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Beta-Gamma Directional Correlations in the Decay of $^{143}_{58}$Ce.

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Summary. — The energy dependence of the 1100 keV β-293 keV γ directional correlation was measured in the decay of ^{143}Ce with a conventional slow-fast scintillation assembly in the beta energy region (750 ÷ 1065) keV. Results from the integral correlation showed that the correlation coefficient ε_4 was zero within experimental errors, while those from the differential correlation experiment showed that the coefficient ε_2 is small and independent of energy. The results presented here agree with the spin assignment of $\frac{5}{2}^+$ to the 351 keV level in ^{143}Pr. The angular correlation results are also discussed on the basis of ξ approximation.

1. – Introduction.

The decay scheme of ^{143}Ce has been investigated by several authors and the prominent energy levels of ^{143}Pr have been well established ([1-5]). The decay scheme is shown in Fig. 1. In particular the 57 and 351 keV levels were in-

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([1]) H. B. Keller and J. M. Cork: *Phys. Rev.*, **84**, 1079 (1951).
([2]) E. Kondaiah, *Phys. Rev.*, **83**, 471 (1951); *Ark. f. Fys.*, **4**, 81 (1952).
([3]) W. M. Burgus: *Phys. Rev.*, **88**, 1129 (1952).
([4]) D. W. Martin, M. K. Brice, J. M. Cork and S. B. Burson: *Phys. Rev.*, **101**, 182 (1956).
([5]) K. P. Gopinathan, M. C. Joshi and E. A. S. Sarma: *Phys. Rev.*, **136**, B 1247 (1964).

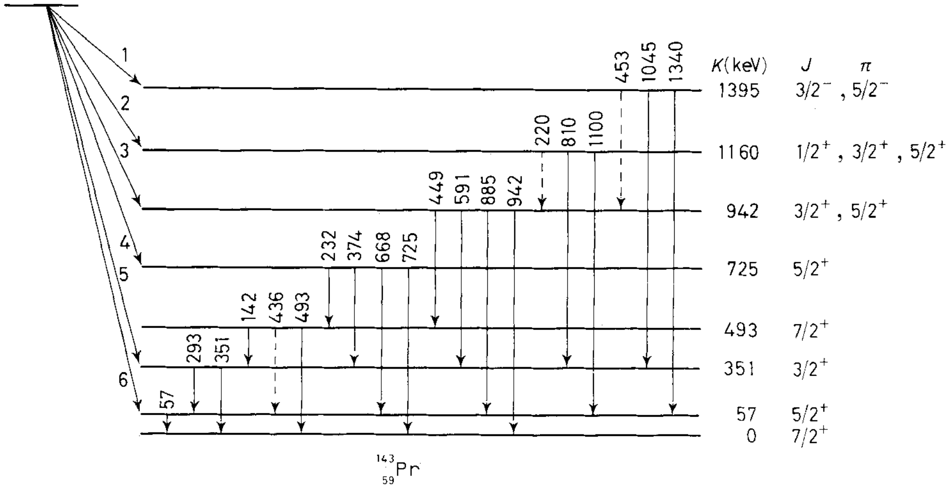

Fig. 1. – Decay scheme of ^{143}Ce.

	keV	%		keV	%
1	65	0.2 [5.5]	4	735	16.2 [7.0]
2	300	1.0 [7.0]	5	1100	45 [7.2]
3	520	2.0 [7.3]	6	1400	38.4 [7.1]

vestigated in greater detail ([6-12]). Although there are some inconsistencies in the spin assignments of the levels by the various investigators, the energy-level structure is well established. RAO and HANS ([11]) measured the directional correlation function for the (293 ÷ 57) keV gamma-gamma cascade and the interpretation of their data was based on the assumed ground-state spin $\frac{5}{2}$ for ^{143}Pr. GRAHAM *et al.* ([12]) interpreted the results of RAO and HANS using the measured ground-state spin ([13]) of $\frac{7}{2}$ for ^{143}Pr. They have shown that the

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([6]) S. GORODETZKY, R. MANQUENOUILLE, R. RICHERT and A. KNIPPER: *Compt. Rend.*, **253**, 428 (1961).

([7]) M. S. EL-NESR and E. BASHANDI: *Phys. Lett.*, **2**, 287 (1962).

