CHECK OF THE STRUCTURE IN PHOTON PAIRS SPECTRA AT THE INVARIANT MASS OF ABOUT 17 MeV/c^2*

Kh.U. Abraamyan

International Center for Advanced Studies, YSU, 0025, Yerevan, Armenia

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The results of an analysis of the invariant mass spectra of photon pairs produced in dC, pC, and dCu interactions at momenta of 2.75, 5.5, and 3.83 GeV/c per nucleon respectively, are presented. Signals in the form of enhanced structures at invariant masses of about 17 and 38 MeV/c^2 are observed. The results of testing the observed signals, including the results of the Monte Carlo simulation are presented. The test results support the conclusion that the observed signals are the consequence of detection of the particles with masses of about 17 and 38 MeV/c^2 decaying into a pair of photons.

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1. Introduction

A series of experiments on the production of photon pairs in the interactions of protons, deuterons, and alpha particles with nuclei was carried out on the internal beams of the Nuclotron at JINR. The experiments were performed on a multichannel two-arm gamma spectrometer of the SPHERE setup (the PHOTON-2 setup). The results of the first analysis on the production of η-mesons (selection of photons from different arms of the spectrometer) have been published in [1].

At the suggestion of van Beveren and Rupp [2], the spectra of photon pairs in the region of invariant masses around 38 MeV/c^2 were analyzed in order to search for the E38 boson. The results of this analysis (photons from the same spectrometer arm) are published in [3].

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In recent experiments at the Institute for Nuclear Research (ATOMKI) [4], an anomalous correlation between the opening angles and the total energies of e^+e^- pairs was observed at the invariant mass of the pairs of about 17 MeV/c^2, which can be interpreted as the result of production and decay of a light boson, called the $X17$ particle.

This anomaly is currently being widely discussed [5]. Various models are proposed that attempt to describe the observed anomaly at 17 MeV/c^2: the search for new physics (the fifth-force interpretation) [6]; an axion [7]; resonant production mechanism [8]; calculations in the frame of effective field theories [9]; a model for different EM transitions and interferences [10]; calculations of particle masses in the open-string model in two-dimensional quantum chromodynamics and quantum electrodynamics model [11–13] and in the flux tube model [14]; an attempt to find AU(1)' solution to the 17 MeV anomaly [15]. In particular, in [13] and in an earlier work [12], it is proposed that a light quark and a light antiquark may be bound and confined by the QED interaction as a neutral isoscalar boson at 17 MeV and a neutral isovector boson at 38 MeV, with the QED $q\widetilde{q}$ isoscalar composite as a possible candidate for the $X17$ boson.

In view of the above many possibilities, it is of great importance to search for possible particles in this region. A very good method to produce these anomalous particles is by relativistic nucleus–nucleus collisions, including proton collisions because the anomalous particles will likely involve quarks and antiquarks. The search effort can be readily facilitated by studying the diphoton decay products of such particles, as it has been demonstrated in our previous work with apparatus on the successful production and detection of π^0 and η mesons. For this anomalous region, it is important to confirm the observation of the $X17$ particle using very different techniques and apparatus.

In our experiments, we measured both the energies and the coordinates of the photons and thus measured the invariant mass of photon pairs. The collected statistics made it possible to obtain, after the background subtraction, statistically significant signals in the range of invariant masses both about 17 and 38 MeV/c^2.

2. Experiment

2.1. General layout

The data acquisition of production of neutral mesons and γ-quanta in interactions of protons and light nuclei with nuclei has been carried out with internal beams of the JINR Nuclotron [1]. The experiments were conducted with internal proton beams at the momentum 5.5 GeV/c incident on a carbon target and with ^{2}H, ^{4}He beams, and internal C-, Al-, Cu-, W-, Au-targets at momenta from 1.7 to 3.8 GeV/c per nucleon. For the first analysis, the data for the $d(2.0\,A\text{ GeV}) + \text{C}$, $d(3.0\,A\text{ GeV}) + \text{Cu}$, and $p(4.6\text{ GeV}) + \text{C}$ reactions were selected. Some results on $\gamma\gamma$ pair production in these reactions, for the effective mass region, $M_{\gamma\gamma} > 100\text{ MeV}/c^2$ (photons in a pair from different arms of the spectrometer) were reported in [1].

