RESONANCE GHOST ANOMALY OF THE ^{8}Be NUCLEUS IN REACTIONS ^{12}C(γ, 3α), ^{12}C(γ, n)^{3}He2α AND ^{12}C(γ, p)^{3}H2α

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On the excitation curve for a system of two 2α-particles in the reactions ^{12}C(γ, 3α), ^{12}C(γ, n)^{3}He2α and ^{12}C(γ, p)^{3}H2α, a resonance structure with a maximum located at E_0 = 0.72 MeV and width $\Gamma \sim$ 0.75 MeV is found between the maxima corresponding to the ground and the first excited state of the ^{8}Be nucleus, and identified as a ghost anomaly (GA). The GA are explanation in the framework of the R-matrix theory of nuclear reactions.

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1. INTRODUCTION

The excited states of the ^{8}Be nucleus were explained as level of the rotation bands [1]. However, in the excitation curve for a system of two α-particles between the maxima corresponding to the ground (GS) and the first excited state of the ^{8}Be nucleus in the multiparticle reactions caused by hadrons has been repeatedly observed the resonance [2, 3] identified as a ghost anomaly (GA). Within the framework of model of the rotation bands GA is not explained.

Various mechanisms of GA formation were proposed. In work [4] is made suggestion that under small energy anomaly can be explained by behavior two-particle phase distribution in multiparticle reaction. But, in our works [5, 6] we have demonstrated that nor one of phase distributions has not the resonance with a maximum located at 0.72 MeV. Was not confirmed this suggestion and in experiments [2, 3] with greater energy swooping particles. In [7] GA existed in branch of the disintegration excited of the ^{9}Be nucleus: ^{9}Be $\rightarrow$ ^{4}He + ^{5}He and ^{9}Be $\rightarrow$ n + ^{8}Be. The difference their threshold around 0.8 MeV. The mix channel could bring the resonance about forming. Therefore, in present experiments for investigation is chose the reactions ^{12}C(γ, 3α) in which on intermediate stage of the ^{9}Be nucleus is not formed.

The most successful was an explanation GA in the framework of the R-matrix theory of nuclear reactions [8] in the singlelevel approximation [9]. The mass of the ^{8}Be nucleus exceeds the mass of two α-particles by 0.092 MeV [10]. On his disintegration influences quickly changing near-threshold the probability for an α-particles through the potential barrier. This brings about distortion of curve GS and formation resonance-satellite. In this case GA must have identical quantum-mechanical numbers with GS [2, 3]: quantum numbers spin and parities J^{π}, dependences of the yield on the intermediate system energy, angular distributions of α-particles in the rest system of the ^{8}Be nucleus, independence parameter the excitation curve GA from type of the reactions. Such information can be obtained in the given experiment carried out with the help of a 4 π-detector.

This report is a continuation of work [5, 6] concerning the study multiparticle reactions of carbon nucleus photodisintegration, ^{12}C(γ, 3α), ^{12}C(γ, n)^{3}He2α and ^{12}C(γ, p)^{3}H2α (in what follows, they will shortly be designated as (γ, α)-, (γ, n)- and (γ, p)-reactions, respectively). It was revealed that the ^{8}Be nucleus is formed at the end of all reactions. The results given here were obtained by using a diffusion chamber placed in a magnetic field and exposed to a beam of bremsstrahlung photons, their endpoint energy being 150 MeV. The undoubted advantage given experiment is that here safely stands out partial channel of the formation of the ^{8}Be nucleus and both products of his disintegration are registered. Here are the pure condition for measurement of the relative output GA and GS. Early we observed GA in (γ, n)- and (γ, p)-reactions [5]. Here results are received on reactions (γ, α) and is executed co-processing analysis on three reactions.

2. SEPARATION OF THE GA

The excitation energy system of two α-particles $E_x = M_{eff} - 2\, m_\alpha$, where M_{eff} is the effective mass equal to the total energy of the system in the rest reference system, m_α is the mass of α-particle.