([8]) I. M. GOVIL and C. S. KHURANA: *Nucl. Phys.*, **49**, 29 (1963).

([9]) E. BOZEK, A. Z. HRYNKIEWIEZ, S. OGAZA, M. RYBICS and J. STYCZEN: *Phys. Lett.*, **6**, 89 (1963).

([10]) J. N. HAAG, D. A. SHIRLEY and D. H. TEMPLETON: *Phys. Rev.*, **129**, 1601 (1963).

([11]) G. N. RAO and H. S. HANS: *Nucl. Phys.*, **41**, 511 (1963).

([12]) R. L. GRAHAM, J. M. HOLLANDER and P. KLEINHEINZ: *Nucl. Phys.*, **49**, 641 (1963).

([13]) B. BUDICK, R. MARRUS, W. M. DOYLE and W. A. NIERENBERG: *Bull. Am. Phys. Soc.*, **7**, 477 (1962); B. BUDICK, R. MARRUS and I. MALEH: *Phys. Rev.*, **135**, B 1281 (1964).

only spin assignments consistent with their L-conversion data and the directional correlation function are either $\frac{3}{2}$ or $\frac{7}{2}$ for the 351 keV level and $\frac{5}{2}$ for the 57 keV level. The spins $\frac{3}{2}$ and $\frac{7}{2}$ for the 351 keV level are also consistent with the nuclear alignment data of LEVI [14]. Later gamma-gamma directional correlation measurements [15-17] in ^{143}Pr confirmed the spin assignment to be either $\frac{3}{2}$ or $\frac{7}{2}$ for the 351 keV level. GOPINATHAN [15] assigned the spin $\frac{3}{2}^+$ combining the results of their angular correlation data with the logft value 7.3 of the beta transition to the 351 keV level. On the other hand the gamma-gamma angular correlation measurements of MANUSCO *et al.* [16] and BADICA *et al.* [17] indicated a spin assignment $\frac{7}{2}^+$. CHOUDHURY *et al.* [18] pointed out that the 351 keV level may arise as a result of the partial excitation of the core in which the $(d_{\frac{5}{2}})^2_0$ proton pair is decoupled and excited from spin state 0 to spin state 2. Furthermore they suggested that $\frac{7}{2}^+$ is the most probable spin of the 351 keV level and that this level can be represented by the configuration $[(d_{\frac{5}{2}})^2_2(g_{\frac{7}{2}})^{-1}_{\frac{7}{2}}]_{\frac{7}{2}}$.

From the results of gamma-gamma angular correlation and L-conversion studies it may be noted that both $\frac{3}{2}^+$ and $\frac{7}{2}^+$ spin values are possible for the 351 keV level in ^{143}Pr. Of the two values some authors favoured $\frac{3}{2}^+$ while some authors favoured $\frac{7}{2}^+$. It can be seen that the parity of the 351 keV level is + and there is a controversy about the spin value to be chosen in between $\frac{3}{2}$ and $\frac{7}{2}$. Thus the beta transition to the 351 keV level must be either a first-forbidden nonunique type or a first-forbidden unique type according as the spin value is $\frac{3}{2}^+$ or $\frac{7}{2}^+$. A beta-gamma directional correlation experiment helps in deciding whether a beta transition is first-forbidden nonunique or first-forbidden unique, since the correlation pattern for a unique transition can be theoretically predicted.

The present investigation is undertaken to decide the spin value between $\frac{3}{2}$ and $\frac{7}{2}$ for the 351 keV level from a measurement of the energy dependence of the beta-gamma directional correlation for the 1100 keV β-293 keV γ cascade in the decay of ^{143}Ce. The angular correlation results are also discussed on the basis of ξ approximation [19-21].

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(14) R. M. LEVI: *Ph. D. Thesis*, Lawrence Radiation Laboratory, Report No. UCRL-11663.

(15) K. P. GOPINATHAN: *Phys. Rev.*, **139**, B 1467 (1965).

(16) R. V. MANUSCO and J. P. ROALSVIG: *Phys. Rev.*, **140**, B 525 (1965).

(17) T. BADICA, N. DECIU, A. GELBERG, P. KEMENY and R. MIHAI: *Rev. Roum. Phys.*, **11**, 179 (1966).

