies the spin 0 assignment to this level.

The model proposed by Ferreira, Castilho, and Aguilera Navarro[35] is based on a Hamiltonian in which there are anharmonic terms which are fourth order in the harmonic-oscillator creation and annihilation operators. Such a term is found to break the U_5 symmetry of the Hamiltonian which results in the lifting of the usual vibrational model level degeneracies. The following expression for the eigenvalues of the Hamiltonian with broken symmetry was derived in Ref. 35:

$$E(\nu L k) = \hbar\omega[\nu + \tfrac{5}{2} + \alpha k(k+1) + \beta L(L+1)];$$

where ν is the phonon number; k stands for Rakavy's seniority number, given in Ref. 35; L is the level angular momentum; and $\hbar\omega$ is the fundamental energy difference between $\alpha = 0$, $\beta = 0$ harmonic-oscillator levels. α, β, and $\hbar\omega$ are free parameters to be fixed by setting $E(\nu L k)$ equal to known vibrational levels in the nucleus in question and obtaining the best set of parameters of least-square fitting techniques.

We have arbitrarily chosen to fit α and β using only the $\nu = 1$ and $\nu = 2$ levels in ^{106}Pd because it is expected that these low-lying levels will be the purest in vibrational character. This results in $\alpha = -0.867 \times 10^{-2}$ and $\beta = 1.177 \times 10^{-2}$ which are the same parameters used by Hattula and Liukkonen[24] in their comparison up to the $\nu = 3$ levels. We have, however, chosen $\hbar\omega = 567$ keV which is the average of the energy differences between the 0^+ states above $\nu = 1$, which we have identified as the nearly pure oscillator levels due to their approximately equal spacings. Averaging in the $\nu = 1$ level energy lowers all the theoretical levels by 10 keV and changes none of the conclusions, while including the $\nu = 3$ levels in the determination of α and β simply shares the discrepancy between theory and experiment between the $\nu = 2$ and $\nu = 3$ energy regions and also changes none of the major conclusions. The theoretical levels generated with the equation are shown in Fig. 5 along with all of the experimental levels from this and earlier decay and reaction investigations. We observe excellent agreement between theory and experiment in the $\nu = 1$ and $\nu = 2$ regions as noted earlier in Ref. 24. In the present investigation we have observed that the 1192-γ–512-γ directional correlation has the characteristic $0 \rightarrow 2 \rightarrow 0$ correlation shape which fixes the spin of the 1704-keV level as 0 and allows us to verify that this is the three-phonon 0^+ level. The four levels between 1558 and 1704 keV can then be identified as the three-phonon 3^+, 0^+, 2^+, and 4^+ vibrational levels; however, the level spacing and the relative position of the 0^+ level are not predicted correctly. There are also many extra levels starting at 1910 keV and up to about 2084 keV. In addition no experimental evidence of a 6^+ level near 1900 keV has been reported. In the $\nu = 4$ region one can identify either the 2189- or the 2241-keV levels with that predicted at 2170. The observed 2282-keV level could possibly be the 4^+ level predicted at 2264 keV, while the observed 4^+ level at 2350 keV is likely that predicted at 2352. Again no experimental evidence of levels corresponding to the predicted four-phonon 5^+, 6^+, or 8^+ levels has been reported, while many unpredicted levels are observed. The establishment of the spin and parity assignment $J^\pi = 0^+$ for the 2278-keV level from the measurement of the 1766-γ-512-γ directional correlation, of the present investigation, allows one to identify the 2278 level with the predicted 2268-keV, 0^+ level. The vibrational model predicts three, four-phonon levels with $J^\pi = 0^+$. These are degenerate in the present model because for $\nu = 4$ the only allowed value of k is 0, hence the energies of all these levels is simply $\frac{13}{2}\hbar\omega$. The existence of the 0^+ level at 2306 keV could possibly indicate that another mechanism, unaccounted for by the model, can lift this degeneracy.

In general the establishment of several more 0^+ levels in ^{106}Pd at the proper energies gives much stronger evidence that this nucleus shows very characteristic vibrational properties even up in the four-phonon energy region. The model of Ferreira, Castilho, and Aguilera Navarro,[35] however, does not give the correct splittings or even in some cases the correct ordering of the energy levels of the same phonon number ν for ν greater than 2.

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[1] Y. Yoshizawa, Phys. Letters 2, 261 (1962).

[2] O. Nathan and S. G. Nilsson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), p. 601.

[3] J. Y. Mei, C. M. Huddleston, and A. C. G. Mitchell, Phys. Rev. 79, 1010 (1950).

