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Setup to study the Compton scattering of entangled annihilation photons

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Abstract. The experimental setup to study the difference between Compton scattering of entangled and decoherent annihilation photons is discussed. The pairs of entangled gammas are born in electron-positron annihilation at rest. The polarization state of each photon in such a pair is not definite and represents the superposition of horizontal and vertical polarizations, while the relative polarizations of the photons are orthogonal. After interaction with the environment (for example, via the Compton scattering) the entangled pair of photons is broken and the pair becomes decoherent with determined polarizations of both gammas. Since the Compton scattering depends on the polarization of the initial photon, the scattering kinematics of entangled and decoherent photons might be quite different. At present, there is no experimental comparison of the Compton scattering kinematics for entangled and decoherent gammas.

1. Introduction

The experimental setup to study the difference between Compton scattering of entangled and decoherent annihilation photons has been designed and constructed at Institute for Nuclear Research (INR), Moscow. Theoretical works dedicated to the topic provide contradictory results, see [1] and [2]. In the first article the calculated scattering kinematics of pairs of entangled or decoherent photons turned out to be the same for both types. Namely, the photons are scattered predominantly at the right azimuthal angles, reflecting the orthogonality of the gamma polarizations. On the contrary, according to the calculations in the second article, the Compton scattering of pair of decoherent photons has no correlation in azimuthal angle. The resolution of this contradiction is important for two reasons: to understand the behavior of entangled and decoherent quantum states at a fundamental level, and for the possible application of the quantum entanglement in positron tomography [2].

2. Design of the experimental setup

The setup (figure 1) consists of two arms, each containing a main scatterer (plastic scintillator) and 16 NaI(Tl) detectors with PMT readout around the scatterer. The angle between two neighbour NaI(Tl) detectors is $\pi/8$. Any two orthogonally positioned NaI(Tl) detectors and the main scatterer of the same arm form a Compton polarimeter. Therefore, each arm consists of 16 Compton polarimeters.

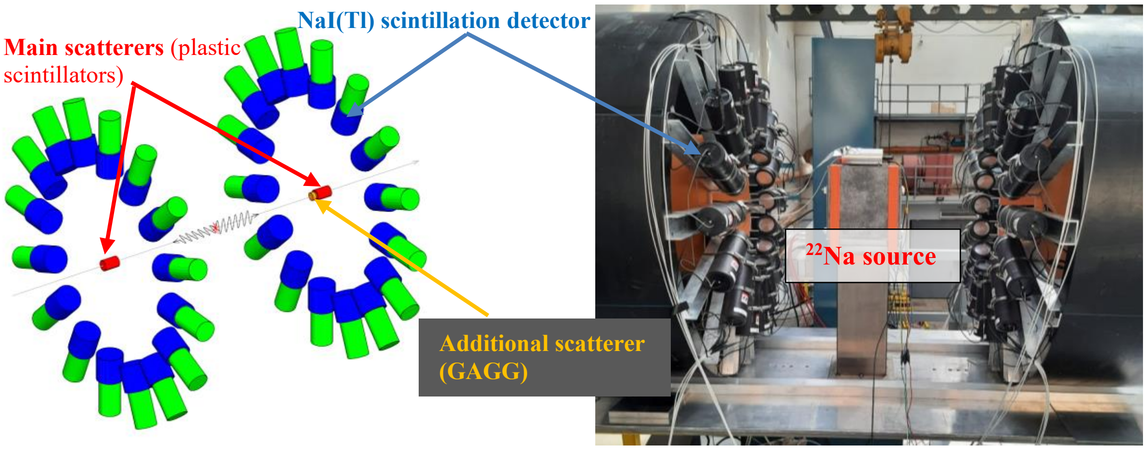


Figure 1. The scheme (left) and photo (right) of the experimental setup.