The distribution of events over E_x at energy < 6 MeV for (γ, α)-reaction is shown by circles in Fig.1,a. Because of identically particles in reactions it is impossible select the pair, formed as a result of disintegration of the ^{8}Be nucleus. Therefore three importances E_x introduced each event at building of the distribution. Two of them corresponded to background $\alpha\alpha$-combination. The circles are delivered in the middle interval. The errors are statistical.

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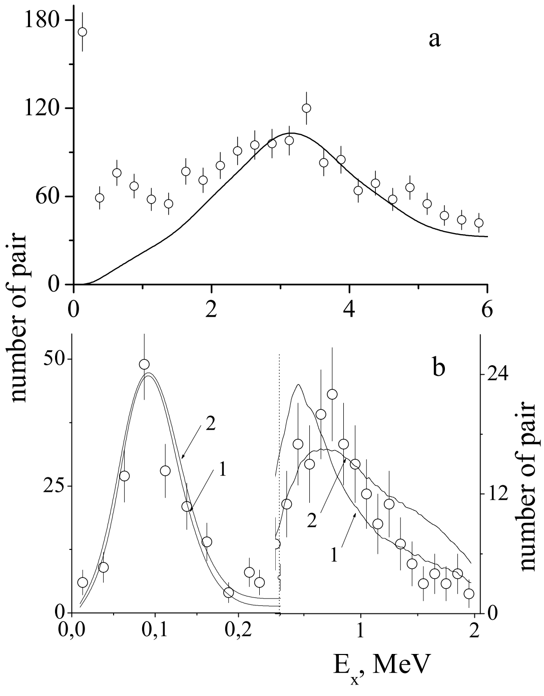

Fig.1. *Excitation energy distribution for the system of two α-particles*

Investment is discovered in distribution from the ground and four excited states of the ^{8}Be nucleus. Method of division of the states and their parameters will are reported later [11]. In Fig.1,a the solid curve exhibits the total contribution from four excited states. Distribution is received after subtraction of the contribution of the excited states shown by circles in Fig.1,b. For the energy of 0.25 MeV, the scale along the abscissa axis was changed. The left axis corresponds to estimation energies lower than 0.25 MeV, the right one to energies above this value. On the left step are 0.025 MeV, on the right are 0.25 MeV. The near-threshold resonances were approximated by the Breit-Wigner distribution with the parameters E_0 = 0.089 ± 0.004, Γ = 0.056 ± 0.003 MeV. A conclusion can be drawn that the resonance are a manifestation of the ^{8}Be nucleus ground state decay, with both the parameters of the nucleus E_0 = 0.092 MeV, Γ = 5.57 eV [10]. The observed resonance width is instrumental in this case and corresponds to the average measurements error of ∼4 MeV/c for the momentum of α-particles. To the right side, there remained a wide resonance with the parameters E_0 = 0.72 ± 0.02, Γ = 0.80 ± 0.06 MeV. The resonance is identified as GA. In the framework of the R-matrix theory of nuclear reactions [8] and in the singlelevel approximation [9], the spectral density looks like [2, 3]

$$\rho(E_x) = \frac{\frac{1}{2}\Gamma_0}{(E_0 - \Delta_0 - E_x)^2 + \left(\frac{1}{2}\Gamma_0\right)^2}, \qquad (1)$$

where the quantities Γ_0 and Δ_0 are associated with the regular, F_0, and irregular, G_0, Coulomb functions: $\Gamma_0 = 2P_0{\gamma_0}^2$, ${\gamma_0}^2$ is the reduced width of α-particle decay, $P_0 = a_0/{A_0}^2$ is the potential barrier permeability, a_0 is the channel radius, and ${A_0}^2 = {F_0}^2 + {G_0}^2$, $\Delta_0 = {S_0}^0{\gamma_0}^2$ - offset of the resonance, ${S_0}^0 = \frac{a_0}{A_0}\frac{\partial A_0}{\partial r}$. The Coulomb functions F_0 and G_0 for the orbital moment $l = 0$ were calculated making use of the method and tables [11]. If the resonance parameters do not depend on energy, it is possible to put [6] E_0-Δ_0 = E_r, where E_r is energy of resonance. In Fig.1,b curve 1 was found for a_0 = 4.44 fm, ${\gamma_0}^2$ = 0.624 MeV, and curve 2 is for a_0 = 3.5 fm, ${\gamma_0}^2$ = 4.28 MeV. This parameters were obtained using the phase analysis of experimental data on scattering [9].