Typical proton and deuteron fluxes were of about 10^8 and 10^9 per pulse respectively. The electromagnetic lead glass calorimeter PHOTON-2 was used to measure both the energies and emission angles of photons. The experimental instrumentation is schematically presented in Fig. 1.

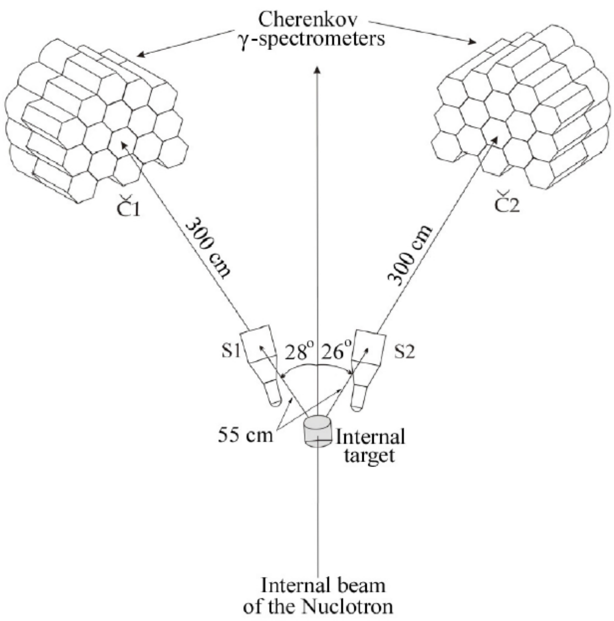

Fig. 1. The schematic drawing of the experimental PHOTON-2 setup. The S1 and S2 are scintillation counters.

The PHOTON-2 setup includes 32 γ-spectrometers of lead glass and scintillation counters S1 and S2 of $2 \times 15 \times 15\text{ cm}^3$ used in front of the lead glass for the charged particle detection [16].

The center of the front surfaces of the lead glass hodoscopes is located 300 cm from the target and at angles of 25.6° and 28.5° with respect to the beam direction. This gives a solid angle of 0.094 sr (0.047 sr for each arm). The internal target consists of carbon wires with the diameter of 8 microns, or a copper wire with the diameter of 50 microns mounted in a rotatable frame. The overall construction is located in the vacuum shell of the accelerator.

Prior the experiment, the energy calibration of the lead glass counters has been carried out with 1.5 GeV/c per nucleon deuteron beam at the JINR Synchrophasotron [17]. The long-term gain stability was continuously monitored for each of the lead glass modules with 32 NaI(Tl) crystals doped with ^{241}Am sources.

The modules of the γ-spectrometer are assembled into two arms of 16 units. The modules in each arm are divided into two groups of 8 units. The output signals of each group from 8 counters are summed up linearly and sent to the inputs of four discriminators (D_i). In these experiments, the discriminator thresholds were at the level of 0.4 GeV for the $p+\mathrm{C}$ and $d+\mathrm{C}$ reactions and 0.35 GeV for the $d+\mathrm{Cu}$ reaction. Triggering takes place when there is a coincidence of signals from two or more groups from different arms

$$(D_1 + D_2) \times (D_3 + D_4) \tag{1}$$

in the $p+\mathrm{C}$ and $d+\mathrm{C}$ experiments and with the additional requirement of anticoincidence with the signals from the scintillation counters in the $d+\mathrm{Cu}$ experiment:

$$(D_1 + D_2) \times (D_3 + D_4) \times \overline{S1} \times \overline{S2}\,. \tag{2}$$

In realizing the trigger conditions, the amplitudes of all 32 modules were recorded on a disc. The dead time of data acquisition is about 150 μs per trigger. The duration of the irradiation cycle is 1 s.

