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# ALPHA CLUSTER UNBOUNDED STATES OF $^{8}$Be AND $^{12}$C NUCLEI FROM THE FOUR-PARTICLE $^{12}C(\alpha,\alpha\alpha)\alpha\alpha$ DECAY REACTION

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In the two-dimensional spectra of $\alpha\alpha$ coincidences obtained as a result of a correlation kinematically-incomplete study of the 4-particle $^{12}C(\alpha,\alpha\alpha)\alpha\alpha$ reaction, at an alpha-particle beam energy of 27.2 MeV, excited states of the $^{12}C^*$ nucleus ($E_{ex}$ = 10.3 MeV and $E_{ex}$ = 9.64 MeV) were observed, which are characterized by both two-particle (on $\alpha$+beryllium 8 nucleus in the ground and excited states) and three-particle (on $\alpha+\alpha+\alpha$) decay channels.

A re-analysis of the two-dimensional spectra of α-α coincidences obtained earlier [1] as a result of studying the reaction (α,2α) on the $^{12}$C nucleus at an alpha particle beam energy of 27.2 MeV for pairs of alpha particle departure angles: 18.9°/22.25° was carried out and aimed at detecting cluster excited states in the $^{12}$C nucleus, the de-excitation of which occurs due to the simultaneous emission of three alpha particles. The detailed features of this experimental study are given in [2].

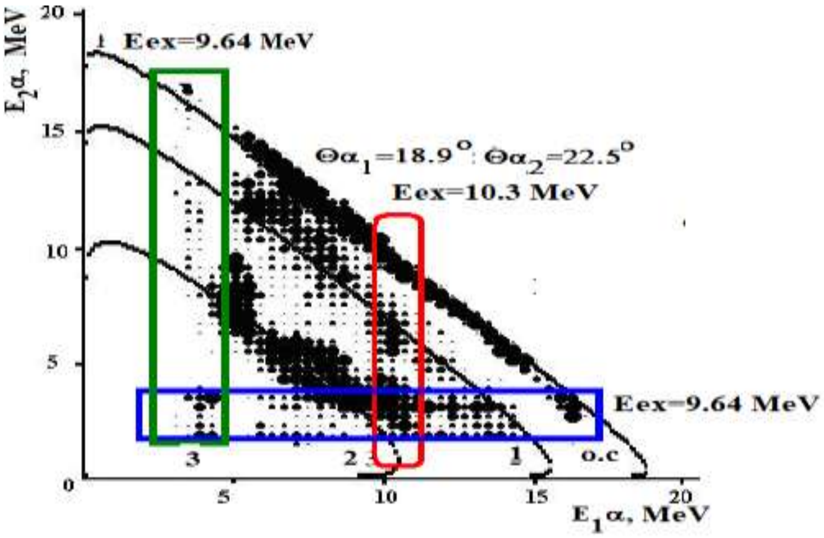


*Fig. 1. Matrix of $\alpha$-$\alpha$ coincidences with $^{12}C(\alpha,\alpha\alpha)\alpha\alpha$ reactions at an alpha particle beam energy of 27.2 MeV*

Fig. 1 shows a two-dimensional spectrum of $\alpha$-$\alpha$ coincidences obtained for the angles of registration of alpha particles 18.9°/22.25°, where the absolute values of the energies of alpha particles in MeV are plotted on the axes $E_1$ and $E_2$.

As can be seen from Fig. 1, three loci of different width and population are observed, which correspond to the formation of the $^{8}$Be nucleus in the ground state and in two excited states. The Monte Carlo method was used to analyze the events of the two-dimensional spectrum. Since the energy values of all three particles are known - two alpha particles (these values were measured in the experiment) and the third quasiparticle, the mass of which was equal to the mass of two unregistered alpha particles and is calculated using the laws of conservation of energy and momentum, the values of the energy balance at each point were determined by the formula $Q_{\text{екс}3i} = E_{\alpha 1i}+E_{\alpha 2i}+E_{3i}-E_{\alpha}$. The spectrum of the heat balance $Q_{3ex}$ is shown in Fig. 2. That is, we obtain in the output channel four alpha-particles, which were formed as a result of $\alpha+^{12}C$ interaction ($E_\alpha$ =27.2 MeV) as follows:

1. $\alpha+^{12}C \rightarrow \alpha+^{8}Be_{\text{o.c}\rightarrow\alpha+\alpha}$
2. $\alpha+^{12}C \rightarrow \alpha+^{8}Be^{*}_{\text{1зб.с. (Eзб=2.94 MeB)}\rightarrow\alpha+\alpha}$
3. $\alpha+^{12}C \rightarrow \alpha+^{8}Be^{*}_{\text{2зб.с. (Eзб=7 MeB )}\rightarrow\alpha+\alpha}$
4. $\alpha+^{12}C \rightarrow \alpha+^{8}Be^{*}_{\text{1зб.с (Eзб=10.74 MeB).}\rightarrow\alpha+\alpha}$