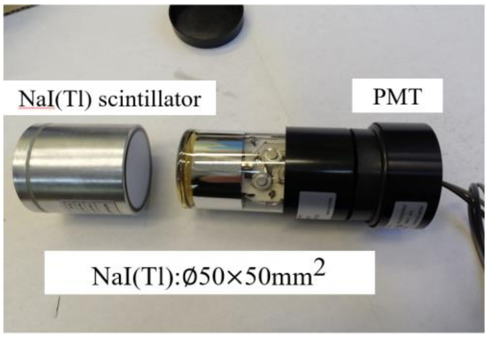
An additional scatterer of 7 mm thick GAGG (Gadolinium Aluminium Gallium Garnet) scintillator with SiPM readout is adjacent to left arm to produce pairs of decoherent gammas. High light yield of this scintillator allows detection of recoil electrons with energies starting from few keVs.

The ^{22}Na source of positrons with activity ~50 MBq is contained in 1 mm thick aluminium absorber placed into cubic 20x20x20 cm^3 lead collimator with a 5 mm diameter hole for the beam of annihilated gammas. ^{22}Na-source is placed closer to left arm with additional scatterer in order to carry out two measurements simultaneously: the analysed pair of photons is decoherent, if there was interaction in additional scatterer prior the interactions in main scatterers. Otherwise, the measured pair of photons is entangled.

Azimuthal symmetry of the setup provides a high acceptance for scattered gammas, which is necessary for the study of decoherent quantum states. In addition, since each NaI(Tl) detector is a part of several Compton polarimeters and analyses the gamma polarization in different directions the azimuthal symmetry compensates the systematic errors caused by possible non-ideal positions of the scintillation counters relative to the setup axis.

3. Parameters of scintillation detectors

The basic elements of the experimental setup are the main scatterers and the NaI(Tl) scintillation detectors. Energy calibration of NaI(Tl) detectors (figure 2, left) was carried out using a ^{22}Na-source of annihilation photons. Typical ^{22}Na spectrum in the detector is shown in figure 2, right. The peak position and energy resolution, which corresponds to the energy deposition of 511 keV can be determined using Gaussian fit.



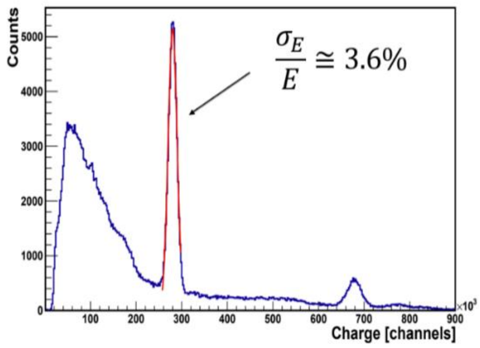


Figure 2. Left – NaI(Tl) detector and Hamamatsu R6231 PMT during assembling. Right – ^{22}Na amplitude spectrum in one of NaI(Tl) detectors. The fitted peak corresponds to 511 keV, right peak corresponds to 1275 keV gamma energy.

The main scatterers are the 20x30 mm^2 cylinders of polystyrene-based scintillator with PMT readout. The initial energy calibration of the scatterers was performed using right cut-off of the Compton spectrum from ^{137}Cs source. Finally, the scatterers were calibrated by selecting the events with the 90^0 scattering angle of annihilation gammas (see figure 4 below).

All signals of scintillation detectors were digitized by pipe-line ADC with 16 ns sampling rate. To exclude the accidental events, coincidence in time of two gammas in opposite arms is necessary. Time of signal was calculated as the average time of waveform (figure 3, left): $t_{signal}=\sum a_i t_i / \sum a_i$. Here, only waveform points higher than 10% of maximum amplitude were taken into account. Time resolution is explicitly determined by sampling rate of ADC.

