Setup to study the Compton scattering of entangled annihilation photons

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This work is devoted to the study of Compton scattering of gammas in different polarization states. The pairs of entangled gammas are born in electron-positron annihilation at rest. The polarization state of each photon in such 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 two-photon state is converted into decoherent one with the definite 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. At the same time, the theoretical works dedicated to the discussed topic provide contradictory results [1,2]. The experimental setup is constructed in Institute for Nuclear Research, Moscow (***Fig.1***) to measure the difference in Compton scattering of gammas in different polarization states.

Experimental Setup

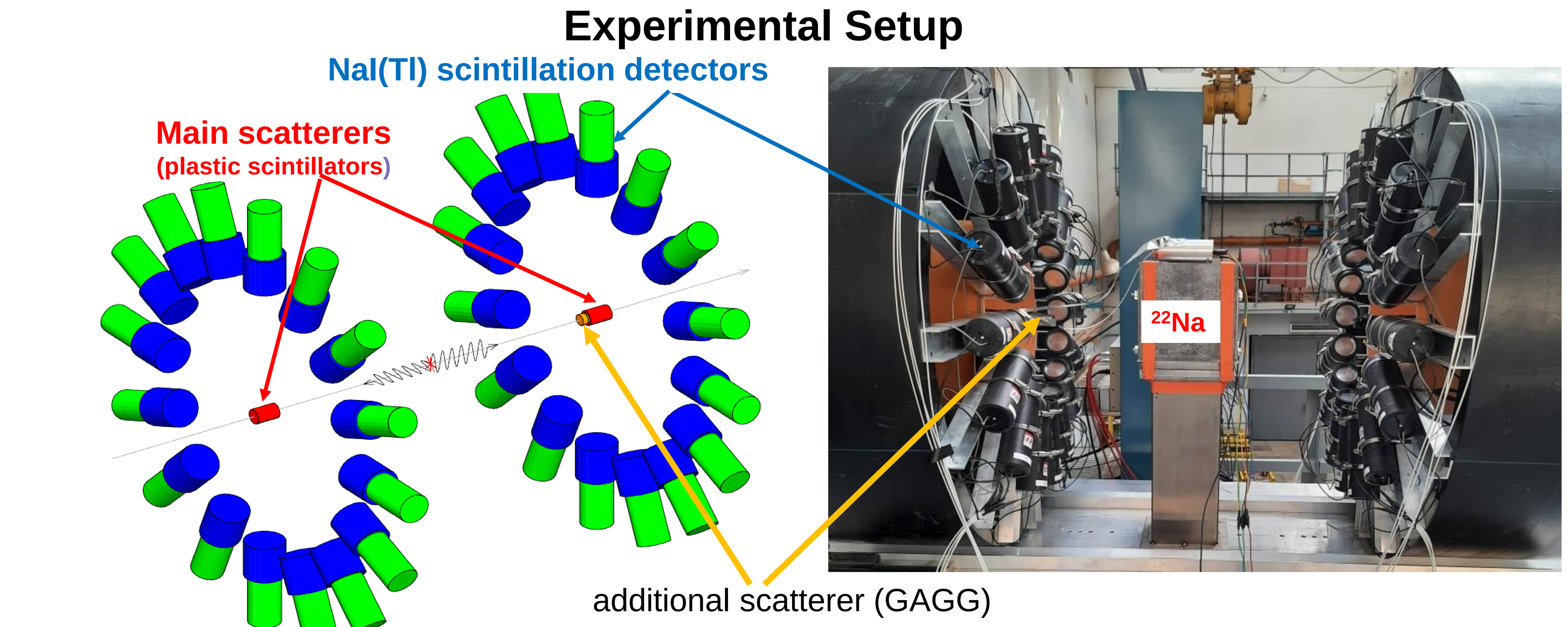

Fig.1 **The experimental setup scheme (left) and photo (right).**

The assembled setup consists of two arms, each containing a plastic scatterer and 16 NaI(Tl) scintillation detectors (***Fig.2(left)***) with PMT readout. The angle between two neighbor NaI(Tl) detectors is $\frac{\pi}{8}$. Any two orthogonally positioned NaI(Tl) detectors and the main scatterer of the same arm form a Compton polarimeters with an analyzing power

$$\alpha(\theta) = \frac{\sin^2\theta}{\frac{E_{\gamma_1}}{E_\gamma} + \frac{E_\gamma}{E_{\gamma_1}} - \sin^2\theta}, \text{where } E_{\gamma(\gamma_1)} - \text{energy of incident (scattered) } \gamma;\ \theta - \text{scattering angle}.$$

Therefore, each arm consists of 16 Compton polarimeters.