(18) D. C. CHOUDHURY and E. KUJSWAKI: *Phys. Rev.*, **144**, 1013 (1966).

(19) E. J. KONOPINSKI and G. F. UHLENBECK: *Phys. Rev.*, **60**, 308 (1941).

(20) T. KOTANI and M. ROSS: *Phys. Rev. Lett.*, **1**, 140 (1958).

(21) H. A. WEIDENMULLER: *Rev. Mod. Phys.*, **33**, 574 (1961).

2. – Experimental procedure and results.

The experimental set-up used in the present work is a conventional slow-fast scintillation assembly. The experimental arrangement is similar to the one given in ref. [22,23] and the experimental details and the treatment of the data can be found in the same references. The gamma-energy calibration is accomplished with the standard sources ^{137}Cs, ^{22}Na, ^{114}In and ^{60}Co. The beta spectrometer is calibrated using the conversion electron sources ^{137}Cs and ^{207}Bi. A ten-channel analyser is used in the differential correlation measurements. The differential correlation experiment at 840 keV is also done on a single-channel analyser to check the performance of the ten-channel analyser.

The ^{143}Ce source is obtained in the form of liquid cerium nitrate from the isotope division, Bhabha Atomic Research Centre, Trombay. The source is prepared by slowly evaporating to dryness a small drop of ^{143}Ce solution on a mylar foil of thickness 0.6 mg/cm^2. A drop of insulin aided uniform spreading of the source. The source is centred properly so as to ensure that the variation of the counting rate in the movable gamma detector lies below 1%. The intrinsic asymmetry of the system is measured by gamma-gamma and beta-gamma correlation experiments with ^{60}Co and found to be zero within experimental errors.

The ^{143}Ce source contains 5% ^{141}Ce and 0.5% ^{144}Ce as impurities. As all the beta energies in both ^{141}Ce and ^{144}Ce are very low they have no influence in coincidence experiments of the present kind. ^{144}Pr, the daughter nucleus of ^{144}Ce, is radioactive, but 95% of ^{144}Pr decays to the ground state of ^{144}Nd. So the radiations from ^{144}Pr are of no consequence in the present measurements.

2·1. *Results of the integral correlation experiment.* – The singles gamma spectrum is shown in Fig. 2. In the 1100 keV β-293 keV γ cascade in the decay of ^{143}Ce, the 293 keV gamma photopeak is accepted in a window of 4 V in integral and differential correlation measurements. For the integral correlation measurements the beta particles of energy 750 keV and above were accepted in the beta channel. The beta-gamma coincidences were collected at 5 angles in between 180° and 90° in steps of $22\frac{1}{2}$°. In Fig. 3 the correlation function $W_{\beta\gamma}(\theta)$ is plotted as $N_{\beta\gamma}(\theta)$ against $\cos^2(\theta)$. $N_{\beta\gamma}(\theta)$ is the pooled counts of beta-gamma coincidences at the angle θ. These are normalized

(22) W. V. S. RAO, V. S. RAO, D. L. SASTRY and S. JNANANANDA: *Phys. Rev.*, **140**, B 1193 (1965).
(23) W. V. S. RAO, K. S. ROW, D. L. SASTRY and S. JNANANANDA: *Proc. Phys. Soc.*, **87**, 917 (1966).

