NSP13 Symposium
Nuclear Structure Physics with Advanced Gamma–Detector Arrays

Padova, June 10 – 12, 2013

AGATA MODULES AS COMPTON POLARIMETERS FOR MEASUREMENTS OF GAMMA RAY LINEAR POLARIZATION

(*Firenze – Padova – Legnaro Collaboration*)

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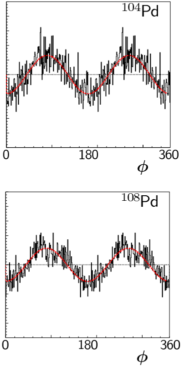
The experiment

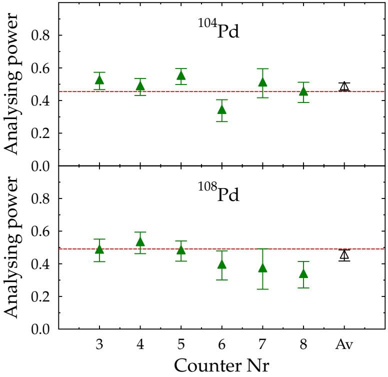
Two AGATA triple clusters, mounted in the AGATA demonstrator at LNL, have been used to detect partially polarized γ rays from CoulEx of ^{104}Pd (555.8 keV) and ^{108}Pd (443.9 keV) by a 32 MeV ^{12}C beam and unpolarized 661 keV γ rays from a ^{137}Cs source.

... and the Results

$A_s \cos 2\phi$
$(C4)$



Azimuthal distribution of Compton Scattering



Experimental and estimated Analysing Power

$$\mathcal{A}_{exp}(i) = \frac{A_s(i)}{\bar{P}(i)}$$

Now, let us see how the results have been obtained

- Experimental and theoretical preliminaries
- Selection criteria
- Data analysis
- Main problems we had to deal with:
  - Uncertainties in the hit position
  - Tracking errors
  - Instrumental asymmetries
  - Unresolved hits

Theoretical preliminaries

Linear polarization of CoulEx γ rays (at angle Θ to the beam):

$P_\gamma(\Theta)$ – Evaluated by means of GOSIA code

Compton cross section

$$\sigma_C(E_\gamma, \theta, \phi) = \sigma_0(E_\gamma, \theta)\,[1 + \mathcal{A}_0(E_\gamma, \theta)\cos 2\phi]$$

Compton analysing power:

$$\mathcal{A}_0(E_\gamma, \theta) = \frac{\sin^2\theta}{E_\gamma/E'_\gamma + E'_\gamma/E_\gamma - \sin^2\theta}$$

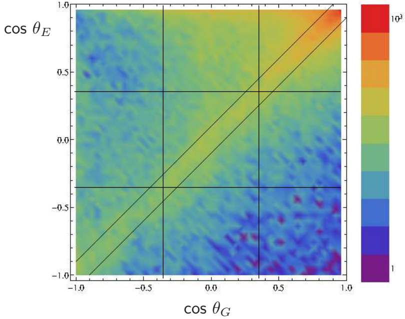
Experimental preliminaries for data analysis

- The pulse-shape analysis of signals from the 36 segments of each Ge crystal provided the coordinates and energy release for each hit. Here, the presence of only 1 hit per segment has been assumed. An improved analysis, able to discard double hits, is under way.
- The standard tracking procedure has been employed to establish the time order of hits. The standard selection criteria used for γ spectroscopy might be not sufficient for the azimuthal angular distribution. Stricter selection criteria have been introduced.

Selection criteria

- Total energy release within $E_\gamma \pm 4$ keV, in one triple cluster.
- Cut on the flight path of the scattered photon:
  $r_{12} > 15$mm
- Cuts on the scattering angle:
  The scattering angle θ can be determined:
  - From the coordinates of the 1st and 2nd hit: $\cos\theta_G = \frac{\vec{r}_1 \cdot \vec{r}_{12}}{r_1 r_{12}}$
  - From the energy released in the 1st hit: $\cos\theta_E = 1 + \frac{m_e c^2}{E_\gamma} - \frac{m_e c^2}{E_\gamma - E_e}$

  We require:
  $|\cos\theta_G| < 0.35$; $|\cos\theta_E| < 0.35$ $|\cos\theta_G - \cos\theta_E| < 0.1$



Correlation plot of $\cos\theta_E$ *vs.* $\cos\theta_G$
Horizontal and vertical lines: $\theta : 70^\circ,\ 110^\circ$

Data analysis

For each event we determine:

- The γ emission angle Θ and the polarization $P_\gamma(\Theta)$
- The flight path r_{12}
- $\cos\theta_G$, $cos\theta_E$ and the error $\Delta^2(\cos\theta_G)$ - *next slide*
- ϕ and its error $\Delta^2(\phi)$ - *next slide*
- The Compton analysing power $A_0(\theta)$

Events have been classified according to the counter where the first interaction took place.