The ^{22}Na source of positrons with activity $\sim 50\,MBq$ is contained in 1 mm thick aluminum absorber placed into cubical 20x20x20 cm^2 lead collimator with 5 mm diameter hole for the beam of annihilated gammas.

Energy calibration of NaI(Tl) detectors was carried out using a ^{22}Na-source. Typical ^{22}Na spectrum in the detector is shown in ***Fig.2(right)***. The peak position and energy resolution, which corresponds to energy deposition of 511 keV can be determined.

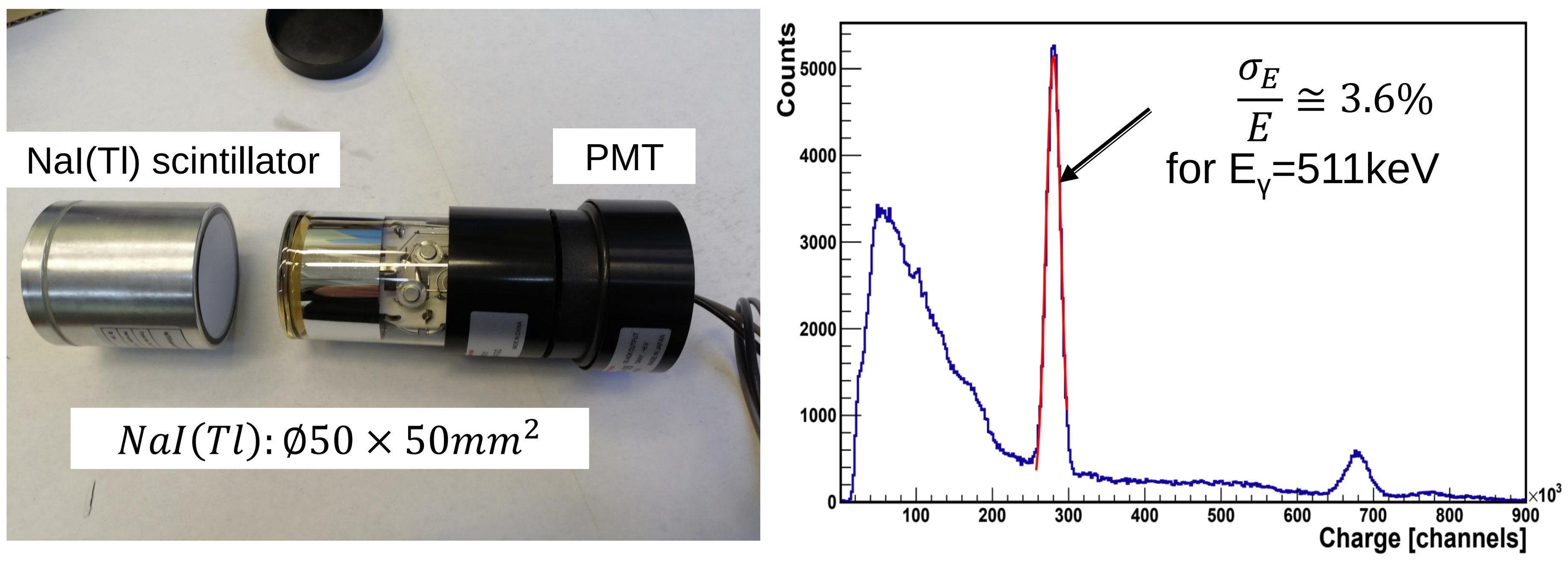

Fig.2 **A scintillatioln detector (left) that comprises NaI(Tl) scintillator and PMT (Hamamatsu PMT R6231) and typical ^{22}Na spectrum in one of NaI(Tl) scintillation detectors (right).**

An additional small scatterer of GAGG scintillator (**Fig.3**) with SiPM readout is placed in one arm to produce the pairs of decoherent gammas. High light yield of this scintillator allows the detection of recoil electrons with energies starting from a few keV. ^{22}Na-source of entangled annihilation gammas is placed closer to arm with additional scatterer in order to carry out two measurements simultaneously: the detected 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.

