Observation of New Resonance Structure in the Invariant Mass Spectrum of Two γ-Quanta in dC-Interactions at Momentum 2.75 GeV/c per Nucleon

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Abstract

A new resonance structure at $M = 355 \pm 6 \pm 9$ MeV is observed in the invariant mass spectrum of two γ-quanta produced in the reaction $d + C \to \gamma + \gamma + x$ at momentum 2.75 GeV/c per nucleon. Preliminary estimates of its width and cross section are $\Gamma = 41 \pm 12$ MeV and $\sigma_{\gamma\gamma} \sim 0.6$ μb. The collected statistics is 2680 ± 310 events of $1.5 \cdot 10^6$ triggered interactions of a total number $3 \cdot 10^{12}$ dC-interactions.

1 Introduction

In connection with the recently developed physics program [1] on the search for a manifestation of a mixed phase of strongly interacting QCD matter in nucleus-nucleus collisions at the Nuclotron, the JINR initiated investigations aimed at finding and studying possible nontrivial structures in the spectrum of invariant effective masses of two photons in the region starting with the two-pion threshold to the ρ-meson mass. This program can be considered as a pilot one for further detailed studies at SIS-100/300 (GSI) and as a part of the international research program on studying the energy dependence of the properties of matter produced in collisions of relativistic nuclei. In this case, it is extremely important to study the evolution of two-photon spectra not only with respect to energy of colliding nuclei, but also to their atomic number.

It is to be noted that starting in 1997, data acquisition on production of neutral mesons and γ-quanta in proton-nucleus and nucleus-nucleus interactions for light nuclei has been carried out with internal beams of the Nuclotron in order to elucidate their production mechanism [2,3]. Experiments were conducted with internal proton beams at momentum 5.5 GeV/c incident on a carbon target and with ^2H, ^4He beams and internal C-, Al-, Cu-, W-, and Au-targets at momenta from 1.7 to 3.8 GeV/c per nucleon. In the light of the ideas recently arisen, analysis of these experimental data may prove to be the first important step in realizing the above program, which is the main impetus of this paper.

For the first analysis there were selected data on dC-interactions at energy $T_d = 2.0$ GeV/nucleon (momentum 2.75 GeV/c per nucleon) - data with maximum statistics.

Analysis of the data led to an intriguing result - a peak was detected which however has not been observed in analogous analysis of other experiments [2-5]. One of the

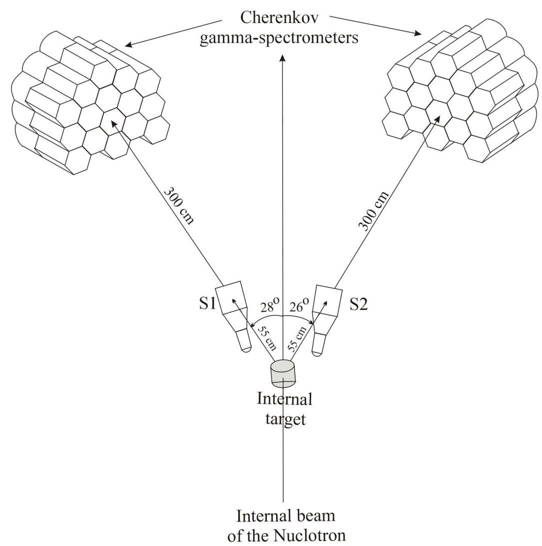

Figure 1: The scheme of the experimental instrumentation

possible explanations is the available statistics in the above-said experiment which essentially exceeds that in other experiments analysed. The requirements imposed on statistics for resolution of signals over the background were discussed in [3].

In this paper, the results are presented of the analysis of experimental data on production of correlated pairs of γ-quanta in the reaction

$$d + C \to \gamma + \gamma + x, \tag{1}$$

at momentum of incident deuterons 2.75 GeV/c per nucleon which were obtained with the 90-channel Cherenkov gamma-spectrometer at the JINR Laboratory of High Energies (setup Photon-2) [2,3,6]. Due to increased interest in the region of effective invariant masses 280-750 MeV [1], the data were analysed under the conditions with a minimal background in the interval 300-400 MeV.

