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Measurements of Directional Correlation from Oriented Nuclei (DCO) and the Band Structure in ^{102}Pd

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A new technique for determining spin sequences and mixing ratios has been used to investigate the ground state band of ^{102}Pd. This new method is based on the observation of coincidences at only one angle rather than measuring a complete angular correlation. The results show that the unusual spin sequence previously proposed for the ground state band of ^{102}Pd is not correct.

In a recent Letter,[1] "forking" in the ground-state band of ^{102}Pd was reported. The proposed spin sequence, which is fundamental to the description of the band, was established on the basis of angular-*distribution* measurements of the γ rays following (HI, *xn*) reactions. In the present work the results of directional *correlation* observations on the ^{102}Pd γ rays using a new and simple method of data analysis are presented showing that the proposed spin assignments are incorrect.

The interpretation of γ-angular-distribution measurements following (HI, *xn*) reactions is often difficult because of γ transitions unresolved from the one of interest. This difficulty may be avoided by observing the directional correlation of two γ rays that are emitted in coincidence from oriented nuclear states populated in (HI, *xn*) reactions (directional correlation from oriented nuclei, DCO). The measurement of a complete directional correlation is unattractive in view of the large accelerator time required. However, the DCO-ratio method proposed by Krane, Steffen, and Wheeler[2] is a practical and powerful method for the determination of multipole-mixing ratios of γ transitions and spin sequences.

The DCO-ratio method uses the coincidence rates $W(A(\gamma_1), B(\gamma_2))$ of two γ rays γ_1 and γ_2 that are emitted from an oriented ensemble of nuclei and are observed by two detectors A and B, respectively. The detectors are fixed at *asymmetric* directions with respect to the orientation axis of the ensemble (e.g., beam direction). If the role of the two detectors is reversed the coincidence rate $W(A(\gamma_2), B(\gamma_1))$ is observed and the ratio $R(A, B) = W(A(\gamma_1), B(\gamma_2))/W(A(\gamma_2), B(\gamma_1))$ of the two coincidence rates provides an observable that is very sensitive to the multipole mixing of, and to the spin changes involved in, the γ transitions. Many DCO ratios $R(A, B)$ can be simultaneously and accurately measured with modern computer-based electronics.

For "monotonic stretched" cascades (i.e., cascades with $\Delta I = \text{const}$ and $L = |\Delta I|$) the DCO ratio

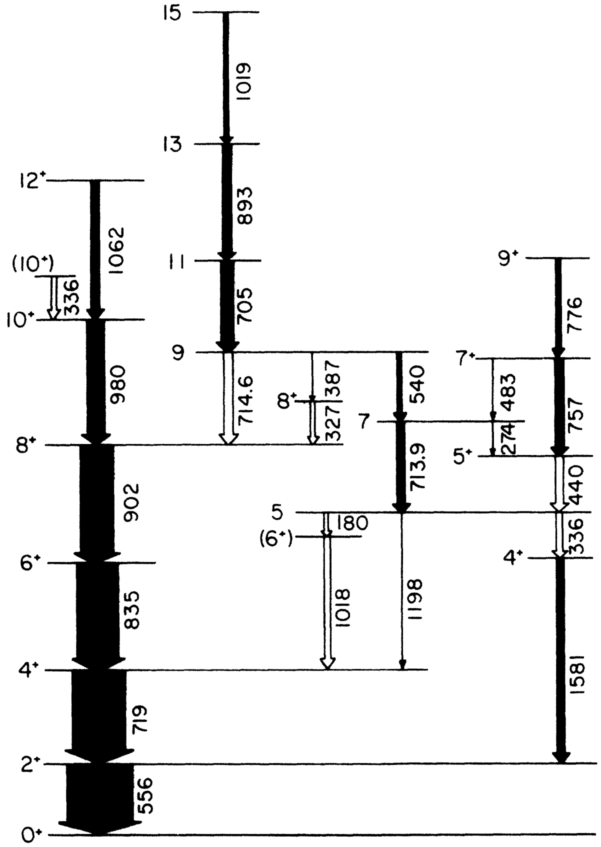

FIG. 1. Levels of ^{102}Pd that are excited in the reaction ^{92}Zr(^{13}C, $3n$)^{102}Pd and that are important in the present analysis. Solid arrows indicate quadrupole transitions.

$R(A, B)$ is unity for any two γ rays of the cascade. For cascades where ΔI is not constant and for cascades involving $L > |\Delta I|$ or mixed multipole transitions, the DCO ratio $R(A, B)$ can be much different from unity depending on the degree of orientation of the initial state.

This Letter reports on the application of the DCO-ratio technique to investigate further the band structure of ^{102}Pd. DCO ratios of more than fifty pairs of γ rays emitted following the reaction ^{92}Zr(^{13}C, $3n$)^{102}Pd were measured [$E(C^{13}) = 51$ MeV]. A detailed level scheme of ^{102}Pd as observed in (HI, xn) reactions has been constructed.[3] The excited states of ^{102}Pd that are important for this study of the ground state band are shown in Fig. 1.