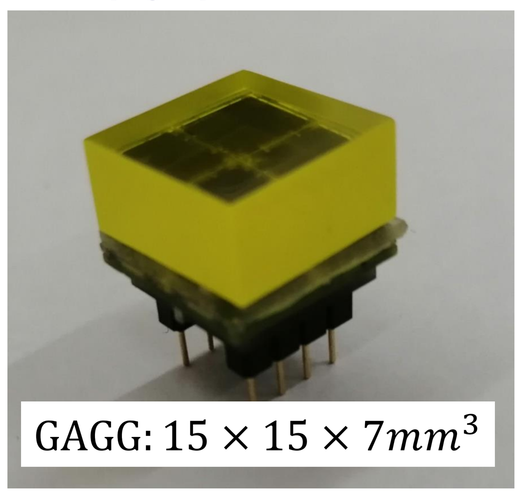

Fig.3 **GAGG detector (additional scatterer)**

Time spectra for entangled gammas in scintillation detectors

All signals were digitized by pipe-line ADC with timestamp 16 ns. Time of signal was calculated as the average time of waveform (***Fig.4***): $t_{signal} = \frac{\sum a_i t_i}{\sum a_i}$. Here, only waveform points with amplitude higher than $0.1 \cdot A_{Max}$ are taken into account. The obtained time resolution of NaI(Tl) scintillation detectors is explicitly determined by ADC timestamp value.

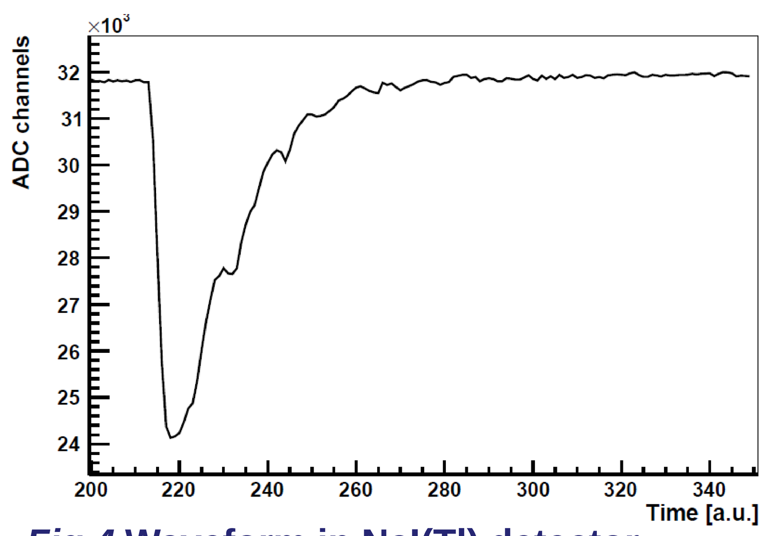

Fig.4 **Waveform in NaI(Tl) detector.**

The histogram in ***Fig. 5, left*** shows the difference in times when gamma interacts in the main scatterer and absorbed in one of NaI(Tl) scintillators of the same arm.

Fig. 5, right spectrum illustrates difference in times of scattered gammas detected by two NaI(Tl) detectors of different arms.