[4] R. W. Hayward, Phys. Rev. 85, 760 (1952).

[5] W. L. Bendel, F. J. Shore, H. N. Brown, and R. A. Becker, Phys. Rev. 90, 888 (1953).

[6] B. Kahn and W. S. Lyon, Phys. Rev. 92, 962 (1953).

[7] R. L. Robinson, F. K. McGowan, and W. G. Smith, Phys. Rev. 119, 1692 (1960).

[8] M. Sakai, H. Ikegami, and T. Yamazaki, J. Phys. Soc. Japan 16, 148 (1961).

[9] S. Y. Ambiye and R. P. Sharma, Nucl. Phys. 29, 657 (1962).

[10] O. J. Segaert, J. Demuynek, A. M. Hoogenboom, and H. van Den Bold, Nucl. Phys. 16, 138 (1960).

[11] D. E. Alburger, Phys. Rev. 88, 339 (1952).

[12] W. G. Smith, Phys. Rev. 122, 1600 (1961).

[13] W. G. Smith, Phys. Rev. 131, 351 (1963).

[14] D. E. Alburger and B. J. Toppel, Phys. Rev. 100, 1357 (1955).

[15] W. Scheuer, T. Suter, P. Reyes-Suter, and E. Aasa, Nucl. Phys. 54, 221 (1964).

[16] E. Y. de Aisenberg and J. F. Suarez, Nucl. Phys. 83, 289 (1966).

[17] R. L. Robinson, P. H. Stelson, F. K. McGowan, J. L. C. Ford, Jr., and W. T. Milner, Nucl. Phys. 74, 281 (1965).

[18] J. K. Temperley and A. A. Temperley, Nucl. Phys. A101, 641 (1967).

[19] P. V. Rao and R. W. Fink, Nucl. Phys. A103, 395 (1967).

[20] H. W. Taylor, N. Neff, and J. D. King, Nucl. Phys. A106, 49 (1968).

[21] K. D. Strutz, Z. Physik 201, 20 (1967).

[22] H. Bakhru and I. L. Preiss, Phys. Rev. 158, 1214 (1967).

[23] Y. Vrzal, E. P. Grigorev, A. V. Zolotavin, J. Liptak, V. O. Sergeev, and J. Urbanets, Izv. Akad. Nauk SSSR Ser. Fiz. 31, 692 (1967) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 31, 692 (1967)].

[24] J. Hattula and E. Liukkonen, Ann. Acad. Sci. Fennicae, 274, 1 (1968).

[25] J. A. Moragues, P. Reyes-Suter, T. Suter, and M. Perez, Nucl. Phys. A106, 289 (1968).

[26] K. D. Strutz, H. J. Strutz, and A. Flammersfeld, Z. Physik 221, 231 (1969).

[27] K. Takahashi, D. L. Swindle, and P. K. Kuroda, Nucl. Phys. A167, 183 (1971).

[28] G. B. Arfken, E. D. Klema, and F. K. McGowan, Phys. Rev. 86, 413 (1952).

[29] J. Koch, F. Munnich, and U. Schotzig, Nucl. Phys. A103, 300 (1967).

[30] E. D. Klema and F. K. McGowan, Phys. Rev. 92, 1469 (1953).

[31] J. Hattula, J. Kantele, and A. Sarmanto, Nucl. Instr. Methods 65, 77 (1968).

[32] P. Weight, P. Herzog, B. Richter, H. Hubel, H. Toschinski, and J. Fechner, Nucl. Phys. A122, 570 (1968).

[33] F. T. Avignone, III, and J. E. Pinkerton, Bull. Am. Phys. Soc. 17, 466 (1972).

[34] H. H. Hsu and S. Hsue, Bull. Am. Phys. Soc. 17, 467 (1972).

[35] P. L. Ferreira, J. A. Castilho, and V. C. Aguilera Navarro, Phys. Rev. 136, 1243 (1964).

[36] F. T. Avignone, III, and G. D. Frey, Rev. Sci. Instr. 40, 1365 (1969).

[37] M. J. L. Yates, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience, New York, 1965), p. 1691.

[38] W. Greiner, Nucl. Phys. 80, 417 (1966).

[39] K. S. Krane and R. M. Steffen, Phys. Rev. C 2, 724 (1970).

[40] F. T. Avignone, III, and G. D. Frey, Phys. Rev. C 4, 912 (1971).

[41] D. L. Dittmer, Ph.D. thesis, University of Pittsburgh, 1969 (unpublished).