# POLARIZATIONAL–DIRECTIONAL CORRELATION FROM ORIENTED NUCLEI*

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A general formula for the correlation of two polarized gamma quanta emitted in a cascade from oriented nuclei is given. The case of polarizational directional correlation of photons emitted from an aligned nucleus is discussed.

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The information about spins and parities of excited states is crucial for nuclear structure studies. To determine these quantities in an "in-beam" spectroscopy, one should combine results of the DCO analysis with linear polarization of $\gamma$-transitions. In a modern multidetector systems the new generation detectors allow for $\gamma$-polarization measurements. The large total efficiency of the multidetector array allows to carry out coincidence measurements between the $\gamma$-ray polarimeters and the remaining $\gamma$-ray detectors.

Let us assume that as a result of the heavy ion reaction nuclear state of spin $I_0$ and parity $\pi_0$ deexcites via successive emission of two photons ($\gamma_1$ and $\gamma_2$) through an intermediate state $I_1$, $\pi_1$ to a final state $I_2$, $\pi_2$

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(Fig. 1). Because of nuclear reaction, the spins of the considered nucleus are aligned. Gamma transitions are observed using large multidetector system from which, for a sake of simplicity we shall consider only two detectors, at least one of them sensitive to polarization. The geometry of the experiment is shown in Fig. 2.

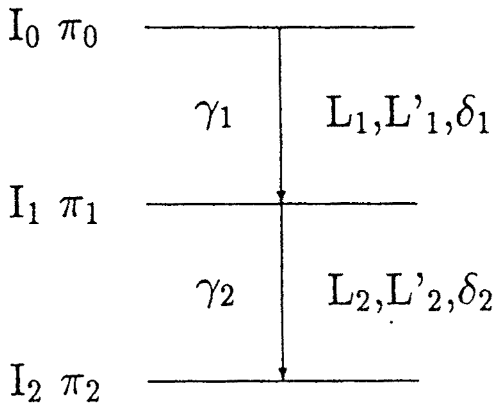


Fig. 1. Decay of an oriented initial nuclear state.

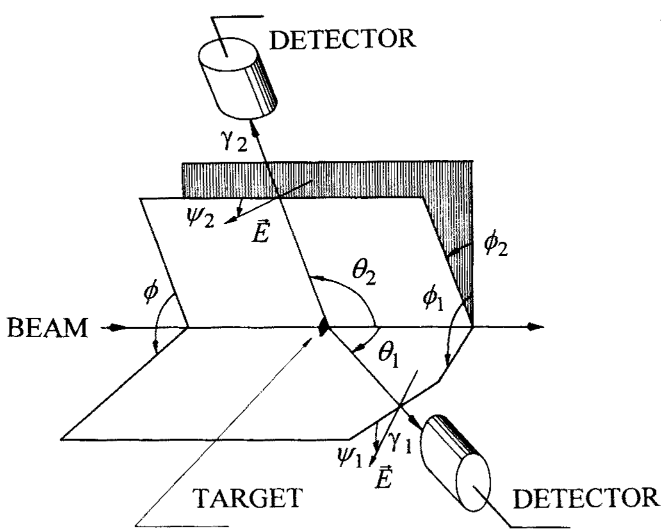


Fig. 2. Two gamma detectors from the multidetector system.

The following formula has been derived after Steffen and Alder [1] for the correlation of two gamma quanta which polarization is conceivably observed:

$$W_{q_1 q_2}(\theta_1,\theta_2,\phi,\psi_1,\psi_2,\gamma_1,\gamma_2) = \frac{(2-q_1)(2-q_2)}{32\pi^2} \sum_{\lambda_0,\lambda_1=\text{even}} B_{\lambda_0}(I_0)$$
$$\times \sum_{\lambda}\sum_{\mu\geq 0} \frac{\langle \lambda_0\ 0\ \lambda_1\ \mu \mid \lambda\ \mu\rangle}{1+\delta_{\mu 0}} \Big\{ A^{\lambda_1\lambda_0}_{\lambda\ 0}(\gamma_1) A^{0\,\lambda_1}_{\lambda_1 0}(\gamma_2) d^{\lambda}_{\mu 0}(\theta_1) d^{\lambda_1}_{\mu 0}(\theta_2)\cos\mu\phi$$
$$- \tfrac{1}{2} q_1 A^{\lambda_1\lambda_0}_{\lambda\ 2}(\gamma_1) A^{0\,\lambda_1}_{\lambda_1 0}(\gamma_2)$$
$$\times \Big[ d^{\lambda}_{\mu 2}(\theta_1)\cos(\mu\phi+2\psi_1) + (-1)^{\lambda} d^{\lambda}_{\mu -2}(\theta_1)\cos(\mu\phi-2\psi_1)\Big] d^{\lambda_1}_{\mu 0}(\theta_2)$$
$$- \tfrac{1}{2} q_2 A^{\lambda_1\lambda_0}_{\lambda\ 0}(\gamma_1) A^{0\,\lambda_1}_{\lambda_1 2}(\gamma_2)$$
$$\times d^{\lambda}_{\mu 0}(\theta_1)\Big[ d^{\lambda_1}_{\mu 2}(\theta_2)\cos(\mu\phi-2\psi_2) + d^{\lambda_1}_{\mu -2}(\theta_2)\cos(\mu\phi+2\psi_2)\Big]$$
$$+ \tfrac{1}{4} q_1 q_2 A^{\lambda_1\lambda_0}_{\lambda\ 2}(\gamma_1) A^{0\,\lambda_1}_{\lambda_1 2}(\gamma_2)$$
$$+ \Big[ d^{\lambda}_{\mu 2}(\theta_1) d^{\lambda_1}_{\mu 2}(\theta_2)\cos(\mu\phi+2\psi_1-2\psi_2)$$
$$+ d^{\lambda}_{\mu 2}(\theta_1) d^{\lambda_1}_{\mu -2}(\theta_2)\cos(\mu\phi+2\psi_1+2\psi_2)$$
$$+ (-1)^{\lambda} d^{\lambda}_{\mu -2}(\theta_1) d^{\lambda_1}_{\mu -2}(\theta_2)\cos(\mu\phi-2\psi_1+2\psi_2)$$
$$+ (-1)^{\lambda} d^{\lambda}_{\mu -2}(\theta_1) d^{\lambda_1}_{\mu 2}(\theta_2)\cos(\mu\phi-2\psi_1-2\psi_2)]\Big\},$$

where $\phi = \phi_1 - \phi_2, \psi_1$ and $\psi_2$ are the angles between the emission planes and directions of the observed electric vectors $\vec{E}$ of photons $\gamma_1$ and $\gamma_2$, respectively, $B_{\lambda_0}(I_0)$ for $\lambda_0 = 0, 2, ...2I_0$ are the orientation parameters of the initial state [2] and $d^{\lambda}_{\mu\nu}$ is a real Wigner function (*cf.* Ref. [3]). The notation of Bohr and Mottelson [3] for the Clebsch–Gordan coefficient is used. When the two lowest possible multipolarities, say $L$ and $L' = L+1$, of the corresponding transition $\gamma(=\gamma_1$ or $\gamma_2)$ are taken into account, the directional and polarizational distribution coefficients are equal to:

$$A^{\lambda'\lambda''}_{\lambda\ 0}(\gamma) \cong \frac{1}{1+\delta^2(\gamma)} \times \Big\{ F^{\lambda'\lambda''}_{\lambda}(L,L,I_f,I_i)$$
$$+ (1+(-1)^{\lambda'+\lambda''+\lambda})\delta(\gamma) F^{\lambda'\lambda''}_{\lambda}(L,L',I_f,I_i)$$
$$+ \delta^2(\gamma) F^{\lambda'\lambda''}_{\lambda}(L',L',I_f,I_i)\Big\}$$

and

$$A^{\lambda'\lambda''}_{\lambda\,2}(\gamma) \cong \frac{\pi_i\pi_f(-1)^L}{1+\delta^2(\gamma)} \times \Big\{ H_\lambda(L,L)F^{\lambda'\lambda''}_\lambda(L,L,I_f,I_i) - (1+(-1)^{\lambda'+\lambda''})\delta(\gamma)H_\lambda(L,L')F^{\lambda'\lambda''}_\lambda(L,L',I_f,I_i) - \delta^2(\gamma)H_\lambda(L',L')F^{\lambda'\lambda''}_\lambda(L',L',I_f,I_i)\Big\},$$

respectively, where $I_i, \pi_i$ and $I_f, \pi_f$ are initial and final spins and parities for transition $\gamma$, respectively, $\delta(\gamma)$ is the corresponding mixing ratio and

$$H_\lambda(L,L') = \frac{\langle L-1L'-1 \mid \lambda-2\rangle}{\langle L-1L'1 \mid \lambda\, 0\rangle}.$$

Tables of the generalized $F$-coefficients are avaliable in Ref. [4].

Indices $q_1$ and $q_2$ are equal to either 1 or 0 when the polarization of photons $\gamma_1$ or $\gamma_2$ either is or is not observed, respectively. So, in the case of PDCO (which is the acronym of Polarizational Directional Correlation from Oriented Nuclei) discussed below one has either $q_1 = 1, q_2 = 0$ or $q_1 = 0, q_2 = 1$. Indices $q_1 = q_2 = 0$ correspond to the double Directional Correlation from Oriented Nuclei (DCO). The case of $q_1 = q_2 = 1$ corresponds to the correlation between polarization of both quanta (PPCO).