The paper is organized as follows. Section 2 is a brief description of the experiment and experimental setup. The main spectra of invariant effective masses of pairs of γ-quanta in reaction (1) are discussed in Section 3. Section 4 is the analysis of systematic errors in measurements of γ-quanta energies and uncertainties coming from describing the background. To elucidate the nature of the peak observed, the dependence of its position and width on the opening angle of $\gamma\gamma$ pairs, energy of individual γ-quanta, and the summed energy of the two γ-quanta is analysed in Section 5. The estimates of the width and production cross section of the observed resonance structure are given in Section 6. The main inferences of the paper are presented in the Conclusion.

2 Experiment

The experiment was carried out with an internal beam of deuterons with momentum 2.75 GeV/c per nucleon and intensity $\sim 10^9$ particle/cycle of the Nuclotron. The experimental instrumentation allowed one to measure both energies and the direction of emission of γ-quanta produced in reaction (1). The experimental instrumentation is schematically represented in Fig.1. The setup includes 32 γ-spectrometers of lead glass and scintillation counters S_1 and S_2 of 15 x 15 cm [6,7].

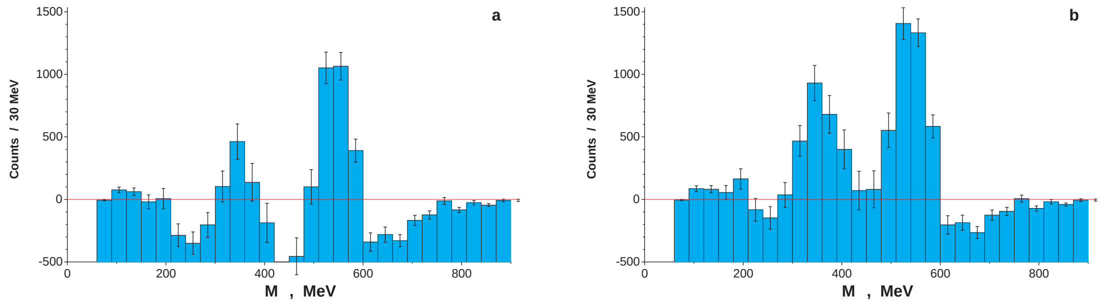

Figure 2: Invariant mass distributions of pairs of γ-quanta in reaction (1) after background subtraction. In Fig. 2a, the background is normalized to the total number of pairs in the spectrum; in Fig. 2b, with allowance made for the presence of resonances in the spectrum (normalization coefficient is 0.976).

The modules of the γ-spectrometer are assembled into two arms with 16 units in each arm. The detectors in each arm are divided into two groups with 8 units in each group. The output signals in each group are summed up linearly and after discrimination by amplitude are used in fast triggering. In this experiment the discriminator thresholds were at the level of 0.4 GeV. The setup was triggered by the coincidence of signals from two or more groups of detectors in different arms.

3 Spectra of invariant masses of pairs of γ-quanta

The invariant mass distribution of pairs of γ-quanta (γ-quanta from different arms of the spectrometer) after background subtraction is shown in Fig. 2. For the combinatorial background suppression, the following selection criteria were used:

a) the number of γ-quanta in an event, $N_\gamma = 2$;

b) the energies of γ-quanta, $E_\gamma > 100$ MeV.

The invariant mass distribution of combinations of two γ-quanta selected by random sampling from different events (the so-called event mixing) were used to estimate the background.

The absence of the peak corresponding to π^0-meson is due to the criteria of selection of events: the setup is triggered if two or more groups of modules with the total energy > 300 MeV are available (see also Fig. 3); therefore, π^0-mesons were mainly registered in events with $N_\gamma > 2$ (a minimal opening angle of γ-quanta registered by the setup equals $42°$, see [2,3]).

The total (without subtraction of the background) spectra of the invariant masses of pairs of γ-quanta and energy distribution of γ-quanta are shown in Fig. 3.