The data presented were collected in experiments to study the production of the η-meson, so a coincidence of both arms of the spectrometer was required for triggering. At the request of [18], we analyzed the recorded data for an excess above the background of coincidences in a single arm of the spectrometer. The requirement of coincidence of both arms reduced the detection efficiency for this purpose (to about 2×10^{-7}), but due to the high collected statistics (about 2×10^{12} $d+\mathrm{C}$ interactions, 10^{11} $p+\mathrm{C}$ interactions, and 0.8×10^{12} $d+\mathrm{Cu}$ interactions), it was possible to observe a significant excess.

2.2. Event selection

Photons in the detector are recognized as isolated and confined clusters (an area of adjacent modules with a signal above the threshold) in the electromagnetic calorimeter. The photon energy is calculated from the energy of the cluster. Cluster characteristics were tested by comparison with the Monte Carlo simulations of electron–photon showers in Cherenkov counters by means of the program package EMCASR [19]. The results obtained earlier with extracted ion beams of the JINR Synchrophasotron have demonstrated a good agreement between experimental and simulated data [20]. Assuming that the photon originates from the target, its direction is determined from the geometrical positions of constituent modules weighted with the corresponding energy deposit in activated modules.

After an analysis of the individual modules and the exclusion of some modules because of their poor performance (6 modules in the left arm and one module in the right arm of the spectrometer were excluded), the data were processed by an event reconstruction program and were recorded on DST. As a result, about 2.8×10^6 events were recorded in the three experiments considered under the following condition: the number N_γ of detected photons in an event with energy $E_\gamma > 50$ MeV is $N_\gamma \geq 2$, such that there are 1 or more photons in each arm [1].

To search for a signal at the low effective masses, we have analyzed photon pairs detected in the same arm of the γ-spectrometer. Below are the results of this analysis for photon pairs detected in the right arm of the γ-spectrometer (situated at an angle of 26°, see Fig. 1).

In order to identify the signal from detected particles, all photon pair combinations are used to calculate the invariant mass in each event.

To see a possible structure of the invariant mass spectra, a background should be subtracted. The so-called event mixing method was used to estimate the combinatorial background: a photon in one event from a group of modules is combined with a photon in other events from the same group. In the mixing, there are involved events in which there are two or more photons in the group satisfying the selection criteria. This background was subtracted from the invariant mass distributions (see bottom panels in Fig. 2).

2.3. Optimal conditions for X17

In order to study the region of small invariant masses, we processed the data obtained in groups not participating in the trigger launch (thanks to the logical addition (see Eqs. (1), (2)), there are such groups in each event). To collect sufficient statistics, we processed the data obtained in several experiments.

Figure 2 shows the invariant mass distributions of $\gamma\gamma$ pairs under optimal conditions for searching for a particle with a mass of 17 MeV/c^2:

(i) the number of detected photons in the group, $N_\gamma = 2$;

(ii) the minimal energy of photons, $E_{\gamma\min} = 40$ MeV;

(iii) the sum of the energies of photons in a pair, $E_{12} > 250$ MeV (effective detection of pairs at the setup geometry);

(iv) the ratio of the energies $E_{\gamma1}/E_{\gamma2} < 0.4$ (suppresses systematic errors due to violation of the energy-momentum conservation laws at the event mixing);

(v) the opening angles of photons in a pair, $\Theta_{\gamma\gamma} > 7°$.

Figure 2 shows the sum of data for two groups that did not participate in the event triggering (after logical addition). Thus, the energy in the specified group could be arbitrary (without the influence of the discriminator thresholds).