One can consider a case in which polarization and direction of $\gamma_1$ and only direction of $\gamma_2$ are measured. Then the linear polarization of $\gamma_1$ (being in coincidence with $\gamma_2$) is define as follows:

$$P = \frac{W_{1\,0}(\psi_1 = 0°) - W_{1\,0}(\psi_1 = 90°)}{W_{1\,0}(\psi_1 = 0°) + W_{1\,0}(\psi_1 = 90°)}.$$

We have found that the polarization depends strongly (Fig. 3) on a spin sequence, mixing ratios and the angles $\theta_1$,$\theta_2$, and $\phi$=$\phi_1$-$\phi_2$ ( for definition see Fig. 2). One can calculate polarization $P$ *vs.* the DCO ratio for different spin sequences and mixing ratios $\delta$. Contours presented in Fig. 4 show ability to distinguish spin sequence as well as mixing ratio. If ambiguity occurs (*e.g.* the contours do cross each other) similar contours plotted for another geometry can be helpful.

If the intensity of the $\gamma$-ray of interest is weak, to increase the statistics one usually adds the coincidence gates obtained for different position of directional detectors. Then the extracted experimental polarization should be compared with the value calculated using PDCO formula integrated over the detectors. If the statistics is sufficient enough, the investigation of PDCO effect for different experimental geometries gives more information about the transitions what can lead to an unique spin assignment.

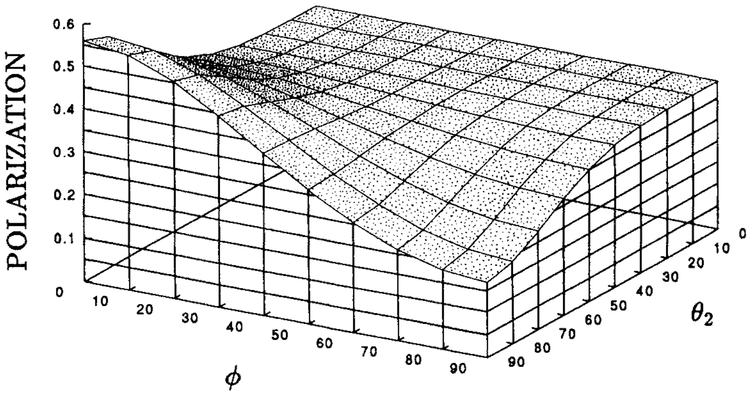


Fig. 3. Polarization $P$ as a function of the directional detector position ($\theta_2$, $\phi$) for the cascade $5 \rightarrow 4 \rightarrow 2$. It is assumed that polarimeter is placed perpendicularly to the beam. The parameter $\sigma/I_0 = 0.3$.

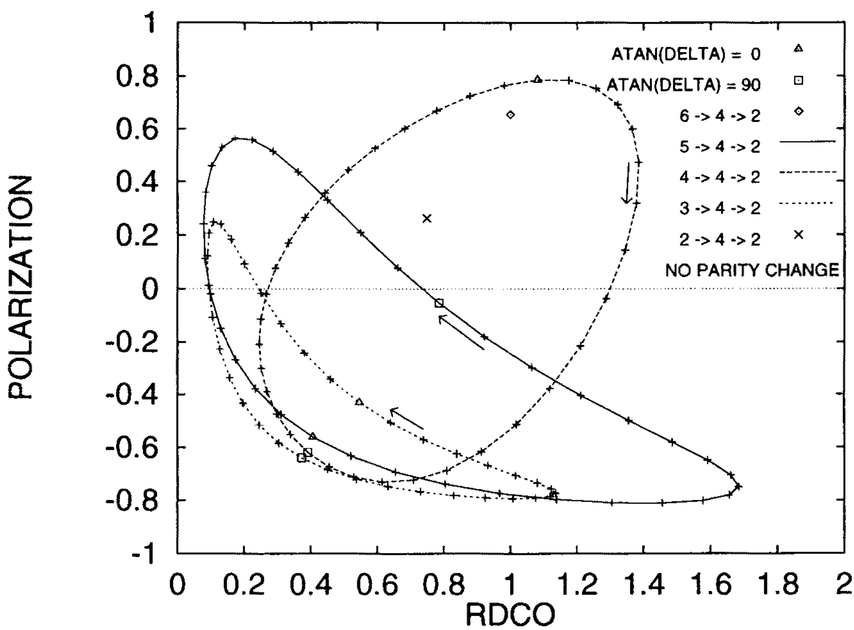


Fig. 4. Contours in the polarization $P$ and DCO ratio plane for different spin sequences and mixing ratios. Squares and triangles on the contour correspond to pure quadrupole and pure dipole radiation respectively. The polarimeter and the directional detector are placed at $\theta_1$=$\theta_2$=90 deg. and $\phi$=0 or 180 deg. The parameter $\sigma/I_0$=0.3 is assumed.

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