This spectrum, in fact, reflects the excitation spectrum of the $^{8}$Be nucleus. The most intense and narrow peak corresponds to the formation of the $^{8}$Be nucleus in the ground state ($Q_0$ ~ -7.3 MeV), and the others – to excited states up to the excitation energy of 12 MeV. Experimental information on the parameters of the first excited level 2+ is very ambiguous. The value of the width of this level, obtained in works varies from 0.2 to 2 MeV. Considering that in the experiments conducted earlier the width of the excited level at E* ~ 3 MeV does not exceed 1.7 MeV when analyzing the spectrum using the least squares method using the Breit-Wigner form factor, a restriction was imposed on the width of the first excited level of -2 MeV. In addition, it is known that in numerous experiments another peak was observed between the ground and broad first excited states, which was called "Ghost anomaly"

(GA) and causes the broadening of the first excited level. Taking into account these conditions, the experimental Q spectra obtained from the coincidence matrices were fitted, which is shown in Fig. 2 by a solid line, the dashed lines indicate the separate contribution of each state, which was taken into account during the fitting. The parameters obtained during the fitting are given in the Table 1.

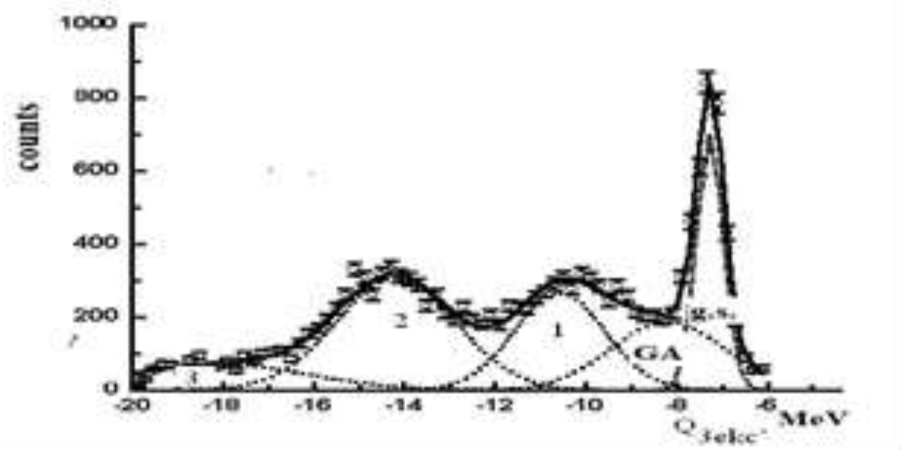


*Fig. 2. Q-spectrum obtained as a result of recalculation of the two-dimensional spectrum of $\alpha$-$\alpha$ coincidences (see Fig. 1)*

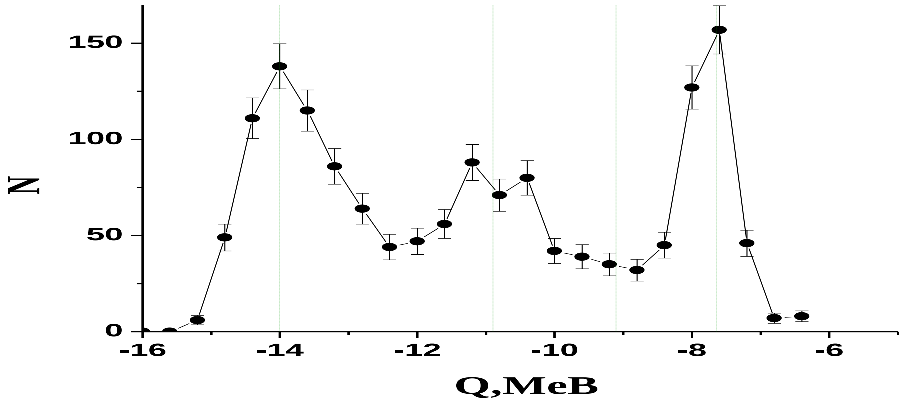


*Fig. 3. Projection of αα-coincidence events highlighted by a green frame (see Fig. 1) caused by the decay of an excited nucleus $^{12}C^*_{10.3MeV}$ onto the energy axis $E_{2\alpha}$ ($\Theta_{\alpha 2}$=22.25°)*