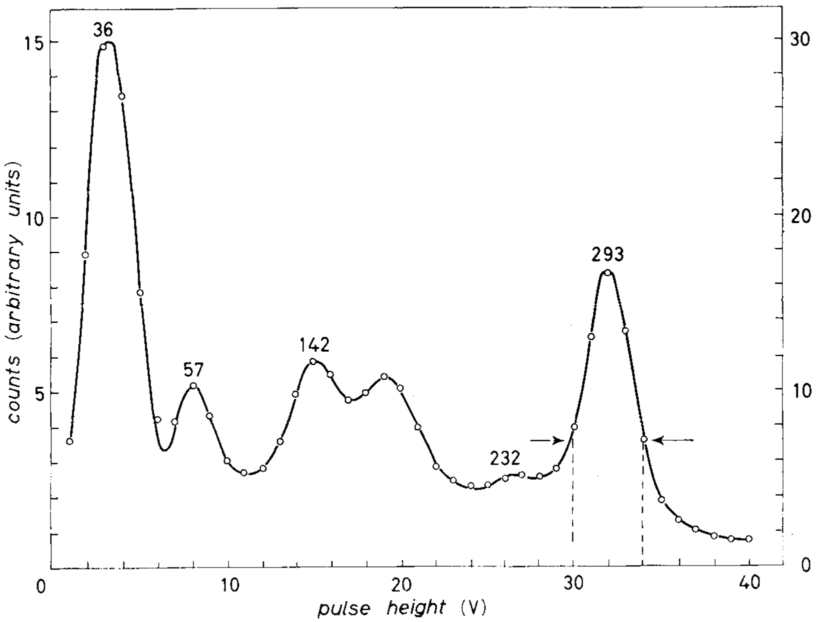

Fig. 2. – Singles gamma spectrum. The portion in between the arrows indicates the channel width used for accepting the gammas in the correlation experiment.

counts and corrected for chance and background. In these measurements gamma-gamma background is very low and insignificant. An application of Rose's method of least squares ([24]) has yielded the correlation function to be

$$W_{\beta\gamma}(\theta) =$$
$$= 1 + (-0.0219 \pm 0.0096) P_2(\cos\theta) +$$
$$+ (0.002 \pm 0.0106) P_4(\cos\theta) .$$

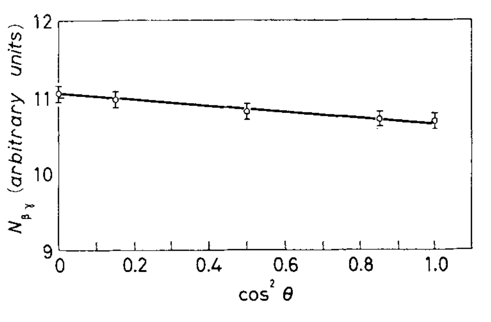

Fig. 3. – ^{143}Ce integral correlation results.

From this can be seen that ε_4 is zero within experimental errors, while ε_2 is small in magnitude. The straight line in Fig. 3 represents a least-squares fit to the data. From this it can be concluded that the 1100 keV beta transition is a first-forbidden beta transition.

([24]) M. E. Rose: *Phys. Rev.*, **91**, 610 (1953).

2'2. *Results of the differential correlation experiment.* – The data were collected at eight beta energies in steps of 45 keV ranging from 750 keV to 1065 keV with a ten-channel analyser. The performance of the ten-channel analyser is checked by repeating the experiment with a single-channel analyser at one energy, 840 keV. The results are in good agreement. The coincidences were recorded only at two angles (180° and 90°), as only ε_2 is involved. The anisotropies were determined using the relationship

$$A(W) = \frac{N(W)_{180^\circ} - N(W)_{90^\circ}}{N(W)_{90^\circ}},$$

where $N(W)_{90^\circ}$ and $N(W)_{180^\circ}$ were the pooled coincidences at the two angles, (these are normalized and true coincidences). To the observed coincidences the decay correction is applied for the 33 h half-life of ^{143}Ce. The differential correlation coefficients were estimated using the relationship $\varepsilon_2 = 2A/(A+3)$.

The values of the anisotropies, the corresponding correlation coefficients and the reduced correlation coefficients $\varepsilon' = \varepsilon(W/p^2)$ (where W is the beta energy in mc^2 units and $p^2 = W^2 - 1$, p being the electron momentum) are summarized in Table I. The correlation coefficients are corrected for the finite solid angle effects of both the detectors.

TABLE I. – *Directional correlation data of* (1100 ÷ 293) keV *beta-gamma cascade in the decay of* ^{143}Ce.

Energy W (mc^2 units)	Anisotropy A	Correlation coefficient ε	Reduced correlation coefficient $\varepsilon' = \varepsilon(W/p^2)$
2.468	-0.02 ± 0.015	-0.014 ± 0.01	-0.007 ± 0.005
2.556	-0.031 ± 0.018	-0.022 ± 0.013	-0.01 ± 0.006
2.644	-0.026 ± 0.017	-0.018 ± 0.012	-0.008 ± 0.005
2.734	-0.035 ± 0.021	-0.025 ± 0.015	-0.011 ± 0.006
2.82	-0.050 ± 0.041	-0.037 ± 0.027	-0.015 ± 0.011
2.908	-0.054 ± 0.042	-0.038 ± 0.029	-0.015 ± 0.011
2.996	-0.019 ± 0.027	-0.014 ± 0.019	-0.0053 ± 0.0071
3.084	-0.0064 ± 0.014	-0.004 ± 0.01	-0.0015 ± 0.0036

3. – Discussion.

