1.E.1: 3.A

Nuclear Physics **A252** (1975) 437–444; © *North-Holland Publishing Co., Amsterdam*

DIRECTIONAL CORRELATIONS OF γ-RAYS IN ^{143}Pr

R. N. CHERRY, Jr. † and M. L. WIEDENBECK

Department of Physics, The University of Michigan,
Ann Arbor, Michigan 48104, USA ††

Received 11 August 1975

Abstract: Directional correlation measurements have been made for γ-transitions in ^{143}Pr following the decay of 33.0 h ^{143}Ce using two Ge(Li) detectors. Correlation coefficients are reported for twelve cascades, of which coefficients for five cascades are previously unreported. Deduced are mixing ratios for thirteen transitions and spins and parities for the following levels: 57 ($\frac{5}{2}^+$), 351 ($\frac{3}{2}^+$), 490 ($\frac{5}{2}^+$), 722 ($\frac{3}{2}^+$), 739 ($\frac{1}{2}^-$), 938 ($\frac{3}{2}^+$), and 1160 ($\frac{5}{2}^+$) keV.

E | RADIOACTIVITY ^{143}Ce [from ^{142}Ce(n, γ)]; measured $\gamma\gamma(\theta)$. ^{143}Pr deduced J, γ mixing ratios.

1. Introduction

Previous investigators [1–10]) of directional correlations of γ-rays in ^{143}Pr following the decay of 33.0 h ^{143}Ce have used at least one NaI(Tl) detector in their experiments. The present work employs two Ge(Li) detectors and uses their better resolution to obtain results for twelve correlations, five for which results have not been previously reported.

In private communications to other authors [11,12]), Sunyar and Thieberger reported an appreciable time-dependent attenuation of the 293-57 keV correlation. Extrapolating their results to zero time and applying this correction to their earlier results [8]), they obtained larger values for the A_{22} coefficients of the 293-57 and 664-57 keV correlations than any previously reported. The present work uses powdered CeO_2 which has a cubic crystal structure [13]) to eliminate the time-dependent attenuation of correlation coefficients for cascades through the 4.2 ns 57 keV level. Results obtained are in agreement with the revised results of Sunyar and Thieberger reported in ref. [11]).

The directional correlation coefficients in the present work and previous internal conversion coefficient results [12,14,15]) are used to deduce the spins and parities of the 57, 351, 490, 722, 739, 938 and 1160 keV levels.

† Present address: Department of Physics, Hamilton College, Clinton, New York 13323.

†† Work supported in part by the National Science Foundation.

2. Experimental procedure

Samples of CeO_2 enriched to 93 % in ^{142}Ce were irradiated in the thermal neutron flux ($\approx 3\times10^{13}$ neutrons/cm^2 sec) of the University of Michigan Ford Nuclear Reactor for periods of approximately five days. The powdered samples were then placed in Lucite holders.

The directional correlation studies utilized 29 and 32 cm^3 Ge(Li) detectors. The apparatus and method of data analysis have been described elsewhere [16]).

3. Results and analysis

The results of the γ-γ directional correlation measurements are given in table 1. A partial level scheme [17]) is presented in fig. 1. Only levels studied in the present investigation are shown. A γ-spectrum taken with the 29 cm^3 detector is presented in fig. 2. Graphs of the normalized data and the correlation function $W(\theta)$ before making geometrical corrections are presented for the 293-57 and the 232-490 keV correlations in figs. 3 and 4, respectively. The sign convention of Krane and Steffen [ref. [18])] for the mixing ratio δ of the γ-transitions is used throughout.