At calculation are taken into account inaccuracy of the measurement of the momentum α-particles that has brought about extension GS. In the course of calculation, the availability of two resonances, which correspond to the GS and the GA, was supposed. The position of the maximum and the width of the ground state practically do not depend on the channel parameters. At the same time, by varying the latter, an agreement between the theoretical shape of the GA curve and experimental results can be attained. The variation of the channel parameters weakly affects the relative probability of resonances, whereas the small variations of E_r change it substantially.

Separation the partial channel of formation of the ^{8}Be nucleus at E_x < 2 MeV in (γ, n)- and (γ, p)-reactions were reported in [5].

3. COMPARISON OF THE GA AND GS

The kinetic energy in system of α + ^{8}Be (γ, α)-reaction T_0 = E_γ - ε_1 - E_x, where E_γ is the photon energy, ε_1 is the threshold to reactions. In Fig.2,a the ratio η between the yields of the GA and GS depending on T_0 are shown with a step of 3 MeV. Within the whole energy interval, this ratio is constant and close to unity. Average mean is η_α = 1.01 ± 0.08.

In this and other figures, the circle correspond (γ, α)-reactions, the square is for (γ, n)-reactions and the triangle is for (γ, p)-reactions. In work [5] was shown, that in (γ, n)- and (γ, p)-reactions proceeds according a sequential-type scheme with formation the excited states ^{11}C and ^{11}B nuclei. The kinetic energy in the ^{3}He(^{3}H) + ^{8}Be system T_0 = E_0 - ε_2 - E_x, where E_0 is the excitation energy of the ^{11}C(^{11}B) nucleus, ε_2 is the threshold to reactions ^{11}C(^{11}B) → ^{3}He(^{3}H) + ^{8}Be. In Fig.2,a the ratio η depending on T_0 was shown with a step of 2 MeV. Average mean for (γ, n)-reactions is η_n = 0.99 ± 0.12 and for (γ, p)-reactions is η_p = 1.01 ± 0.18. Within errors relations coincide.

Received here relative output GA exceeds given other experiment, where he varies from a few to 70 % in various reactions [2, 3]. Difficulties of separating the GA are connected with background conditions. In our experiment favorable background conditions for separation GA: safely stands out channel to reactions, both products of the disintegration of the ^{8}Be nucleus are registered. Possible, exactly difficulty of the separation of the channel in other experiment was a reason both different values of the relative output in various reactions, and understated its values.

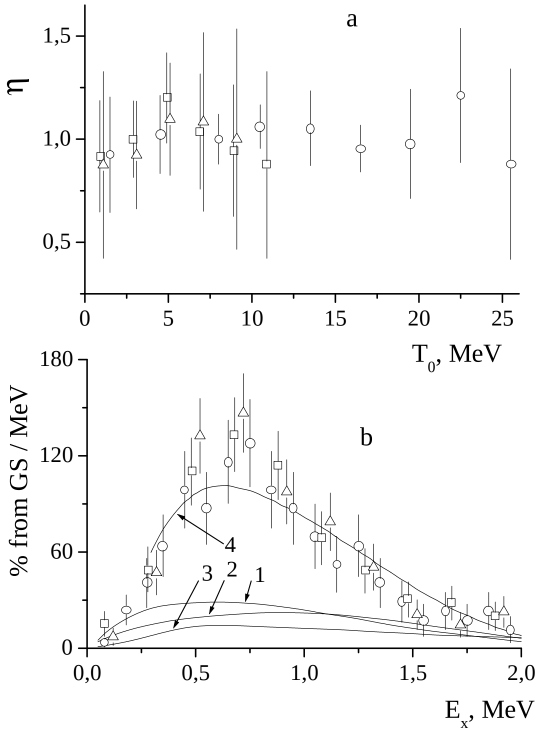

Fig.2. *a) The ratio η between the yields of the GA and the GS depending on energy of system, b) excitation function for the GA*