Thus, in the reaction $d + C \rightarrow \gamma + \gamma + x$ at momentum 2.75 GeV/c per nucleon one can observe a pronounced peak in the interval 300-420 MeV in the invariant mass spectrum of two γ-quanta (see Fig. 2b). The parameters of the observed peak are given in more detail below (see Figs. 4 and 5).

The errors displayed in Figs. 2,3 are statistical.

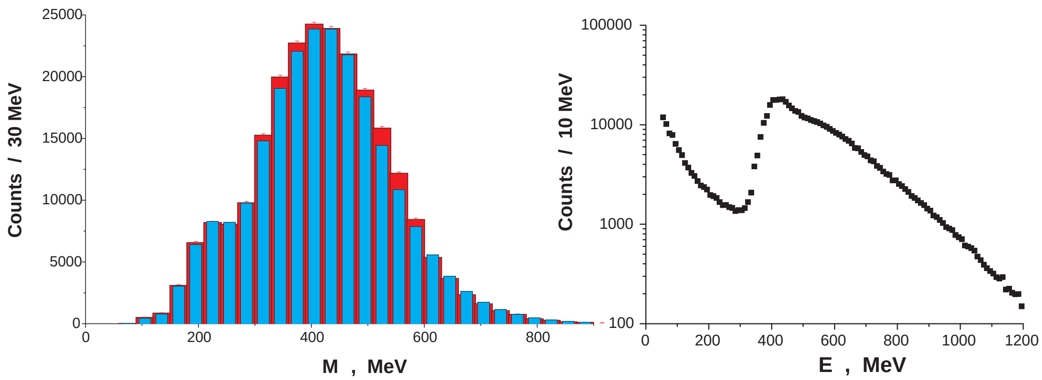

Figure 3: Invariant mass distribution of pairs of γ-quanta and energy distribution of γ-quanta in reaction (1) in selecting events with the number of γ-quanta equal to 2.

4 Systematic errors

Systematic errors may be due to:

• errors in measurements of energies of γ-quanta,

• errors in estimates of a combinatorial background.

The method of energy reconstruction of events is described in detail in [6,7]. One of the criteria of accuracy of energy reconstruction is the conformity of the positions of peaks corresponding to the known particles with their table mass values. As is seen in Fig. 2, the position of the peak corresponding to η-mesons (as well as to π^0-mesons, see [2]) is in qualitative agreement with the table values of their masses. A more precise determination of the position of peaks requires minimization of systematic errors in describing the background which arise, in particular, due to the violation of the energy-momentum conservation laws in selecting γ-quanta by random sampling from different events (for instance, this is the reason for the presence of a traditional dip following the peak of η-mesons).

Figure 4 shows the distribution over the invariant mass $M_{\gamma\gamma}$ of pairs of γ-quanta after the background subtraction. It is obtained by random sampling of γ-quanta from different events under the following selection criteria:

1) the summed energy in an event ≤ 1.7 GeV (about 99% of all events),

2) the sum of energies of γ-quanta selected accidentally from different events $E_{\gamma 1} + E_{\gamma 2} \leq 1.7$ GeV.

The curves in Fig. 4 are the result of data approximation by the Gauss distribution, including an additional free parameter y_0:

$$\frac{dN}{dM} = y_0 + \frac{2N_0}{w\sqrt{2\pi}} e^{-\frac{2(M-M_0)^2}{w^2}} \quad (1/MeV). \tag{2}$$

The values for the parameters $y_0,\ N_0,\ w,\ M_0$ and χ^2 are given below.