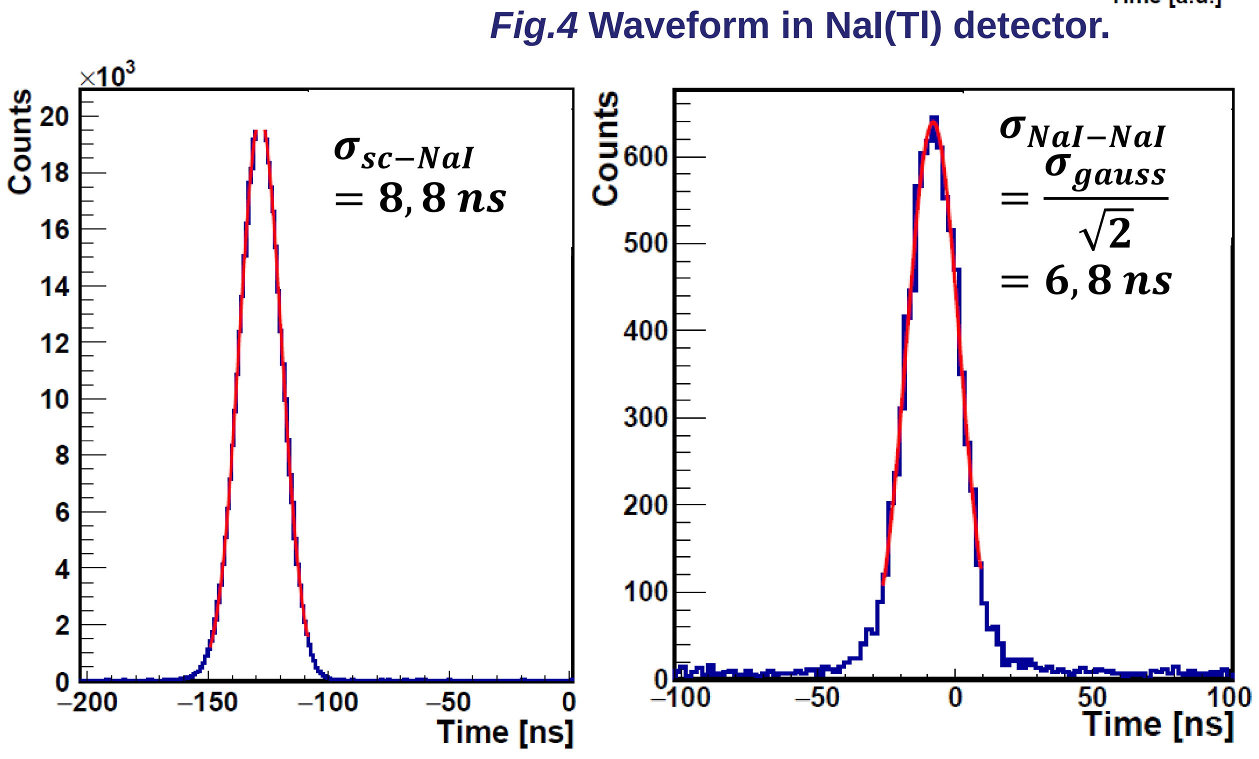

Fig.5 Time spectra for different combinations of scintillation counters.

Amplitude spectra for entangled gammas

According to kinematics of Compton scattering at 90^0, the energy deposition of annihilation photon in main scatterer is 250 keV and in NaI(Tl) detector is 260 keV. These numbers were used for the energy calibration of experimental setup.

In ***Fig. 6 (left)*** a energy spectrum in main scatterer is presented regardless of the detection of gamma in NaI(Tl). In case of detection of scattered gamma in one of NaI(Tl) scintillators, the obtained energy spectrum in main scatterer is shown in **Fig.6, *center***. Here, the time coincidence between main scatterer and NaI detectors was applied. The peak corresponds to energy deposition of 250 keV.

The spectrum in ***Fig. 6, right*** shows typical energy deposition in NaI(Tl) scintillation detector. The largest is a photo-peak of gamma absorption in NaI(Tl) for the scattering angles $90^0 \pm 7^0$ corresponding to the geometrical acceptance of a single NaI(Tl) detector.