In Fig.2,b the spectral distribution of the GA density after subtracting events corresponded to the GS (Fig.1,b) is shown in comparison with literary data. Graph is built in received at literature coordinates. The ratio (in percent) between the number of events that fall within the given energy interval and the total number of GS events, divided by the 0.2 MeV interval width, is put along the ordinate axis. Within errors relations coincide. Curve of excitement GA has a resonance type. Fitting by the Breit-Wigner curve resulted in the following values of parameters: $E_0 = 0.72 \pm 0.02$, $\Gamma = 0.80 \pm 0.06$ MeV for (γ, α)-reactions, $E_0 = 0.72 \pm 0.03$, $\Gamma = 0.75 \pm 0.09$ MeV for (γ, n)-reactions, $E_0 = 0.72 \pm 0.04$, $\Gamma = 0.69 \pm 0.12$ MeV for (γ, p)-reactions. Within errors parameters resonance coincide. With respect to the maximum position and the curve shape, our results agree with the data of work [3] for reaction ^{9}Be(p, d)^{8}Be (curve 1), whereas, in the reaction ^{9}Be(d, t)^{8}Be (curve 2) [3], the maximum is shifted towards higher energies and the distribution is broad.

The spectral distribution has been repeatedly calculated in the framework of the R-matrix formalism and the single-level approximation. Curve 3 demonstrates the results of calculations for the reaction ^{9}Be(p, d)^{8}Be made in work [2]. The probability of GA formation is considerably smaller, and the resonance width is larger. The possible reason for such a discrepancy may be a very large value of the channel radius, $a_0 = 7$ fm. Curve 4 depicts the results of calculations made in work [2] for the reaction ^{10}B(p, ^{3}He)^{8}Be and the channel radius, $a_0 = 3$ fm, normalized, with respect to the area, by our data. The distribution is close to our data both by the curve shape and the maximum position. The results presenting experiment witness that parameters of the resonance GA and relative output do not hang from type of the reactions. Thus, the second resonance appeared owing to the modulation of the spectral distribution curve for the ground state density by the permeability of the potential barrier, and is its part.

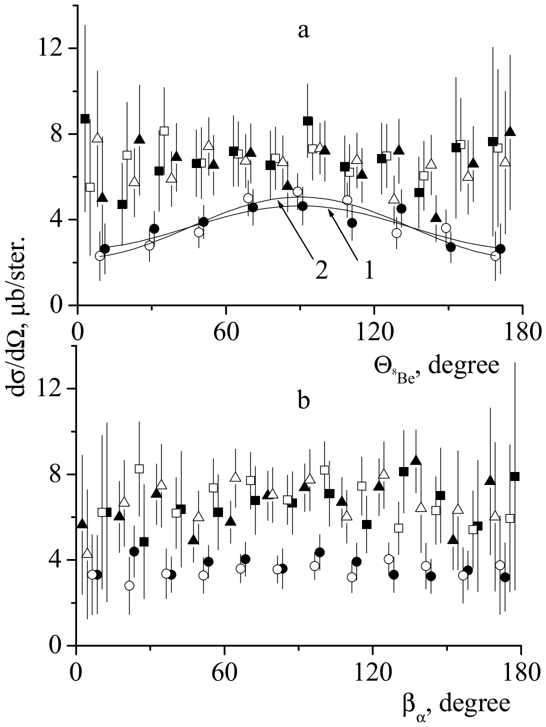

Fig.3. *a) Angular distributions of the ^{8}Be nucleus in the CMS; b) angular distribution of α-particles in the CMS of the ^{8}Be nucleus. The GA - open points, the GS - close points*