The directional correlation function $W(\theta)$ may be written as

$$W(\theta) = 1+A_{22}(\gamma_1, \gamma_2)P_2(\cos\theta)+A_{44}(\gamma_1, \gamma_2)P_4(\cos\theta),$$

where θ is the angle between the detectors, γ_1 and γ_2 are the first and second γ-transitions in the cascade, respectively, and the P_k are Legendre polynomials. The A_{kk} may be written as

$$A_{kk}(\gamma_1, \gamma_2) = A_k(\gamma_1)B_k(\gamma_2),$$

where $A_k(\gamma_1)$ and $B_k(\gamma_2)$ are functions only of parameters associated with their respective γ-transitions, i.e., the spins of the upper and lower levels of the transition

TABLE 1

γ-γ directional correlation coefficients in ^{143}Pr

Cascade (E in keV)	A_{22}	A_{44}
293-57	0.166 ± 0.003	-0.005 ± 0.004
433-57	0.049 ± 0.037	0.004 ± 0.050
587-57	0.081 ± 0.051	-0.056 ± 0.070
664-57	0.150 ± 0.008	-0.005 ± 0.011
880-57	0.140 ± 0.009	-0.062 ± 0.012
1103-57	0.143 ± 0.021	-0.028 ± 0.029
232-140	0.116 ± 0.021	-0.009 ± 0.029
232-490	-0.195 ± 0.005	0.021 ± 0.006
371-293	-0.256 ± 0.044	0.021 ± 0.059
390-293	0.172 ± 0.036	-0.053 ± 0.049
587-293	0.259 ± 0.022	-0.036 ± 0.029
447-490	-0.063 ± 0.032	0.047 ± 0.043

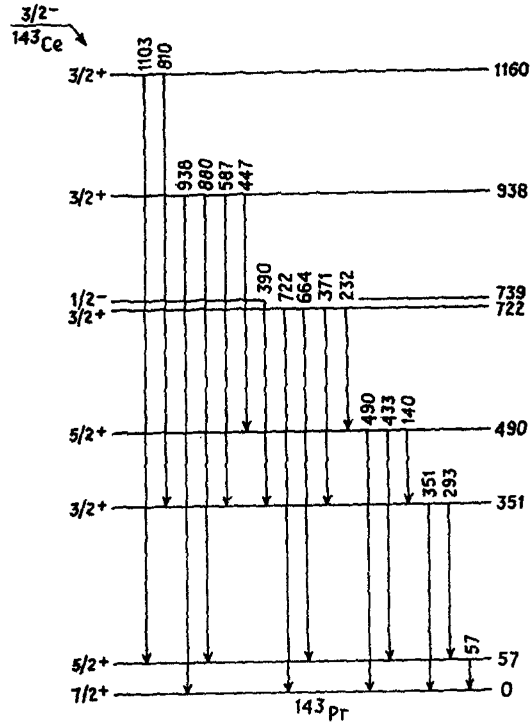

Fig. 1. Partial level scheme of ^{143}Pr with spins and parities deduced in the present study.