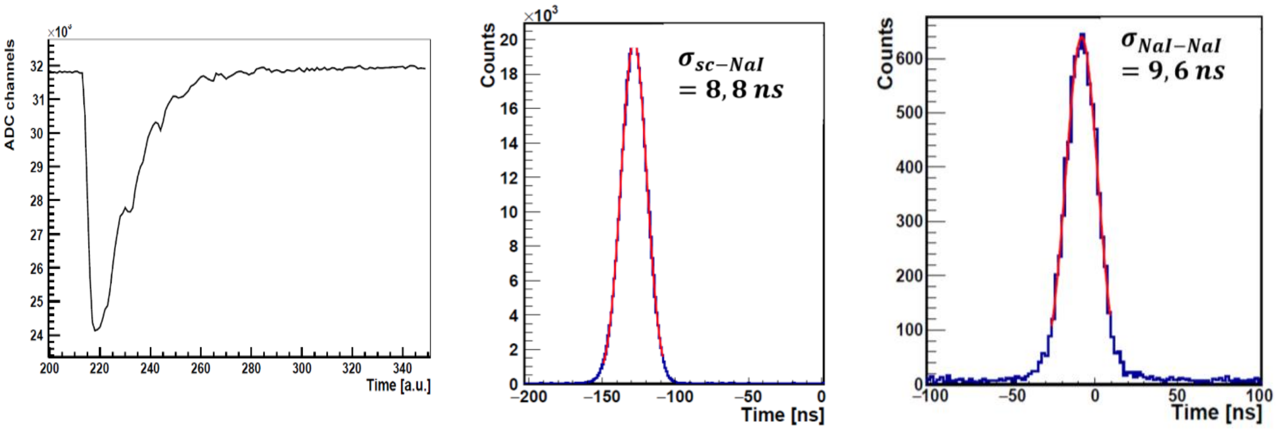


Figure 3. Left – ADC signal waveform for NaI(Tl) detector. Center – time spectrum between main scatterer and one of the NaI(Tl) scintillation detectors. Right – time spectrum between two NaI(Tl) scintillation detectors of the opposite arms of the setup.

4. Energy spectra in detectors for entangled photons

The trigger for data acquisition requires coincidence of gamma interactions in both main scatterers regardless of their subsequent detection in NaI(Tl) scintillators. Therefore, only a small percentage of recorded events has signals in NaI(Tl). According to kinematics of Compton scattering at 90^0, the energy depositions of annihilation photon in main scatterers and in NaI(Tl) detectors are 250 keV and 260 keV, respectively. These numbers were used for the cross-check of the detector's energy calibrations during the data acquisition.

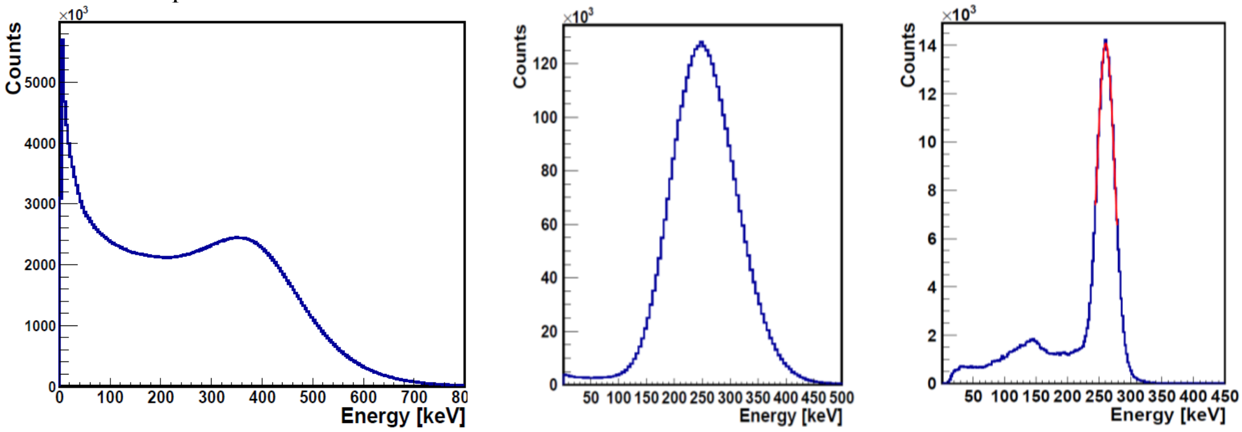


Figure 4. Left – energy spectra in one of the main scatterers for all recorded events. Center – energy spectra in main scatterers if scattered photon is detected in NaI(Tl) scintillator. Right – energy spectrum in NaI(Tl) detector.