Two Ge(Li) detectors (full width at half-maximum $\simeq$ 2.0 keV) A and B were positioned in a plane with the beam, A at an angle $\theta_A = +\pi/2$, and B at $\theta_B = 0$, $\theta_B = -\pi/2$ (for calibration purposes), and $\theta_B = -\pi/4$ (for additional checks). For any cascade the DCO ratio $R(\pi/2, -\pi/2)$ for $\theta_A = \pi/2$ and $\theta_B = -\pi/2$ must be unity. The observed values of $R(\pi/2, -\pi/2)$ for all cascades shown in Fig. 1 are consistent with unity. For example, the average value of $R(\pi/2, -\pi/2)$ for all pairs involving the 714.6-keV transition was 0.96 ± 0.10; similarly, for the 556-keV, $R = 1.01 \pm 0.06$. These results serve as a test of the equipment and of the methods of data analysis.

Some representative values of the observed DCO ratios $R(\pi/2, 0)$ for $\theta_A = +\pi/2$ and $\theta_B = 0$ are listed in Table I, together with the theoretical values $R(\pi/2, 0)_{\text{theor}}$ computed for the γ-γ cascades indicated in column 5 of Table I. Unless otherwise indicated, the calculations were performed for pure $L = \Delta I$ transitions. Unobserved intermediate transitions are enclosed in brackets. Values of R indicated by an asterisk are intensity-weighted averages of two cascades as indicated in column 5. The orientation parameters $B_\lambda(I_i)$ used in the computation of R_{theor} were taken from new directional distribution data.[3] The computed values $R(\pi/2, 0)_{\text{theor}}$ have been corrected for the finite solid angles of the detectors.

All of the fifteen observed DCO ratios $R(\pi/2, 0)$ for the main 1062-980-901-835-719-556-keV cascade are unity within limits of error (some examples are shown in Table I), and are consistent with the spin assignments $10 \to 8 \to 6 \to 4 \to 2 \to 0$ first proposed by the Purdue tandem group.[4]

γ-γ coincidence measurements revealed the presence of a reasonable strong secondary 1019-893-705-714.6-902-835-719-556-keV cascade, where the last four γ rays are the $8 \to 6 \to 4 \to 2 \to 0$ transitions of the main cascade. The quantitative analysis of the coincidence and singles spectra showed clearly that there are two independent γ rays near 714-keV energy of about the same intensity: a 714.6-keV transition that is a part of the above mentioned secondary cascade, and a 713.9-keV transition that is in coincidence with the 180-, 336-, 540-, 705-, 893-, 1198-, and 1580-keV transitions and also with the 556-keV ground-state transition, but *not* with the 902- and the 835-keV transitions (see Fig. 1). The results of the DCO-ratio measurements on the secondary cascade are all in agreement with unity, except the ones involving the 714.6-keV γ transition (see Table I).

The fact that the 714.6-902- and 714.6-835-keV DCO-ratio measurements, in which the 714.6-keV γ radiation is completely resolved, yield val-

TABLE I. Experimental and theoretical DCO ratios $R(\pi/2,0)$ for the γ-γ cascades in ^{102}Pd following the reaction ^{92}Zr(^{13}C, 3*n*)^{102}Pd. The values indicated by asterisks are intensity-weighted averages of two DCO ratios. The value indicated by a double asterisk is the average value of R_{exp} for 336^a–980-, –902-, –835-, –719-keV coincidences.

γ_1 keV	γ_2 keV	$R(\pi/2,0)_{\mathrm{exp}}$	$R(\pi/2,0)_{\mathrm{th}}$	$R(\pi/2,0)_{\mathrm{th}}$ computed for $I_1 \to I_2 (\to) \ldots\ldots (\to) I_{N-1} \to I_N$ cascades with $L=I_n-I_{n+1}$, (→) indicates unobserved transition	
1062	979	1.00 ± 0.25	1.00	12→10→8	
979	902	1.19 ± 0.28	1.00	10→8→6	
902	835	1.06 ± 0.27	1.00	8→6→4	
835	719	1.08 ± 0.08	1.00	6→4→2	
719	556	1.03 ± 0.04	1.00	4→2→0	
893	705	1.02 ± 0.20	1.00	13→11→9	
893	714.6	0.52 ± 0.17	0.63*	13→11 (→) 9→8	(80%)
893	713.9			13→11 (→) 7→5	(20%)
705	714.6	0.70 ± 0.13	0.63*	11→9→8	(80%)
705	713.9			11→9 (→) 7→5	(20%)
714.6	902	2.16 ± 0.50	1.96	9→8→6	
714.6	835	2.00 ± 0.60	1.96	9→8 (→) 6→4	
714.6	719	1.98 ± 0.43	1.71*	9→8 (→) 6 (→) 4→2	(80%)
713.9				7→5 (→) 6 (→) 4→2	(20%)
714.6	556	1.28 ± 0.15	1.48*	9→8 (→) 6 (→) 4 (→) 2→0	(50%)
713.9				7→5 (→) 4 (→) 2→0	(50%)
713.9	336^b	0.42 ± 0.13	0.50	7→5→4	
705	336^b	0.66 ± 0.25	0.50	11→9 (→) 7 (→) 5→4	
440	336^b	0.36 ± 0.08	0.49	$5 \xrightarrow{L=1} 5 \to 4$	
336^a	980 902 835 719	0.96 ± 0.14**	0.88 or 1.00	$10 \xrightarrow{L=1} 10 \to 8 \to 6 \to 4 \to 2$ or $12 \to 10 \to 8 \to 6 \to 4 \to 2$	
336^{a+b}	556	1.44 ± 0.13	1.44*	$10 \xrightarrow{L=1} 10 (\to) 8 (\to) 6 (\to) 4 (\to) 2 \to 0$	(50%)
				5→4 (→) 2→0	(50%)