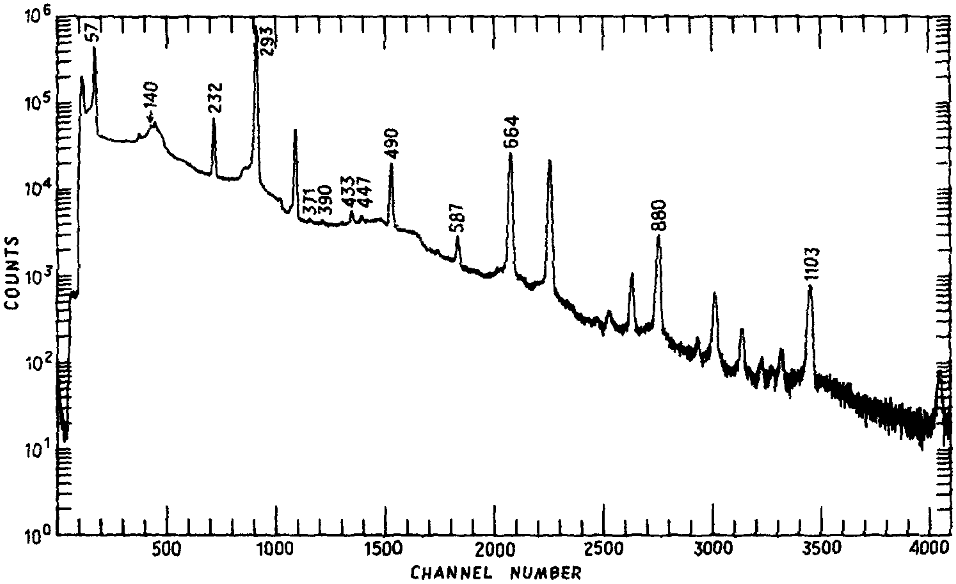

Fig. 2. Gamma ray spectrum following the decay of 33.0 h ^{143}Ce to levels in ^{143}Pr. Only transitions used in the correlations are labeled.

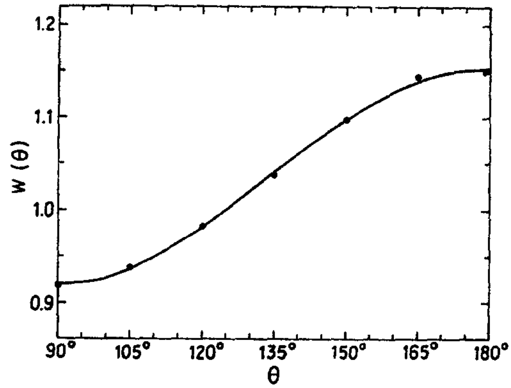

Fig. 3. Normalized data values and the correlation function $W(\theta)$ (before geometric corrections) versus the angle θ between the detectors for the 293-57 keV correlation. Errors of the data values are less than 0.1 %.

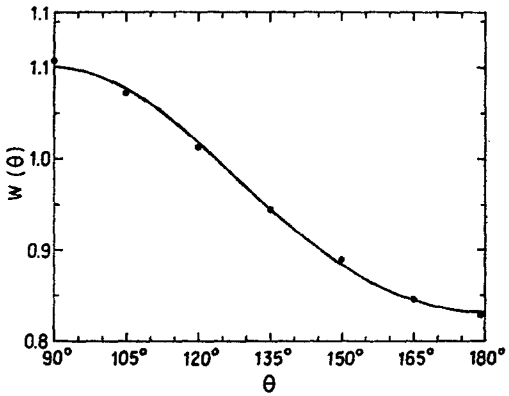

Fig. 4. Normalized data values and the correlation function $W(\theta)$ (before geometric corrections) versus the angle θ between the detectors for the 232-490 keV correlation. Errors of the data values are less than 0.3 %.

and the mixing ratio of the transition. Tables were prepared for the A_k and B_k as functions of δ for various spin sequences and used in the analysis.

Internal conversion coefficient (ICC) data [12]) and the theoretical calculations of Hager and Seltzer [19]) were used to calculate δ for the 293 and 57 keV transitions. These values for δ were then used to calculate the A_{22} coefficients for all possible spin sequences for the 293-57 keV correlation. The ground state spin of ^{143}Pr has been assigned $\frac{7}{2}$ from atomic beam experiments [20]). Only four spin sequences yield values for A_{22} in the neighborhood of the experimental value. Since the ground state spin of ^{143}Ce is known to be $\frac{3}{2}$ from atomic-beam experiments [21]), the log ft value [17]) for the 351 keV level may be used to eliminate the sequences with $\frac{9}{2}$ or $\frac{11}{2}$ for the spin of the 351 keV level. The remaining sequences assign $\frac{3}{2}$ or $\frac{7}{2}$ as the spin of the 351 keV level and $\frac{5}{2}$ as the spin of the 57 keV level. Positive parity is indicated for these levels by the magnetic moment of the 57 keV level and the multipolarities of the transitions [17]).