For the population of events which passed the selection criteria, the distributions of the azimuthal angles ϕ have been deduced separately for the different counters.

For the same ensemble, the average values $\bar{P}$ of $P(\Theta)$, $\bar{A}_0$ of $A_0(\theta)$ and $\overline{\Delta^2(\phi)}$ have been detemined.

The average value $\overline{\Delta^2(\cos\theta_G)}$ and the distribution of differences $\delta\cos\theta = \cos\theta_G - \cos\theta_E$ has been evaluated for events which passed all selection criteria apart from $|\cos\theta_G - \cos\theta_E| < 0.1$.

Effects of Errors on the coordinates

We assume

$$\Delta_x^2 = \Delta_y^2 = \Delta_z^2 \approx b/E_e$$

If the tracking of the event is correct (in spite of these errors) one can deduce the statistical uncertainties on the scattering angles:

$$\Delta^2(\phi) = \frac{\Delta_x^2(E_1) + \Delta_x^2(E_2)}{(r_{12}\sin\theta)^2}$$

$$\Delta^2(\cos\theta_G) = \frac{\left[\Delta_x^2(E_1) + \Delta_x^2(E_2)\right]\sin^2\theta}{r_{12}^2}$$

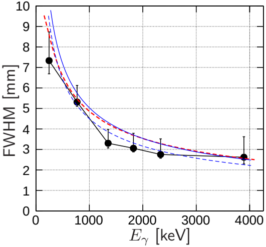
The error on ϕ determines a decrease of the coefficient of $\cos 2\phi$. For a Gaussian distribution of the errors with variance $\Delta^2\phi$, the reduction coefficient is

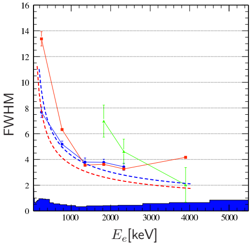
$$F_\Delta = e^{-2\Delta^2(\phi)}$$

... now, how to determine the value of b?

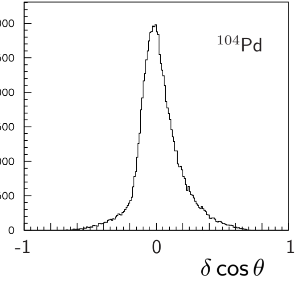
Experimental investigations of errors on hit position

(from S. Akkoyun et al., NIM A 668 (2012) 26; P.A. Söderströ al., NIM A 638 (2011) 96.)





A first approximation has been obtained by a fit of these results...



... but a fine tuning is obtained by comparing the estimate of $\Delta^2(\cos\theta_G)$ determined by the error Δ_x with the variance of the experimental distribution of $\delta\cos\theta = \cos\theta_G - \cos\theta_E$ (the error on $\cos\theta_E$ is negligible).

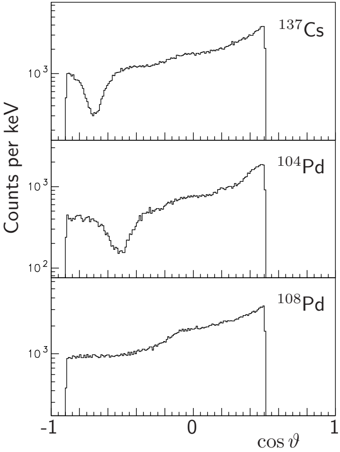
Tracking errors

Tracking errors can result as a consequence of the finite precision in the determination of hit positions.

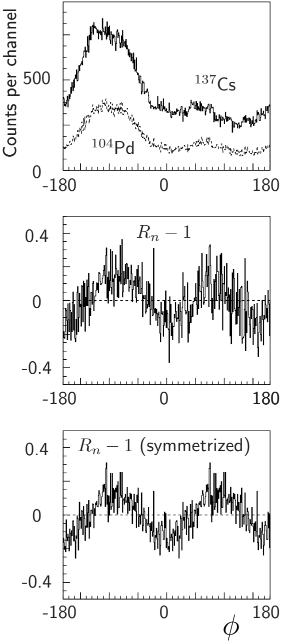
Most of them will be discarded by the strict selection criteria.

Instead, for $E_\gamma > m_e c^2$, the tracking of events consisting of only 2 hits presents an unresolvable ambiguity for a couple of angles θ_1 and $\theta_2 \approx \pi - \theta_1$ such that $E'_\gamma(E_\gamma, \theta_1) = E_\gamma - E'_\gamma(E_\gamma, \theta_2)$.