Table 1

Parameters of the $^8Be$ levels obtained from the Q spectrum

| Levels of $^8$Be | Q (ΔQ), MeV | E*(Δ),MeV | Γ(Δ Γ), MeV |
|---|---|---|---|
| Ground | -7.31(0.06) | 0(0.06) | 0.70(0.05) |
| GP | -8.20(1.66) | 0.90(1.72) | 3.00(2.61) |
| 1 | -10.27(0.06) | 2.96(0.12) | 2.00(0.19) |
| 2 | -14.33(0.04) | 7.023(0.10) | 2.97(0.10) |
| 3 | -18.06(0.24) | 10.73(0.30) | 3.00(0.57) |

But in addition to the two-particle decay of excited levels of $^{12}$C due to the emission of an alpha particle and the $^8$Be nucleus in the main or in one of the excited states, for some of these excited states, simultaneous decay into three alpha particles occurs. Thus, in the obtained two-dimensional spectra of α-α coincidences, bands were observed, which were identified as a manifestation of the population of 3α cluster excited states of $^{12}$C with excitation energies of 9.64 MeV (marked by green and blue frames) and 10.3 MeV (red frame) and their decay by simultaneous emission of three α-particles, schematically such a mechanism is described as $^{12}C(\alpha,\alpha)^{12}C^*_{Eex.=10.3\ MeV}$ ($^{12}C^*_{Eex.=9.64\ MeV}$)→α+α+α. For more details on the features of use, see the work [4].

Figs. 4, 5 shows the projections onto the energy axis $E_{2\alpha}$ of the αα-coincidence bands highlighted by green and red frames and red frames, and in Fig. 5, the projection onto the energy axis $E_{1\alpha}$ of the αα-run band highlighted by a blue frame.

The projections of these stripes onto the alpha-particle axis carry information about the ratio of decay modes of the above-mentioned excited levels of the $^{12}$C nucleus. Thus, in the case of the excited level of the $^{12}$C nucleus $E_{ex}$=10.3 MeV, such simple mechanisms of formation of 4 alpha particles in the output channel are possible, which are indicated in Table 2.

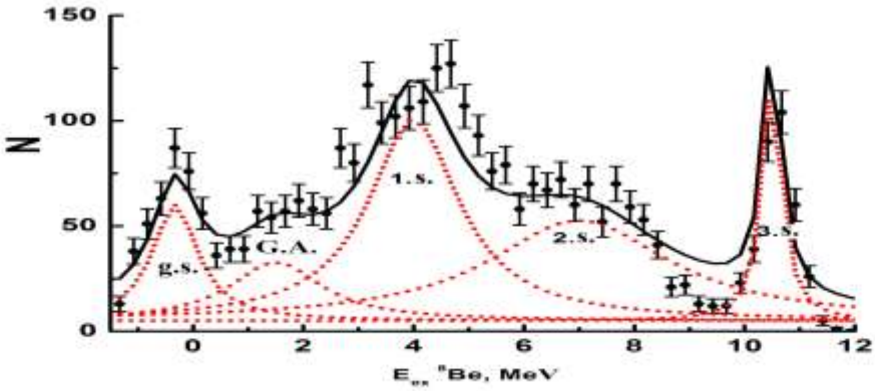


*Fig. 4. Projection of αα-coincidence events highlighted by a red frame (see Fig. 1) caused by the decay of an excited nucleus $^{12}C^*_{9.64MeV}$ onto the energy axis $E_{2\alpha}$ ($\Theta_{\alpha 1}$=22.25°)*

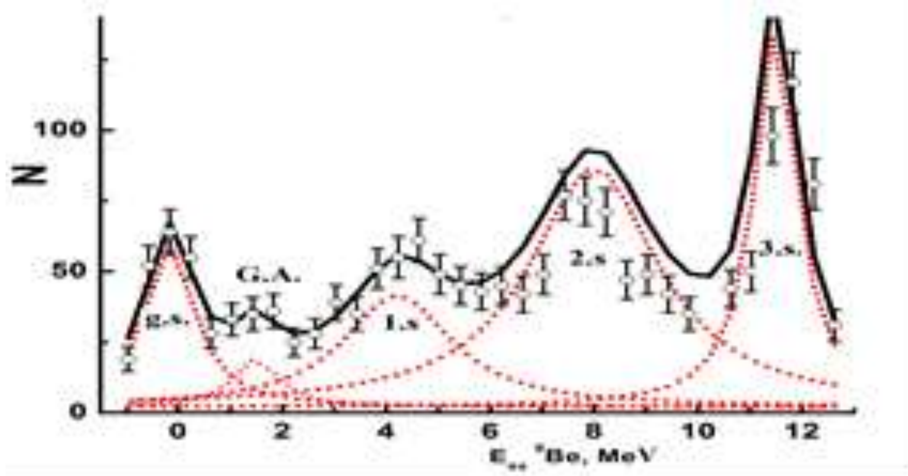


*Рис. 5. Projection of αα-coincidence events highlighted by a green frame (see Fig. 1) caused by the decay of an excited nucleus $^{12}C^*_{9.64MeV}$ onto the energy axis $E_{1\alpha}$ ($\Theta_{\alpha 1}$=18.9°)*