The 722, 938 and 1160 keV levels all have spins and parities indicated to be $\frac{3}{2}^+$ or $\frac{7}{2}^+$ by the magnitudes of the $A_2(\gamma_1)$ coefficients for the 664-57, 880-57 and 1103-57 keV correlations, respectively, and by the multipolarities of the transitions from ICC data [15]). The spin of the 490 keV level cannot be $\frac{1}{2}$ or $\frac{3}{2}$ because A_{22} and A_{44} for the 232-490 keV correlation are both non-zero.

The 232-490 keV correlation then allows the spin seqences $\frac{3}{2}$-$\frac{5}{2}$, $\frac{3}{2}$-$\frac{7}{2}$, $\frac{7}{2}$-$\frac{7}{2}$ or $\frac{7}{2}$-$\frac{9}{2}$ for the 722 and 490 keV levels, respectively. However, $\frac{3}{2}$-$\frac{7}{2}$ is ruled out by the 447-490 keV correlation if the spin of the 938 keV level is $\frac{3}{2}$ because the magnitude of the resulting A_{44} coefficient is much larger than the magnitude of the experimental A_{44} coefficient.

The 371-293 keV correlation does not allow the spin sequences $\frac{3}{2}$-$\frac{7}{2}$ and $\frac{7}{2}$-$\frac{3}{2}$ for the 722 and 351 keV levels, respectively. The former sequence is ruled out because

TABLE 2

Mixing ratios deduced in the present study

E_γ (keV)	Sequence [a])	δ
57	$\frac{5}{2}$(D, Q)$\frac{7}{2}$	0.016±0.002
140	$\frac{5}{2}$(D, Q)$\frac{3}{2}$	0.138±0.010
		0.30 ±0.02
232	$\frac{3}{2}$(D, Q)$\frac{5}{2}$	−0.582±0.013
		0.7 ±0.3
293	$\frac{3}{2}$(D, Q)$\frac{5}{2}$	0.62 ±0.04
371	$\frac{3}{2}$(D, Q)$\frac{3}{2}$	−4.2 ±0.7
		0.02 ±0.04
390	$\frac{1}{2}$(D, Q)$\frac{3}{2}$	−0.14 ±0.03
		2.45 ±0.18
433	$\frac{5}{2}$(D, Q)$\frac{5}{2}$	0.8 ±0.4
		$\lvert\delta\rvert > 4$
447	$\frac{3}{2}$(D, Q)$\frac{5}{2}$	−0.30 ±0.06
		−0.01 ±0.09
		3.5 ±1.3
		$\lvert\delta\rvert > 20$
490	$\frac{5}{2}$(D, Q)$\frac{7}{2}$	−2.50 ±0.03
		$\lvert\delta\rvert > 80$
587	$\frac{3}{2}$(D, Q)$\frac{3}{2}$	0.58 ±0.04
		3.6 ±0.4
664	$\frac{3}{2}$(D, Q)$\frac{5}{2}$	0.41 ±0.06
		1.24 ±0.13
880	$\frac{3}{2}$(D, Q)$\frac{5}{2}$	0.35 ±0.06
		1.39 ±0.15
1103	$\frac{3}{2}$(D, Q)$\frac{5}{2}$	0.37 ±0.15
		1.3 ±0.4

The sign convention of Krane and Steffen [18]) is used for δ.

[a]) Dipole and quadrupole radiation are denoted by D and Q, respectively.

the magnitude of the resulting A_{44} coefficient is much larger than the magnitude of the experimental A_{44} coefficient, and the latter is eliminated because the resulting magnitude of δ is twice as large as that found from ICC data [15]) and indicates more than 10 % octupole radiation for the 371 keV transition. Similarly, the 587-293 keV correlation eliminates these sequences for the 938 and 351 keV levels.