In the interval $0.18 \leq M_{\gamma\gamma} \leq 0.45$ GeV:

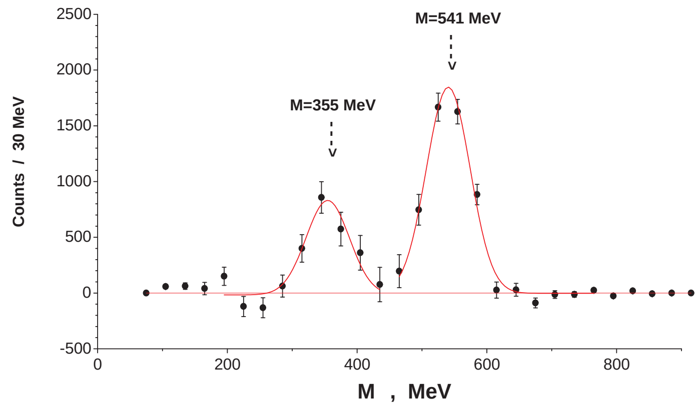

Figure 4: Invariant mass distribution of pairs of γ-quanta in reaction (1) after the background subtraction by selecting accidentally γ-quanta from different events under criteria 1) and 2) (see the text).

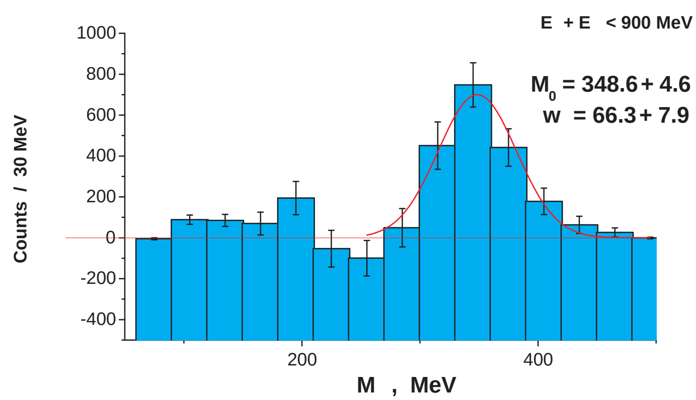

Figure 5: Invariant mass distribution of pairs of γ-quanta in reaction (1) with the background subtracted in selecting pairs with the total energy less than 900 MeV.

$M_0 = 354.6 \pm 5.5$ MeV; $w = 66.8 \pm 12.0$ MeV; $N_0 = 2357 \pm 453$; $y_0 = -0.5 \pm 1.7$; $\chi^2 = 1.8$.

In the interval $0.45 \leq M_{\gamma\gamma} \leq 0.78$ GeV:

$M_0 = 540.5 \pm 2.1$ MeV; $w = 67.2 \pm 4.0$ MeV; $N_0 = 5199 \pm 291$; $y_0 = -0.08 \pm 0.43$; $\chi^2 = 1.6$.

The signals-to-background ratios for the invariant mass intervals 300-420 MeV and 480-600 MeV (the vicinity of η-meson mass) are $2.7 \cdot 10^{-2}$ and $8.9 \cdot 10^{-2}$, respectively. For comparison, analogous values without the background suppression (without the selection criteria a) and b) of Section 3) are $(4.0 \pm 1.4) \cdot 10^{-3}$ and $3.2 \cdot 10^{-2}$.

To determine the parameters of the observed peak more precisely, pairs of γ-quanta with the total energy $E_{\gamma 1} + E_{\gamma 2} \leq 0.9$ GeV (Fig. 5) were analyzed. Under the above conditions the efficiency of recording η-mesons is almost equal to zero (a maximal opening angle of γ-quanta registered by the setup equals 66°).

The curve in Fig. 5 is the result of data approximation by the Gauss distribution (2) in the interval $0.24 \div 0.51$ GeV. Below we give the values for the parameters y_0, N_0, w, M_0, and χ^2:

$M_0 = 348.6 \pm 4.6$ MeV; $w = 66.3 \pm 7.9$ MeV; $N_0 = 1940 \pm 228$; $y_0 = 0.003 \pm 0.120$; $\chi^2 = 1.04$.

Thus, the position and width of the peak corresponding to η-meson (see Fig. 4) are in good agreement with the table value of its mass (systematic errors do not exceed 1.5%) and with the mass resolution of the instrumentation (see eq. (7) below). The total number of events registered in the η-meson region 450-660 MeV after background subtraction is 5177 ± 293.

The width estimates of the observed new resonance structure are given in Section 6.