ues considerably larger than unity, clearly indicates that the 714.6 keV *cannot* be a $\Delta I = 2$, $L = 2$ transition as previously proposed.[1]

Furthermore, the 893–(714.6 + 713.9)-, 705–(714.6 + 713.9)-, (714.6 + 713.9)–719-, and (714.6 + 713.9)–556-keV DCO ratios are all considerably different from unity. Since the 713.9-keV γ transition contributes significantly to these measurements, the multipole character of the 713.9-keV transition must be determined before a meaningful analysis of these DCO results is attempted. This can be done on the basis of the 713.9–336-keV DCO ratio. The coincidence data reveal the presence of two independent γ rays of 336.2 ± 0.3 keV energy. One of these, the 336^a-keV transition, is in coincidence with most of the main-cascade γ rays; the other, the 336^b transition, is involved in a tertiary 776–757–440–336^b–1581–556-keV cascade. The DCO and directional distribution data show that the 336^b-keV transition in the tertiary cascade must be a dipole transition (e.g., 705–336^b-, 440–336^b-, 336^{a+b}–556-keV DCO ratios). The 713.9-keV transition, but not the 714.6-keV γ ray, is in coincidence with the 336^b-keV γ ray (see Fig. 1). The 713.9–336^b-keV DCO ratio is in good agreement with a 7 → 5 → 4 spin assignment, the 713.9-keV transition being a pure quadrapole and the 336^b-keV transition being a dipole ($|\delta| < 0.1$). With the 7 → 5 quadrupole assignment to the 713.9-keV transition the DCO ratios involving the composite (714.6 + 713.9)-keV peak can now be analyzed, together with the directional distribution data. All data are consistent with the 714.6-keV transition being an essentially pure ($|\delta| < 0.1$) $9 \rightarrow 8$ transition. The possibility of a mixed $8 \rightarrow 8$ transition with $\delta \approx +2.0$ (in the definition of Krane and Steffen[5]), cannot entirely be excluded from the DCO and directional distribution data. This assignment, however, is unlikely in view of the absence of crossover transitions to the 6^+ state.

All coincidence rates, DCO, and directional-distribution data are consistent with the level scheme of ^{102}Pd that is shown in Fig. 1. The fact that *all* possible DCO ratios involving the 714.6-keV γ transition are far from unity clearly demonstrates that the 1019-892-705-714.6-keV cascade in ^{102}Pd is not an extension of the ground-state band as previously proposed.[1] It is more likely that this cascade corresponds to another $\Delta I = 2$ band built upon a $J = 9$ state. A band of this type, built on a $J = 7$ state, has been observed in the neighbor nucleus ^{104}Pd.[6,7] It is also to be noted that the 1019-893-705-540-713.9-keV transitions form a $15 \rightarrow 13 \rightarrow 11 \rightarrow 9 \rightarrow 7 \rightarrow 5$ sequence of states. The parity of these states has not been determined experimentally and this spin sequence could possibly correspond to an odd-parity band with a strong accidental overlap of its 9^- state with the 8^+ state of the ground-state band.

The measurements described here show that DCO-ratio observations are practical and very useful for the determination of the multipole character of, and spin changes in, γ transitions that take place in the complex decay of nuclei produced in (HI, xn) reactions. A more detailed account of the DCO and directional-distribution measurements on the ^{102}Pd γ rays following the (^{13}C, xn) reaction will be published in the near future.[3]

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Observation of an Anomalous Angular Distribution in the Single-Nucleon–Transfer Reaction ^{12}C(^{14}N, ^{13}N)^{13}C at 100 MeV*

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The reaction ^{12}C(^{14}N, ^{13}N)^{13}C has been studied at a bombarding energy of 100 MeV. The measured differential cross sections have been compared with exact finite-range distorted-wave Born approximation calculations including recoil. The angular distribution of the reaction populating the $2s_{1/2}$ state in ^{13}C at 3.09 MeV shows pronounced oscillations which are out of phase with those of the predicted angular distribution.

Recently it has been shown that the inclusion of "recoil" in numerical distorted-wave Born-approximation calculations of heavy-ion transfer cross sections strongly affects the predicted differential cross sections in both shape and magnitude, particularly at higher energies, and explains many observations which were not previously understood.[1,2] In particular, the inclusion