3'1. *Spin of the* 351 keV *level.* – The ground-state spin of ^{143}Ce has been measured ([25]) to be $\frac{3}{2}^-$. The 1100 keV beta transition involves a nuclear spin change of two units under the assumption of spin $\frac{7}{2}^+$ for the 351 keV level

([25]) I. MALEH: *Phys. Rev.*, **138**, B 766 (1965).

in ^{143}Pr. In such a case, this will be a unique beta transition and, the magnitude and the beta energy dependence of the $A_2(\beta)$ coefficient $[\varepsilon = A_2(\beta)A_2(\gamma)]$ may be calculated without ambiguity. The coefficient $A_2(\beta)$ is calculated using the relationship ([26])

$$A_2(\beta) = \frac{7\lambda_1 p^2}{5(q^2+\lambda_1 p^2)} F_2(2\,2\,I_i I)\,,$$

λ_1 is taken as unity using exact electron radial wave functions ([27]) $A_2(\beta)$ is also calculated from the experimentally observed correlation coefficient. The experimental and theoretical $A_2(\beta)$ coefficients are given in Table II and

TABLE II. – *$A_2(\beta)$ experimental, and $A_2(\beta)$ theoretical for* 351 keV *level vs. energy.*

Energy W (mc^2 units)	$A_2(\beta)$ experimental	$A_2(\beta)$ theoretical
2.468	-0.015 ± 0.01	-0.598
2.556	-0.022 ± 0.014	-0.616
2.644	-0.018 ± 0.012	-0.629
2.734	-0.025 ± 0.016	-0.639
2.82	-0.035 ± 0.026	-0.646
2.908	-0.038 ± 0.03	-0.652
2.996	-0.015 ± 0.02	-0.654

plotted against beta energy in Fig. 4. The experimental values of $A_2(\beta)$ are observed to differ drastically from the $A_2(\beta)$ values estimated under the assumption that the spin of the 351 keV level is $\frac{7}{2}^+$. Furthermore the experimental values of $A_2(\beta)$ are almost independent of beta energy within the limits of experimental errors. The disagreement indicates that the 1100 keV beta transition cannot be a unique first-forbidden beta transition and hence the spin of the 351 keV level cannot be $\frac{7}{2}$. Thus the beta transition under consideration should be of the

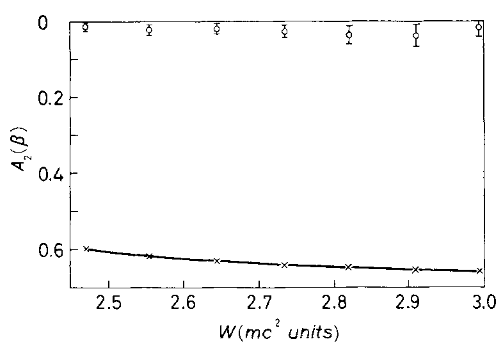

Fig. 4. – *W vs. $A_2(\beta)$*: × theoretical points; o experimental points.

([26]) R. M. STEFFEN: *Alpha, Beta, Gamma Ray Spectroscopy*, vol. **2**, Edited by K. SIEGBAHN (Amsterdam, 1965).

([27]) W. BUHRING: *Nucl. Phys.*, **61**, 110 (1965).

nonunique first-forbidden type. Hence the spin of the 351 keV level must be $\frac{1}{2}^+$, $\frac{3}{2}^+$ or $\frac{5}{2}^+$. However $\frac{1}{2}^+$ and $\frac{5}{2}^+$ spin assignments are ruled out by the gamma-gamma angular correlation measurements and conversion measurements. Hence the spin of 351 keV level must be $\frac{3}{2}^+$. This spin assignment is consistent with the log *ft* value 7.3 of the 1100 keV beta transition and also with the internal conversion measurements on the 351 keV gamma ray reported by BASHANDI *et al.* [28]. In the lines of CHOUDHURY *et al.*, the 351 keV level can now be represented by the configuration $[(d_{\frac{5}{2}})^2_2(g_{\frac{7}{2}})^{-1}_{\frac{7}{2}}]_{\frac{3}{2}}$. The 293 keV gamma transition from the 351 keV level to the 57 keV level in ^{143}Pr is known to have an $E2$ enchancement [12] over the single-particle estimate. It is therefore not possible to completely describe the 351 keV state by such pure configurations. It is possible that this state also includes some collective amplitudes in its wave function. Work is in progress in this laboratory to understand the collective nature of the 351 keV level.