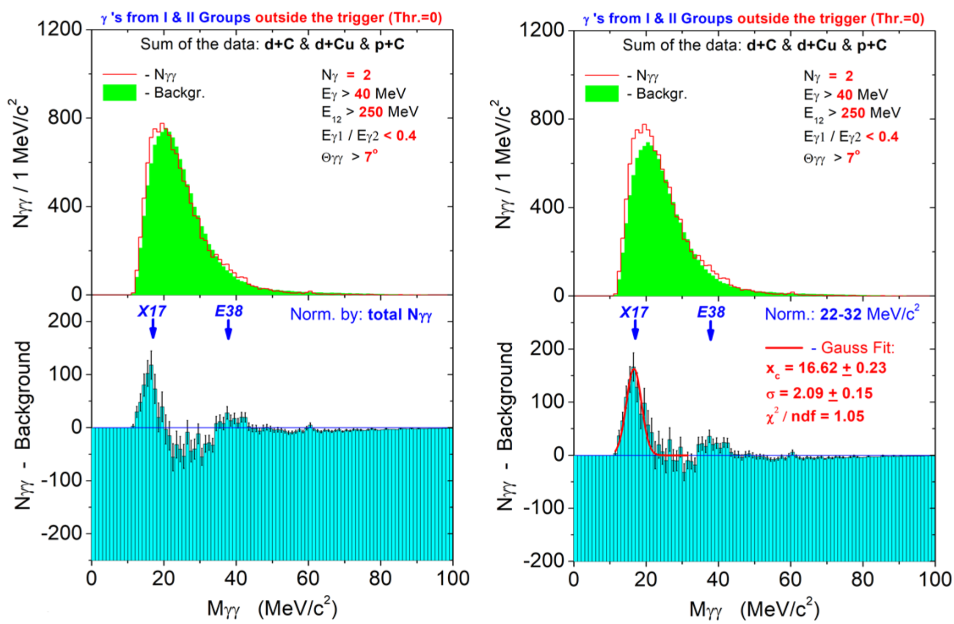

Fig. 2. Invariant mass distributions of $\gamma\gamma$ pairs satisfying criteria *(i)–(v)* without (upper panels) and with (bottom panels) the background subtraction obtained for the $d+\mathrm{C}$, $d+\mathrm{Cu}$, and $p+\mathrm{C}$ reactions. The backgrounds are normalized to the total pair numbers in the spectra (left) and by the numbers of pairs in the range of 22–32 MeV$/c^2$.

The curve in Fig. 2 is the Gaussian approximation of the experimental points in the range of 11–32 MeV$/c^2$

$$\frac{\mathrm{d}N}{\mathrm{d}M_{\gamma\gamma}} = \frac{N_0}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(M_{\gamma\gamma}-x_c)^2}{2\sigma^2}\right) . \tag{3}$$

The number of $\gamma\gamma$ pairs in the range of 12–22 MeV$/c^2$ after the background subtraction in the sum of three experiments is 924 ± 77. The values of the obtained fitting parameters in (3) are in the pictures. The parameter N_0 for the sum of the data obtained in the $p+\mathrm{C}$, $d+\mathrm{C}$, and $d+\mathrm{Cu}$ experiments, is

$$N_0 = 856 \pm 75 .$$

Thus, the statistics in the observed structure about 17 MeV/c^2 is more than 11 standard deviations. Based on the changes of the signal position (x_c parameter) in the different experiments (from 16.4 to 17.7 MeV/c^2), we estimate the possible systematic errors to be no more than ± 0.7 MeV/c^2.

3. Check of the observed peaks

Systematic errors may be due to uncertainty in measurements of γ energies and inaccuracy in estimates of the combinatorial background. The method of energy reconstruction of events is described in detail in Refs. [17, 20]. Possible overlapping effects were investigated previously for the reaction with the higher masses of the colliding nuclei and at higher energies — in the reaction of C+C at 4.5 GeV/c per nucleon [20]. It was found that the average displacement of the effective masses of $\gamma\gamma$-pairs in the reaction is only 6%. Thus, the influence of the overlap in the present experiment is negligible.

3.1. Data simulation

To simulate the d + Cu reaction, we use a transport code. At high energies, it is the Quark–Gluon String Model (QGSM) [21] and at the energy of a few GeV, the string dynamics is reduced to the earlier developed Dubna Cascade Model (DCM) [22] with the upgrade of elementary cross sections involved [23].