If the 351 keV level is assigned a spin of $\frac{3}{2}$, the 390-293 keV correlation indicates that the spin of the 739 keV level is less than or equal $\frac{7}{2}$. If the 351 keV level is assigned a spin of $\frac{7}{2}$, the 390-293 keV correlation and the log *ft* value [17]) for the 739 level limit the spin of the 739 keV level to $\frac{5}{2}$, $\frac{7}{2}$ or $\frac{9}{2}$. Since no other transitions from the 739 keV level have been observed and since ICC data [15]) indicate that the 351 keV transition is probably E2 and the 390 keV transition is probably E1 + M2, $\frac{3}{2}^+$ and $\frac{1}{2}^-$ are assigned as values for the spin and parity of the 351 and 739 keV levels, respectively. Assignment of $\frac{3}{2}$ as the spin of the 351 keV level is also supported by β-γ directional correlation experiments [22]). Spin and parity assignments for the 490, 722 and 938 keV levels then follow from the above analysis.

Since no transition is observed from the 1160 keV level to the ground state, $\frac{3}{2}^+$ is favored over $\frac{7}{2}^+$ for the spin and parity of the 1160 keV level. The log *ft* value for the 1160 keV level [17]) is not in disagreement with this assignment.

Spins and parities deduced in the present study are shown in fig. 1. Mixing ratios deduced are presented in table 2.

4. Discussion

A list of previous results of γ-γ directional correlation experiments is given in table 3 for comparison with the present results. It may be observed that for correlations involving the 4.2 ns 57 keV level the present results are in close agreement with the coefficients of Sunyar and Thieberger which were corrected for time-dependent perturbation effects as reported in ref. [11]). Coefficients reported by other experimenters who used liquid sources are smaller in magnitude than the present results. Therefore, it is believed that using a cubic crystal powdered sample of CeO_2 as a source in directional correlation experiments adequately eliminates time-dependent perturbation effects across the 4.2 ns 57 keV level.

The value of the A_{44} coefficient for the 880-57 keV correlation is expected to be approximately zero because of the very small value of the $B_4(\gamma_2)$ coefficient for the 57 keV transition. The nearness of the 880 keV peak to the 891 keV peak and to the Compton edge of the 1103 keV transition may account for the magnitude of the observed value of the A_{44} coefficient for the 880-57 keV correlation.

Several authors [23-26]) have attempted a theoretical description of the level structure of ^{143}Pr. Kisslinger and Sorensen [23]) use a quasi-particle random-phase approximation with the pairing plus quadrupole force as a residual interaction but do not predict the crossing of the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states which occurs between ^{141}Pr and ^{143}Pr. Pal and Mitra [24]) include the n-p interaction as a perturbation in the

TABLE 3

Previously measured directional correlation coefficients in ^{143}Pr

Cascade (E in keV)	A_{22}	A_{44}	Ref.
293-57	0.132±0.010	0.00 ±0.01	[1]
	0.132±0.019	0.008±0.020	[2]
	0.133±0.007	0.000±0.006	[3]
	0.106±0.010	(0)	[4]
	0.112±0.009	0.000±0.014	[5]
	0.123±0.011	(0)	[6]
	0.099±0.006	0.006±0.007	[7]
	0.139±0.005	(0)	[8]
	0.125±0.006	(0)	[9]
	0.18 ±0.01	(0)	[a]
	0.098±0.006	0.005±0.008	[10]
	0.166±0.003	−0.005±0.004	present work
587-57	−0.31 ±0.17	−0.1 ±0.3	[7]
	0.081±0.051	−0.056±0.070	present work
664-57	0.104±0.011	(0)	[4]
	0.063±0.018	(0)	[5]
	0.075±0.011	(0)	[6]
	0.063±0.009	(0)	[7]
	0.111±0.009	(0)	[8]
	0.144±0.012	(0)	[a]
	0.150±0.008	−0.005±0.011	present work
880-57	0.11 ±0.03	(0)	[7]
	0.077±0.027	(0)	[8]
	0.099±0.035	(0)	[a]
	0.140±0.009	−0.062±0.012	present work
1103-57	0.01 ±0.03	(0)	[7]
	0.143±0.021	−0.028±0.029	present work
232-490	−0.186±0.028	−0.04 ±0.15	[4]
	−0.176±0.008	−0.001±0.012	[5]
	−0.227±0.016	−0.035±0.028	[6]
	−0.173±0.010	0.008±0.013	[8]
	−0.195±0.005	0.021±0.006	present work
587-293	0.146±0.015	0.003±0.026	[5]
	0.285±0.029	(0)	[8]
	0.259±0.022	−0.036±0.029	present work