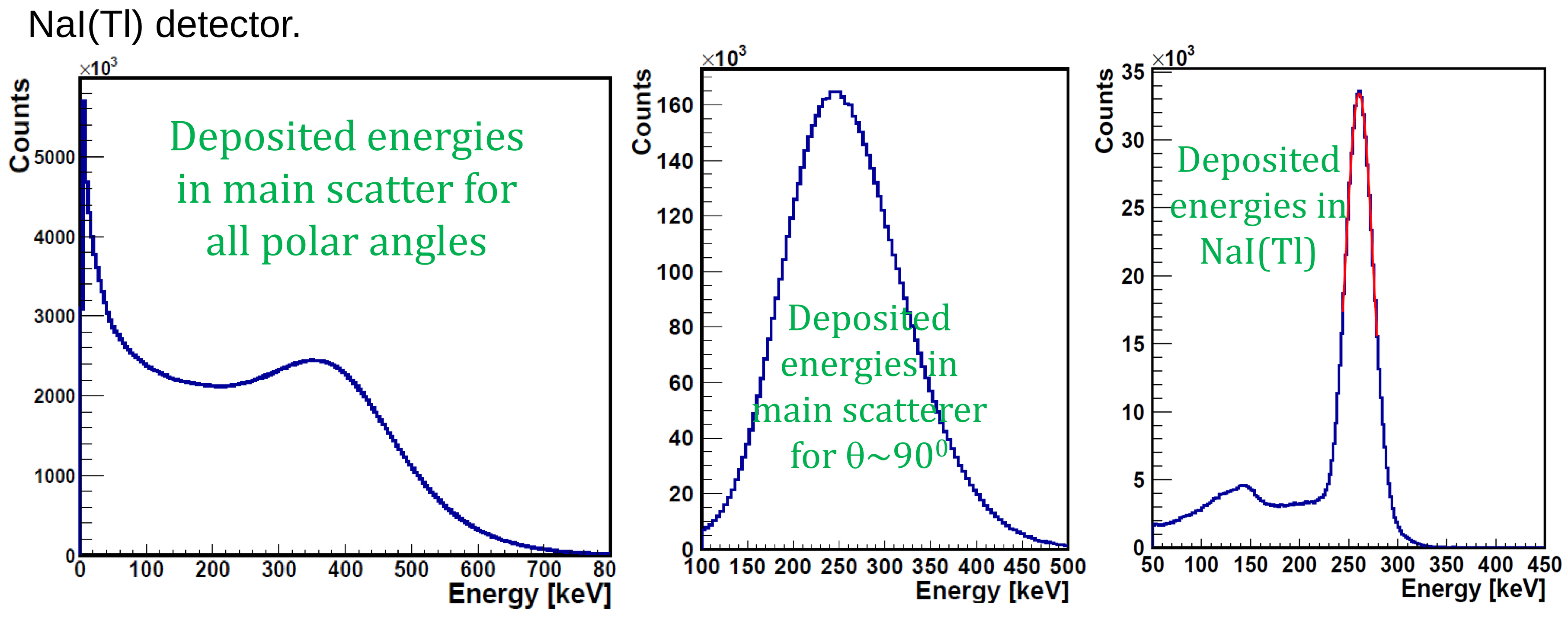

Fig.6 **Energy spectra in the main scatterers (left), in the same scatterer if scattered gammas are registered by NaI(Tl) detector (center) and in one of the NaI(Tl) detectors (right).**

Asymmetry in Compton scattering of entangled and decoherent gammas

According to [3], one can get the following dependence of probability of registering the pair photons with scattering angles $\boldsymbol{\theta_1, \theta_2}$ by the detectors in different arms with angles $\boldsymbol{\phi_1, \phi_2}$: $\boldsymbol{P_{12}(\theta_1, \theta_2, \phi = \phi_2 - \phi_1) \sim 1 - \alpha(\theta_1)\alpha(\theta_2)\cos(2\phi)}$

Here, $\alpha(\theta)$ is the analyzing power of Compton polarimeter. Therefore, the number of registered pairs of scattered entangled annihilation gammas is described by the formula $\boldsymbol{N(\phi) = A + B \cdot \cos(2\phi)}$.

The preliminary results for the number of detected gammas in NaI(Tl) detectors are shown in the ***Fig.7*** for entangled (***left***) and decoherent (***right***) gamma pairs. Pairs of scattered gamma are identified as decoherent if the non-zero energy was deposited in additional scatterer within the true coincidence time window. The $N(\phi)$ experimental dependence for entangled gammas is in agreement with theoretical predictions (red fitting line in Fig.7, left).