Angular distributions GA and GS of the ^{8}Be nucleus in the CMS $\alpha + {^8}$Be (γ, α)-reactions was shown in Fig.3,a with a step of 20°. In this and other figures, the open points correspond GA and the close points correspond GS. Angular distributions have like type. Angular distributions (γ, α)-reactions was executed fitting function $f(\theta) = a + b \sin^2\theta$. The parameters was determinants: for GA is $a = 2.21 \pm 0.94$, $b = 2.84 \pm 0.77$, χ^2/number of points = 0.89 (curve 1 on Fig.3,a), for GS is $a = 2.63 \pm 0.96$, $b = 2.02 \pm 0.76$, χ^2/number of points = 0.81 (curve 2 on Fig.3,a). Within errors means coincide.

An angular distributions GA and GS of the ^{8}Be nucleus in the CMS disintegrating nuclei ^{11}C and ^{11}B were shown in Fig.3,a with a step of 15°. The distribution for (γ, n)- and (γ, p)-reactions are nearly isotropic. This confirms once more out conclusion made [12] about that $J^\pi = \frac{1}{2}^+$ for intermediate disintegrating nuclei ^{11}C and ^{11}B.

In the experiment concerned, the differential cross-sections of α-particles in the CMS of the ^{8}Be nucleus can be measured. In Fig.3b the angular distributions for the GA and the GS were shown. The polar angle is reckoned from the direction of the ^{8}Be nucleus motion. Step of histogram is 15°. Angular distributions in all three reactions are isotropic. This means [12] that the orbital moment $l = 0$, whence it follows that the GA quantum numbers are $J^{\pi} = 0^{+}$, as it is in the GS [10].

4. CONCLUSIONS

On the excitation curve for a system of two α-particles in the reactions ^{12}C(γ, 3α), ^{12}C(γ, n)^{3}He2α and ^{12}C(γ, p)^{3}H2α, a resonance structure with a maximum located at $E_0 = 0.72$ MeV, possessing the width $\Gamma \sim 0.75$ MeV, and identified as a ghost anomaly (GA) was revealed between the ground state (GS) and the first excited state of the ^{8}Be nucleus. In the single-level approximation, it has been demonstrated that the appearance of the resonance can be explained by modulation of the excitation curve of ^{8}Be nucleus in the ground state exerted by the probability for a α-particles to penetrate through the potential barrier. In photonuclear reaction GA has been observed for the first time.

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РЕЗОНАНС АНОМАЛИЯ-ПРИЗРАК ЯДРА ^{8}Be В РЕАКЦИЯХ ^{12}C(γ, 3α), ^{12}C(γ,n)^{3}He2α и ^{12}C(γ,p)^{3}H2α

С.Н. Афанасьев, Д.В. Гущин, А.Ф. Ходячих

В кривой возбуждения 2α-системы в реакциях ^{12}C(γ, 3α), ^{12}C(γ, n)^{3}He2α и ^{12}C(γ, p)^{3}H2α между основным и первым возбужденным состояниями ядра ^{8}Be обнаружен резонанс с максимумом $E_0 = 0.72$ МэВ и шириной $\Gamma \sim 0.75$ МэВ, идентифицированный как аномалия-призрак (АП). Характеристики АП объяснены в рамках R-матричной теории ядерных реакций.

РЕЗОНАНС АНОМАЛІЯ-ПРИМАРА ЯДРА ^{8}Be В РЕАКЦІЯХ ^{12}C(γ, 3α), ^{12}C(γ,n)^{3}He2α I ^{12}C(γ,p)^{3}H2α

С.М. Афанасьев, Д.В. Гущин, О.Ф. Ходячих

У кривій збудження 2α-системи в реакціях ^{12}C(γ, 3α), ^{12}C(γ, n)^{3}He2α і ^{12}C(γ, p)^{3}H2α між основним і першим збудженим станами ядра ^{8}Be виявлено резонансну структуру з максимумом $E_0 = 0.72$ MeB і шириною $\Gamma \sim 0.75$ MeB, ідентифіковану як аномалія-примара (АП). Характеристики АП пояснені в рамках R-матричної теорії ядерних реакцій.