Table 2

Decay modes of the excited state of the $^{12}$C nucleus $E_{ex}$=10.3 MeV

| Exit channel | 1 step | 2 step | 3 step |
|---|---|---|---|
| | | $\rightarrow\alpha+{}^8Be_{g.s}$ | ${}^8Be_{g.s}\rightarrow\alpha+\alpha$. |
| | | $\rightarrow\alpha+{}^8Be^*_{G.A.}$ | ${}^8Be^*_{G.A.}\rightarrow\alpha+\alpha$ |
| $\alpha+{}^{12}C\rightarrow$ | $\alpha+{}^{12}C^*$ | $\rightarrow\alpha+{}^8Be^*_{2.96MeV}$ | ${}^8Be^*_{2.96MeV}\rightarrow\alpha+\alpha$ |
| | $E_{ex}$=10.3MeV | $\rightarrow\alpha+{}^8Be^*_{7.023MeV}$ | ${}^8Be^*_{7.02MeV}\rightarrow\alpha+\alpha$ |
| | | $\rightarrow\alpha+\alpha+\alpha$ | |

In the case of the excited level of the $^{12}$C* nucleus ($E_{ex}$=9.64 MeV) in the obtained projections of events from the strips bounded by green and blue frames (see Figs. 5, 6), another decay mechanism is manifested - through the emission of an alpha particle and the $^8$Be nucleus in the third excited state (see also Table 3).

To assess the ratio of decay modes of the detected two excited states of the $^{12}$C* nucleus ($E_{ex}$=10.3 MeV and $E_{ex}$=9.64 MeV) through different channels (two-particle and three-particle) decays, Monte Carlo modeling is required taking into account the simultaneous, so-called democratic, decay of the excited states of the $^{12}$C* nucleus ($E_{ex}$=10.3 MeV and $E_{ex}$=9.64 MeV) into three alpha particles.

Table 3

Decay modes of the excited state of the $^{12}C$ nucleus $E_{ex}$=9.64 MeV

| Exit channel | 1 step | 2 step | 3 step |
|---|---|---|---|
| | | $\rightarrow \alpha + {}^8Be_{g.s}$ | ${}^8Be_{g.s} \rightarrow \alpha + \alpha$ |
| | | $\rightarrow \alpha + {}^8Be^*_{G.A.}$ | ${}^8Be^*_{G.A.} \rightarrow \alpha + \alpha$ |
| $\alpha + {}^{12}C \rightarrow$ | $\alpha + {}^{12}C^*$ | $\rightarrow \alpha + {}^8Be^*_{2.96MeV}$ | ${}^8Be^*_{2.96MeV} \rightarrow \alpha + \alpha$ |
| | Езб.=9.64 MeV | $\rightarrow \alpha + {}^8Be^*_{7.02MeV}$ | ${}^8Be^*_{7.02MeV} \rightarrow \alpha + \alpha$ |
| | | $\rightarrow \alpha + {}^8Be^*_{10.73MeV}$ | ${}^8Be^*_{10.73MeV} \rightarrow \alpha + \alpha$ |
| | | $\rightarrow \alpha + \alpha + \alpha$ | |

By studying the formation of four particles in the output channel by registering only two particles at the coincidence, it is possible to obtain detailed information about the mechanisms of the 4-particle reaction and the characteristics of two- and three-particle unbound states of nuclei, despite the kinematically incomplete nature of the experiment.

By recalculating the $\alpha$-$\alpha$ coincidence matrices from the $^{12}C(\alpha,\alpha\alpha)^8Be$ reaction in the Q-spectra for this reaction, in addition to the known ground, first and second excited states of the $^8Be$ nucleus, another level with E=7.02(0.10) MeV, $\Gamma$=2.97(0.10) MeV was observed, the manifestation of which between the known first and second excited levels of the $^8Be$ nucleus restores the long-standing problem of the existence of the so-called

In the two-dimensional spectra of $\alpha$-$\alpha$ coincidences obtained as a result of the correlation kinematically-incomplete study of the 4-particle $^{12}C(\alpha,\alpha\alpha)\alpha\alpha$ reaction, the presence of excited levels of the $^{12}C^*$ nucleus ($E_{ex}$.=10.3 MeV and $E_{ex.}$=9.64 MeV) was revealed, which are characterized by both two-particle decay channels on the $\alpha$+ beryllium nucleus $^8Be$ in the ground and excited states, and three-particle decay channels (on $\alpha+\alpha+\alpha$). An “intruder” level was observed in the excitation spectrum of the $^8Be$ nucleus, with excitation energy E=7.02(0.10) MeV, and width $\Gamma$=2.97(0.10) MeV.

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