In the distribution of $\cos\theta$ for ^{137}Cs and ^{104}Pd, a deep minimum at backward angles is apparent. Missing events in this region have been wrongly attributed to the corresponding forward angle.



In our case, these events are eliminated by the cut on $|\cos\theta| < 0.35$.



Instrumental Asymmetries

A typical example (counter C4)

The measured $F(\phi)$ distributions reflect the asymmetric structure of the cluster.

The ratio $R(\phi) = F_{Pd}(\phi)/F_{Cs}(\phi)$ shows the expected dependence on $\cos 2\phi$ but also contains small contributions from odd terms in the Fourier expansion, due to non-compensating edge effects.

To cancel them, we use symmetrized distributions $F_s(\phi) = F(\phi) + F(\pi + \phi)$ to obtain $R(\phi)$. A minimum χ^2 of the normalized ratio $R_n(\phi) = R(\phi)/\bar{R}$ with

$$R_n(\phi) = 1 + A_{exp} \cos 2\phi$$

gives the average asymmetry A_{exp} for Compton scattering events in the counter.

Some more details

To correct for instrumental asymmetries we divide the distribution of ϕ for Compton scattering of CoulEx γ rays by that of ^{137}Cs.

However:

The angular distribution of Compton scattering of ^{137}Cs γ rays is obviously independent of ϕ, but, due to the different E_γ, has a different dependence on θ.

At a given θ, the mean flight path $\lambda = 1/\mu$ of the scattered photon is different, due to the different E'_γ.

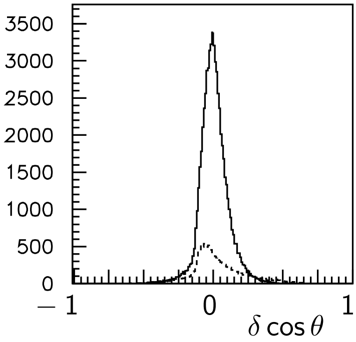
To compensate for these difference, to each event of ^{137}Cs it was assigned a weight

$$w(\theta, r_{12}) = \frac{\sigma_C(E_{\gamma Pd}, \theta)}{\sigma_C(E_{\gamma Cs}, \theta)} \cdot \frac{\left[\mu(E'_{\gamma Pd}) e^{-\mu(E'_{\gamma Pd}) r_{12}}\right]_\theta}{\left[\mu(E'_{\gamma Cs}) e^{-\mu(E'_{\gamma Cs}) r_{12}}\right]_\theta}$$

Unresolved hits

If the 'first-interaction point' consists of two unresolved hits:

- The energy release and the scattering angle do not follow the Compton kinematics.
- The azimuthal angle ϕ keeps (almost) no memory of the initial polarization.
- These events should be (preferably) discarded, or their effect must be estimated by a MonteCarlo simulation.



Example of MonteCarlo simulation for ^{104}Pd, showing the $\delta \cos\theta$ distributions for 'good' events and for unresolved hits. Only a small region around the maximum is accepted by the selection criteria. If the accepted 'wrong' events are a fraction F_{2h} of the total, the expected analysing power is reduced by a factor $1 - F_{2h}$.

Conclusions

- The ability of Agata triple clusters to measure the linear polarization at γ energy around 500 keV is proved.
- Comparison with the azimuthal distribution of unpolarized γ rays is necessary to account for instrumental asymmetries.
- The effect of uncertainties in the hit coordinates is relatively small (< 10 %) and can be kept under control.
- The reduction in analysing power due to the fraction of unresolved hits at the first interaction point is somewhat larger (around 20 %).
  A new analysis to discard these events is under way.
- Good perspective for the analysis of polarization correlation of entangled γ rays from singlet positronium
  (with two triple clusters ad distances from a few cm to 3 m)

The Firenze – Padova – Legnaro Collaboration

P.G. B., P. Sona, C. Michelagnoli, D. Bazzacco, E. Farnea, B. Melon, A.M. Bizzeti-Sona, G. de Angelis, A. Gadea, A. Gottardo, S. Lunardi, S.M. Lenzi, R. Menegazzo, D. Mengoni, A. Nannini, D.R. Napoli, A. Perego, F. Recchia, E. Sahin, J.J. Valiente–Dobon, C.A. Ur, R. Livi, P. Verrucchi

I am pleased to thank all collaborators
and the Technical staff of LNL.
I particularly dedicate this work to the memory
of our colleague, collaborator and friend
Enrico Farnea