5 Analysis of the obtained data

To elucidate the nature of the observed peak, we have investigated the dependence of its position and width on

- an interval of the opening angles of γ-quanta,
- a level of energy selection of γ-quanta,
- a level of summed energy selection of pairs of γ-quanta.

Figure 6 shows the invariant mass distribution of pairs of γ-quanta for two different intervals of the opening angle of γ-quanta.

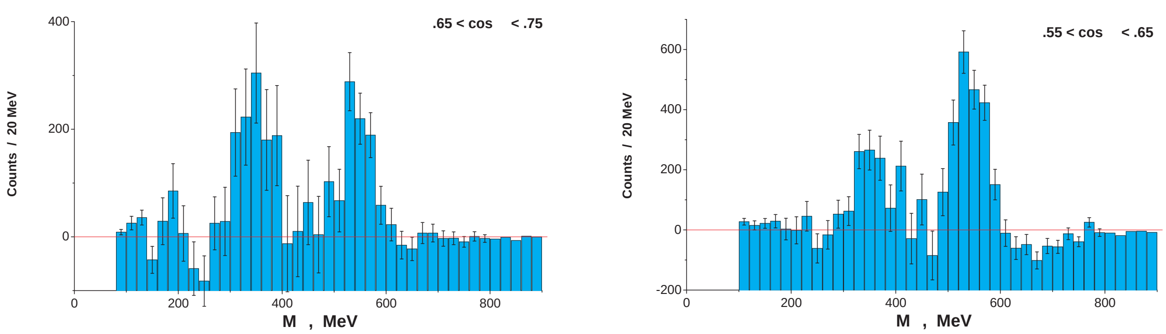

Figure 6: The same as in Fig. 2b, for two different intervals of the opening angle of γ-quanta.

The invariant mass spectra at different levels of energy selection of γ-quanta are displayed in Fig. 7.

The invariant mass spectra in different intervals of summed energy of two γ-quanta are shown in Fig. 5 ($E_1 + E_2 < 900$ MeV) and Fig. 8 ($E_1 + E_2 > 900$ MeV).

As is seen from Figs. 5-8, the position and width of the observed peak remain almost unchanged in different intervals of both the energies and the opening angles of γ-quanta: the mean value of the mass under different conditions varies in the range $348 \div 365$ MeV. The total number of events registered in the region 280-450 MeV (a summed number of pairs in the histograms in Figs. 5 and 8) is 2680 ± 310.

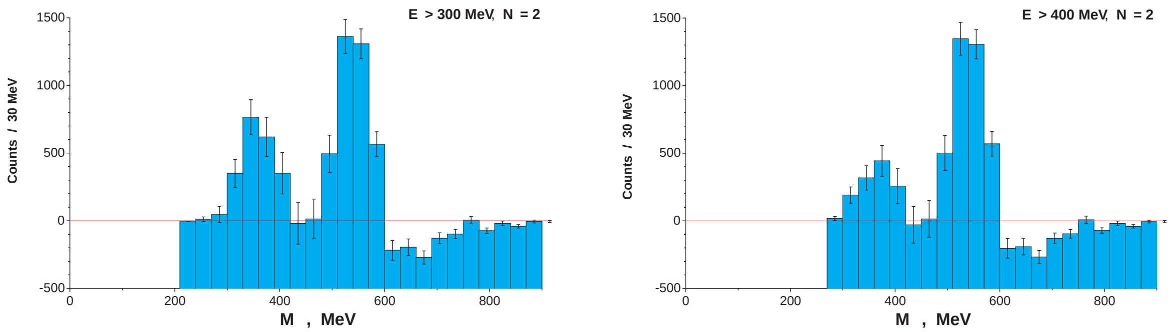

Figure 7: The same as in Fig. 2b, at different levels of energy selection of γ-quanta.