The following γ-decay channels are taken into account: the direct decays of π^0, η, η' hadrons into two γs, $\omega \to \pi^0\gamma$, $\Delta \to N\gamma$, and the Dalitz decay of $\eta \to \pi^+\pi^-\gamma$, $\eta \to \gamma + e^+ + e^-$, and $\pi^0 \to \gamma + e^+ + e^-$, the $\eta' \to \rho^0 + \gamma$, $\Sigma \to \Lambda + \gamma$, πN, and NN-bremsstrahlung. One should note that in accordance with the HADES data [24], the pn-bremsstrahlung turned out to be higher by a factor of about 5 than a standard estimate, and weakly depends on the energy. This finding, being in agreement with the result of Ref. [25], allowed one to resolve the old DLS puzzle [26]. This enhancement factor is included in our calculations. Tests of this model in detail are described in [1].

3.2. Estimates of systematic errors in the combinatorial background

For a quantitative check of the signals, the result of processing the simulated data was compared with the sum of the spectra (after the background subtraction), obtained in three experiments (see Fig. 3). The right panel of Fig. 3 shows t*i.e.* the accounts in the experimental data (in the left panel) were multiplied by a factor equal to the ratio of the numbers of $\gamma\gamma$ pairs in the range of 22–32 MeV/c^2

$$K_N = N_{\gamma\gamma}^{\mathrm{model}} \left(22 < M_{\gamma\gamma} < 32\,\mathrm{MeV}/c^2\right) / N_{\gamma\gamma}^{\mathrm{exp}} \left(22 < M_{\gamma\gamma} < 32\,\mathrm{MeV}/c^2\right) . \quad (4)$$

As seen from the figure, the signal at an invariant mass of ~ 17 MeV$/c^2$ is statistically significant. A more rigorous quantitative verification of the signal at ~ 38 MeV$/c^2$ was given in Ref. [3].

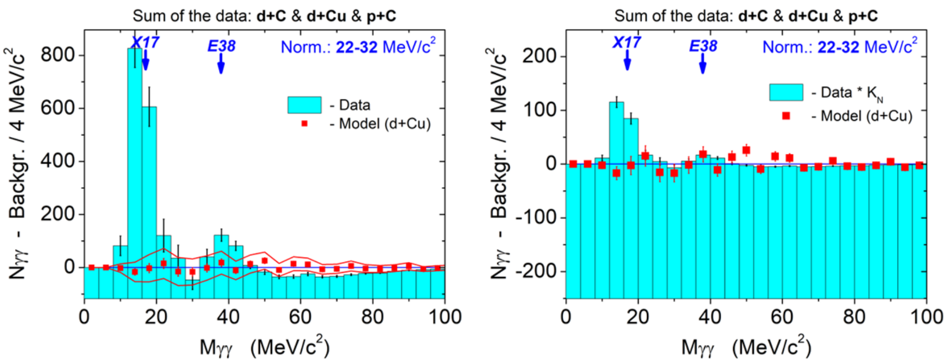

Fig. 3. Comparison of the experimental and simulated spectra after the background subtraction for the sum of the spectra, obtained in three experiments (indicated in the figure). Left: The curves indicate the interval of ± 3 standard statistical errors in the simulated data. Right: The same, but after reducing the experimental data (see the text, Eq. (4)).

4. Conclusion

Along with π^0 mesons, signals in the form of enhanced structures at invariant masses of about 17 and 38 MeV$/c^2$ are observed in the $p + \mathrm{C} \to \gamma + \gamma + x$, $d + \mathrm{C} \to \gamma + \gamma + x$, and $d + \mathrm{Cu} \to \gamma + \gamma + x$ reactions at momenta 5.5 GeV$/c$, 2.75 GeV$/c$, and 3.83 GeV$/c$ per nucleon, respectively. The results of testing the observed signals, including the results of the Monte Carlo simulation support the conclusion that the observed signals are the consequence of detection of the particles with masses of about 17 and 38 MeV$/c^2$ decaying into a pair of photons.

In view of the above many theoretical possibilities, it is of great importance to confirm the occurrence of $X17$ at different initial conditions and from different decay channels. The decay of both channels is in agreement with the composite picture of $X17$ and $E38$, proposed in [13].

The presented evidence of both $X17$ and $E38$, together with the earlier evidence of the $E38$ [3], suggests that there are several particles in the anomalous region (the region of masses less than the π^0 mass).

Further, a more detailed analysis of the available theoretical models and planning of new experiments are needed.

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