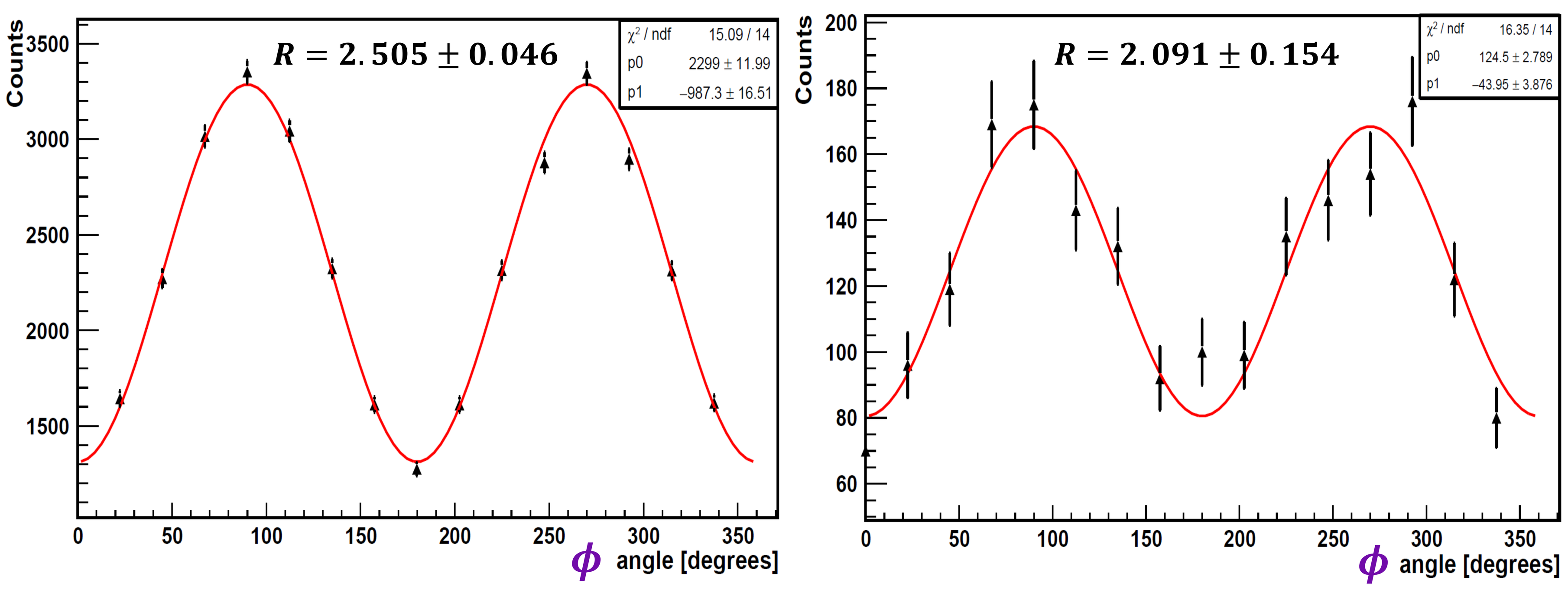

Fig.7 **(Preliminary) Dependence of number of scattered annihilation gammas simultaneously registered by two NaI(Tl) detectors on the azimuthal angle between these detectors for entangled (left) and decoherent (right) gammas.**

Conclusion

Experimental setup is constructed to study the scattering of entangled and decoherent gammas in different polarization states. It consists of two arms, each comprising 16 Compton polarimeters. Azimuthal symmetry of the setup compensates the systematic errors caused by non-ideal positions of the scintillation counters relatively the setup axis.

Measured ratio of Max/Min numbers of entangled gammas $\boldsymbol{R_{experiment}(\theta = 90^0) = 2.51 \pm 0.05}$ corresponds to the theoretical prediction $\boldsymbol{R_{theory}(\theta = 90^0) = 2.6}$.

Measured ratio for decoherent gammas is $\boldsymbol{R_{decoherent}(\theta = 90^0) = 2.09 \pm 0.15}$. In the last case the polarization vectors of decoherent photons is not orthogonal to the setup axis as the photons after interaction in additional (GAGG) scatterer have the scattering angles within 36^0 respective the setup axis.

References

1. **Hiesmayr, B.C., Moskal, P. Witnessing Entanglement In Compton Scattering Processes Via Mutually Unbiased Bases. Sci Rep 9, 8166 (2019).**
2. **Peter Caradonna *et al*, 2019 J. Phys. Commun. 3 105005**
3. **PRYCE, M., WARD, J. Angular Correlation Effects with Annihilation Radiation. Nature 160, 435 (1947).**