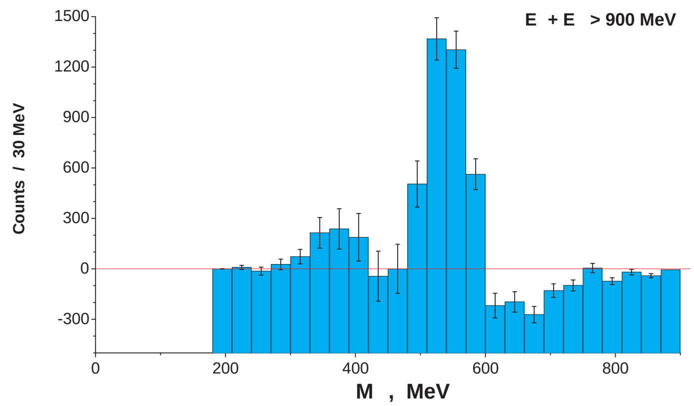

Figure 8: The same as in Fig. 2b, at the total energy of two γ-quanta, $E_1 + E_2 > 900$ MeV.

6 Estimates of the width and production cross section of the observed resonance structure

Values for the width w in (2) are also specified by the instrumentation resolution. The corresponding contribution to w can be estimated by the formula

$$(1/4)w_{app}^2 = (\frac{\partial M}{\partial E_1}\Delta E_1)^2 + (\frac{\partial M}{\partial E_2}\Delta E_2)^2 + (\frac{\partial M}{\partial \theta_{\gamma\gamma}}\Delta\theta_{\gamma\gamma})^2, \quad (3)$$

where $\Delta E_1,\ \Delta E_2$, and $\Delta\theta_{\gamma\gamma}$ are standard errors in measurements of γ-quanta energies and the opening angle,

$$\Delta E_i \simeq 0.068 \cdot \sqrt{E_i},\ \ E_i(GeV),\ \ i = 1, 2;$$

$$\Delta\theta_{\gamma\gamma} \leq \sqrt{2} \cdot \frac{12cm}{\sqrt{12}} \cdot \frac{1}{300cm} = 0.016.$$

Energy distributions of γ-quanta in combinations with the invariant mass $340 \leq M \leq 360$ MeV are displayed in Fig. 9.

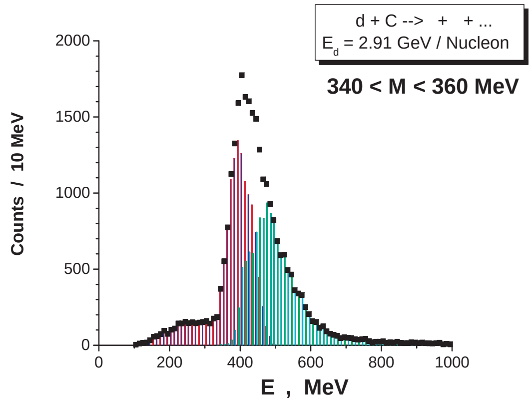

Figure 9: Energy distributions of γ-quanta in combinations with the invariant mass in the interval 340-360 MeV. The histograms show the distributions of γ-quanta with the lowest and highest energy in each pair.

Mean energy values for γ-quanta in a pair in the given interval of invariant masses amounts to $E_1 \simeq 380$ MeV; $E_2 \simeq 520$ MeV.

Analogous values for the invariant mass interval 540-560 MeV (in the vicinity of the η-meson mass) are $E_1 \simeq 520$ MeV; $E_2 \simeq 750$ MeV.

Below we give the results of calculations by formula (3) with the use of the above values for E_1 and E_2:

$$w_{app}(340 < M < 360MeV) = 52.6\ MeV, \tag{4}$$

$$w_{app}(540 < M < 560MeV) = 68.6\ MeV. \tag{5}$$

Correspondingly, the intrinsic widths of detected resonances are

$$w_{intr}(R \to \gamma\gamma) \simeq (w^2 - w_{app}^2)^{1/2} \simeq 40.6 \pm 11.8, \tag{6}$$

$$w_{intr}(\eta \to \gamma\gamma) \simeq (w^2 - w_{app}^2)^{1/2} \approx 0. \tag{7}$$

As one can see, a width of the η-meson, as expected, is practically equal to 0, whereas it essentially differs from zero in the observed resonance. The value of the width Γ in the Breit-Wigner function (see Fig. 10) practically coincides with w in Gauss distribution (2); thus, the intrinsic width of the observed resonance structure is about 41 ± 12 MeV.