[a]) These values are the coefficients of ref. [8]) corrected for time-dependent perturbation effects by Sunyar and Thieberger as reported in ref. [11]).

pairing force model but also do not predict the crossing of states. Choudhury and Kujawski [25]) and Heyde and Brussard [26]) studied ^{143}Pr using the intermediate coupling approach in the unified model. Each work predicts a spin and parity of $\frac{7}{2}^+$ for the ground state and $\frac{5}{2}^+$ for the first excited state, but agreement with the present results is poor for the higher levels.

The authors wish to thank Dr. Peter L. Gardulski for his helpful discussions and Mr. Peter J. Wiedenbeck for his program improving the efficiency of utilization of the PDP-8/I computer.

References

1) E. Bozek, A. Z. Hrynkiewicz, S. Ogaza, M. Rybicka and J. Styczen, Phys. Lett. **6** (1963) 89
2) G. N. Rao and H. S. Hans, Nucl. Phys. **41** (1963) 511
3) R. M. Levy, Thesis, University of California, UCRL-11663 (1964)
4) L. Simons, A. Anttila and S. Bergstrom, Soc. Sci. Fennica, Commentationes Phys. Math. **30**, no. 3 (1964)
5) K. P. Gopinathan, Phys. Rev. **139** (1965) B1467
6) R. V. Mancusco, J. P. Roalsvig and R. G. Arns, Phys. Rev. **140** (1965) B525
7) T. Badica, N. Deciu, A. Gelburg, P. Kemeny and R. Mihai, Rev. Roum. Phys. **11** (1966) 179
8) A. W. Sunyar and P. Thieberger, Bull. Am. Phys. Soc. **11** (1966) 407
9) H. Zmora, S. Ofer and M. Rakavy, Nucl. Phys. **89** (1966) 225
10) S. Venkataratnam, G. Satyanarayana and V. Lakshminarayana, Nuovo Cim. **21** (1974) 687
11) L. W. Chiao and S. Raman, Nucl. Data Sheets **B2** (1967) 25
12) W. Gelletly, J. S. Geiger and R. L. Graham, Bull. Am. Phys. Soc. **12** (1967) 55; Phys. Rev. **168** (1968) 1336
13) R. C. Weast, ed., Handbook of chemistry and physics, 51st ed. (The Chemical Rubber Co., Cleveland, Ohio, 1970) p. B-81
14) E. Bashandy, S. G. Hanna and A. Abd El-Haliem, J. Phys. Soc. Japan **22** (1967) 960
15) E. Bashandy, Z. Naturf. **26** (1971) 683
16) R. N. Cherry, Jr. and M. L. Wiedenbeck, Nucl. Phys. **A252** (1975) 445
17) J. F. Lemming, Nucl. Data Sheets **13** (1974) 229
18) K. S. Krane and R. M. Steffen, Phys. Rev. **C2** (1970) 724
19) R. S. Hager and E. C. Seltzer, Nucl. Data **A4** (1968) 1
20) B. Budick, I. Maleh and R. Marrus, Phys. Rev. **135** (1964) B1281
21) I. Maleh, Phys. Rev. **138** (1965) B766
22) M. L. Raju, D. L. Sastry and E. Kondaiah, Nuovo Cim. **56B** (1968) 29
23) L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35** (1963) 853
24) M. K. Pal and D. Mitra, Nucl. Phys. **42** (1963) 221
25) D. C. Choudhury and E. Kujawski, Phys. Rev. **144** (1966) 1013
26) K. Heyde and P. J. Brussard, Nucl. Phys. **A104** (1967) 81