In figure 4, left the energy spectrum in main scatterer is presented regardless of the detection of gamma in NaI(Tl). If scattered photons are registered by NaI(Tl) scintillators the obtained energy spectrum in main scatterer is shown in center of figure 4. Here, the time coincidences between main scatterer and NaI detectors and between main scatterers was applied. The peak corresponds to energy deposition of 250 keV. The right spectrum in figure 4 shows energy deposition in NaI(Tl) scintillation detector. The dominant peak is a photo-peak of full gamma absorption in NaI(Tl) for the scattering angles in range $90^0 \pm 7^0$ that corresponds to the geometrical acceptance of a single NaI(Tl) detector.

5. Angular distributions of scattered pairs of entangled and decoherent gammas

According to the theoretical calculations in [1], [2] for double differential cross-section of Compton scattering of entangled photons, the dependence of probability of registering the pair with scattering angles θ_1, θ_2 by the detectors with azimuthal angles ϕ_1, ϕ_2 is:

$$P_{12}\left(\theta_1, \theta_2, \phi = \phi_2 - \phi_1\right) \sim 1 - \alpha(\theta_1)\alpha(\theta_2)\cos(2\phi)$$

Here, $\alpha(\theta_i)$ are coefficients equal to the analysing power of corresponding Compton polarimeter. Therefore, the number of detected pairs is described by the formula $N(\phi) = A + B \cdot \cos(2\phi)$. The preliminary results for the number of registered gamma pairs by NaI(Tl) scintillation detectors are shown in figure 5 for pairs of entangled and decoherent gammas. The pair of photons is identified as decoherent one if non-zero energy was deposited in additional scatterer within the true coincidence time window. Measured ratio of maximum/minimum numbers of entangled gammas $R_{experiment}\,(\theta = 90^0) = 2.51 \pm 0.05$ is close to the theoretical $R_{theory}\,(\theta = 90^0) = 2.6$ [2][3]. The same ratio for decoherent gammas is $R_{decoherent}\,(\theta = 90^0) = 2.09 \pm 0.15$. In the latter case, the polarization vectors of photons are not orthogonal to the axis of setup as the photons after interaction in an additional scatterer have the scattering angles up to 40^0 that reduces the observed azimuthal asymmetry of detected photons.

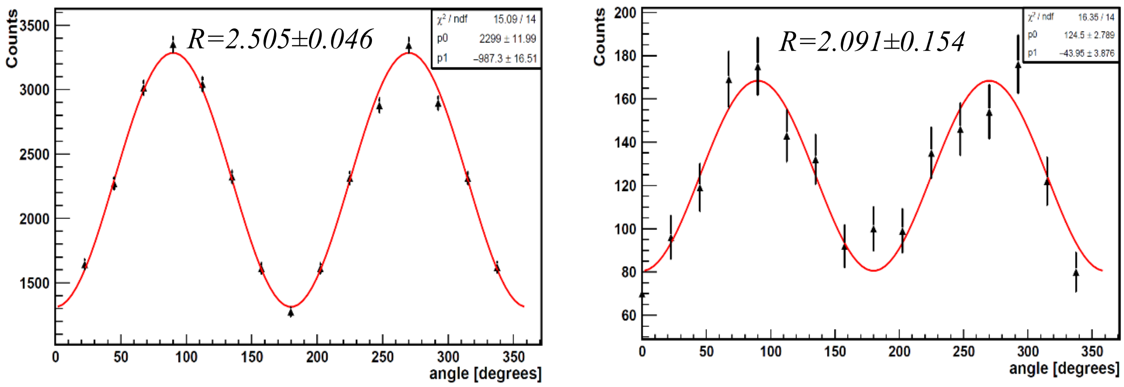


Figure 5. The dependence of number of scattered gamma's pairs on their relative azimuthal angle for initially entangled (left) and decoherent (right) gammas. Error bars are statistical only. Red lines correspond to the fit function $A + B \cdot cos(2\phi)$. R is ratio of maximum/minimum counts.

6. Conclusion

The experimental setup was constructed to study Compton scattering of entangled and decoherent photons in different polarization states. For the first time, the decoherent pairs of annihilation gammas were investigated due to presence of an additional active scatterer that identifies the decoherence of photons. Azimuthal asymmetry in number of scattered gammas is rather similar for both entangled and decoherent states.

References

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