It should be emphasized that the values for both the mass and width of the observed resonance structure have to be determined more accurately. Some shift of these values may be due to strict selection criteria of events in energy which are more appropriate for registration of η-mesons.

The summed number of dC-interactions in the experiment amounts to $\sim 3 \cdot 10^{12}$. With allowance made for the efficiency of registration, $\varepsilon \sim 10^{-3}$, the cross section of the observed process (for the total cross section of dC-interactions the value 612 mb was used [8]) is

$$\sigma_{\gamma\gamma} \approx \frac{2.7 \cdot 10^3}{3 \cdot 10^{12} \cdot \varepsilon} \cdot \sigma_{tot}(dC) \sim 0.6\ \mu b.$$

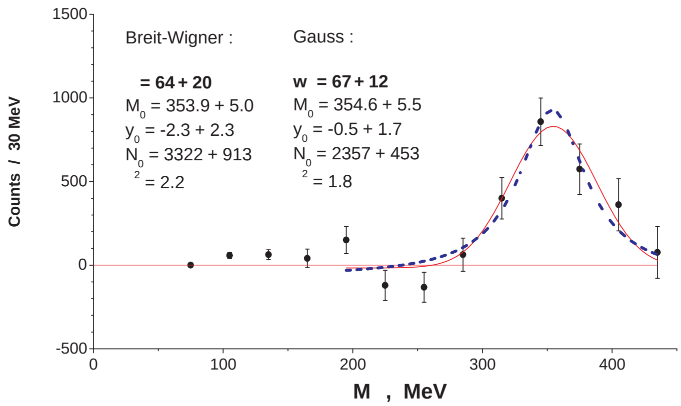

Figure 10: Comparison of the data (see fig. 4) approximation by the Breit-Wigner function $\frac{dN}{dM} = y_0 + (2N_0/\pi) \cdot [\Gamma/(4(M - M_0)^2 + \Gamma^2)]$ (the dashed line) and by Gauss distribution.

7 Conclusion

Thus, based on a thorough analysis of experimental data measured at the JINR Nuclotron and record statistics of 2680 ± 310 events of $1.5 \cdot 10^6$ triggered interactions of a total number $3 \cdot 10^{12}$ dC-interactions there was observed a new resonance structure with the mass $M = 355 \pm 6 \pm 9$ MeV, width $\Gamma = 41 \pm 12$ MeV, and preliminary production cross section $\sigma_{\gamma\gamma} \sim 0.6\ \mu b$ in the invariant mass spectrum of two γ-quanta produced in dC-interactions at momentum of incident deuterons 2.75 GeV/c per nucleon. To verify the above conclusions, measurement of quantum numbers, and more accurate determination of mass, width and cross section of the observed resonance structure, new experiments are required to be carried out under conditions appropriate for registration of pairs of γ-quanta with the invariant mass 300-400 MeV. We hope to conduct detailed analysis of the available experimental data, and dwell upon a physical character and possible interpretations of the observed resonance in our further publications.

Acknowledgements

We are grateful to S.B. Gerasimov, M.I. Gorenstein, G.M. Zinovjev, M.K. Suleymanov, O.V. Teryaev, V.D. Toneev, A.S. Khrykin, and V.L. Yudichev for numerous fruitful discussions. We thank V.V. Arkhipov, A.F. Elishev, A.D. Kovalenko, A.I. Malakhov, G.L. Melkumov, S.G. Reznikov, and the staff of the Nuclotron for their help in conducting the experiment, as well as A.V. Belozerov, M.A. Kozhin, M.A. Nazarenko, S.A. Nikitin and V.V.Skokov for their help in analyzing data. We would like also to express special thanks to V.G. Kadyshevsky, V.A. Matveev and A.N. Tavkhelidze for their interest to this paper.

The work was supported in part by the Russian Foundation for Basic Research, grant 05-02-17695 and a special program of the Ministry of Education and Science of the Russian Federation, grant RNP.2.1.1.5409.

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