3·2. *Validity of ξ approximation.* – The values of the anisotropies, correlation coefficients and the reduced correlation coefficients are all very small. The correlation coefficient and the reduced correlation coefficient are plotted against beta-energy in Fig. 5*a*) and 5*b*). It is to be noted that no resolution correction has been applied for the finite resolution of the beta spectrometer as the resolution correction is expected to fall within experimental errors. From these Figures it can be seen that the correlation coefficients and the reduced correlation coefficients are fairly independent of the beta energy within the limits of the experimental error. Further the shape of the 1100 keV beta group is allowed. All these facts are consistent with the ξ-approximation. The uncertainties involved in the present measurements are of the order of 60 % or more. Though the uncertainties are large it may be concluded from the data presented in this paper that there exists possibly a small negative anisotropy in accordance with ξ-approximation.

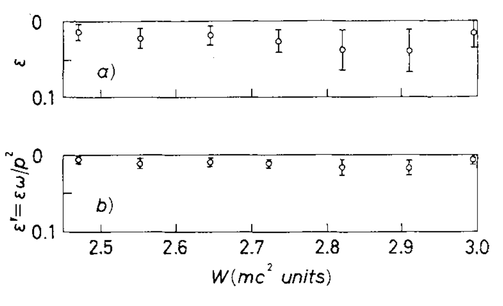

Fig. 5. – *a*) *W*, the beta energy in mc² units *vs.* the correlation coefficient. *b*) *W vs.* the reduced correlation coefficient.

([28]) E. BASHANDI, S. G. HANNA and A. ABD EL-HALIEM: *Journ. Phys. Soc. Japan*, **22**, 960 (1967).

4. – Conclusions.

It may be finally concluded from the present work that the spin of the 351 keV level in ^{143}Pr is not $\frac{7}{2}$, the results presented here agree with the assignment of $\frac{3}{2}$ to this level. The 1100 keV beta transition in ^{143}Ce fits into ξ-approximation.

RIASSUNTO (*)

Si è misurata la dipendenza dall'energia della correlazione direzionale β di 1100 keV-γ di 293 keV nel decadimento del ^{143}Ce con un'apparecchiatura a scintillazione lenta-rapida convenzionale nella regione di energia dei β (750 ÷ 1065) keV. I risultati della correlazione integrale hanno mostrato che il coefficiente di correlazione ε_4 era zero entro gli errori sperimentali, mentre quelli dell'esperimento di correlazione differenziale hanno mostrato che il coefficiente ε_2 è piccolo e non dipende dall'energia. I risultati riportati qui concordano con l'assegnazione dello spin $\frac{3}{2}^+$ al livello di 351 keV nel ^{143}Pr. Si discutono anche i risultati della correlazione angolare sulla base dell'approssimazione ξ.

(*) *Traduzione a cura della Redazione.*

Корреляции β-γ направлений при распаде $^{143}_{58}$Ce.

Резюме (*). — Измерялась зависимость от энергии корреляции 1100 кэВ π-293 кэВ γ направлений при распаде ^{143}Ce с помощью обычного медленно-быстрого сцинцилляционного агрегата в области π-энергий (750 ÷ 1065) кэВ. Результаты из интегральной корреляции показали, что коэффициент корреляции ε_4 равен нулю в пределах экспериментальных ошибок, в то время как результаты, полученные из эксперимента по определению дифференциальной корреляции, показали, что коэффициент ε_2 мал и не зависит от энергии. Представленные здесь результаты согласуются с приписыванием спина $\frac{3}{2}^+$ для уровня 351 кэВ в ^{143}Pr. Также, на основе ξ приближения, обсуждаются результаты для угловий корреляции.

(*) *Переведено редакцией.*