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PRELIMINARY RESULTS ON COLLINEAR CLUSTER TRIPARTITION IN ^{232}Th $+ d$ (10 MeV) REACTION

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Results of the first direct observation of the true ternary fission of ^{234}Pa* nucleus are presented. The yield of the effect depending on the experimental geometry is about 10^{-5}/binary fission. Mass of the lightest fragment in the triplet lies mainly in the range of 20–40 a.m.u. An intimate connection between the effect and known cluster decay as well as conventional binary fission is briefly discussed.

Представлены результаты первого прямого наблюдения истинно тройного деления ^{234}Pa*. Выход эффекта, зависящий от геометрии эксперимента, составляет около 10^{-5}/бинарное деление. Масса самого легкого осколка в триплете лежит, в основном, в диапазоне 20–40 а. е. м. Кратко обсуждается тесная связь эффекта с известным кластерным распадом и обычным бинарным делением.

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INTRODUCTION

Fission of low excited heavy nuclei into three fragments of comparable masses, so-called «true ternary fission» has not been unequivocally detected so far [1, 2] despite of multiple attempts to find such a decay channel till the early fifties of the last century. At the same time, fragmentation of the cold nuclear matter is of great interest in view of nuclear quantum, structural effects that stand behind. One of the brightest examples of such a kind is the heavy ion or cluster radioactivity when a strongly bounded nucleus close to Pb, being double magic, is preformed in the body of the mother system. Cluster radioactivity is a binary process. Bearing in mind that the magicity of one of the decay partners plays a key role in the process, the question arises whether multicluster decays appear to occur. Searching for decays of heavy nuclei in magic constituents (clusters by definition) seems to be a very promising topic of investigations.

In the early experiments at the FOBOS spectrometer [3] at the Flerov Laboratory of the JINR (Dubna, Russia) some unusual structures in the mass–mass plot of fission fragments (FF) from spontaneous fission of ^{248}Cm and ^{252}Cf nuclei were observed. These structures had the yield level of $\sim 10^{-5}$–10^{-6} with respect to conventional binary fission and were treated as an indication for new exotic decay — collinear cluster tripartition (CCT) [4, 5].

1. EXPERIMENT AND RESULTS

For better understanding of the effect revealed the programme of studying of its manifestations in different nuclear systems in a wide range of excitations was adopted. From the methodical point of view direct detection of all decay partners proves to be more convincing experimental approach reference to «missing mass» method used earlier. Thus, much more complicated spectrometer of high granularity is needed. Experimental facility of such a kind was used for searching for CCT channel in the reaction $^{232}\mathrm{Th} + d$ (10 MeV) (Fig. 1). The experiment was performed by the collaboration FLNR (JINR)–ATOMKI (Hungary). Two microchannel (MCP) based timing detectors and mosaic of nine 2×2 cm Si surface-barrier semiconductor detectors in each spectrometer arm were used in order to measure fragments masses in the frame of both double-velocity and velocity-energy methods. Each Si detector delivered both energy and timing signals in the events discussed below, while «start» signal was taken from the timing detector located at 170 mm from the mosaic. About $5.5 \cdot 10^6$ fission events were analyzed all in all.

Two different approaches were used for calibration of time-of-flight (TOF) and FF energy. More simple and rough one looks as follows. Known FF velocity spectrum for $^{252}\mathrm{Cf}$ (sf) was used for calculating the two coefficients in linear TOF calibration function. Energy losses in the source backing and timing detectors foils were ignored. In order to determine parabolic calibration dependence «channel-energy» known positions of the peaks in the double humped energy spectrum of the FF for $^{252}\mathrm{Cf}$ (sf) and corresponding alphas were exploited. This approach is called below as «3-point» calibration. Resultant spectrum of the FF M_{te} masses (velocity-energy method) summed over all Si detectors is shown in Fig. 2.

As can be referred from the figure both mass peaks of the light (L) and heavy (H) fragments in the spectrum obtained in our experiment are shifted to the center, but so that $\langle M_L \rangle + \langle M_H \rangle \approx 230$ a.m.u. what gives approximately correct post-neutron total mass of fragments.

The second calibration procedure used is based on parameterization of pulse height defect in Si surface-barrier detectors proposed in [7]. Energy losses of the FF over the flight path are also taken into account. Unknown calibration parameters are calculated by fitting of the experimental M_{te} quasimass spectrum to the known one for $^{252}\mathrm{Cf}$ (sf) [8, 9]. Unfortunately, the quality of the Si diodes let us exploit them in the run only at relatively low voltage.

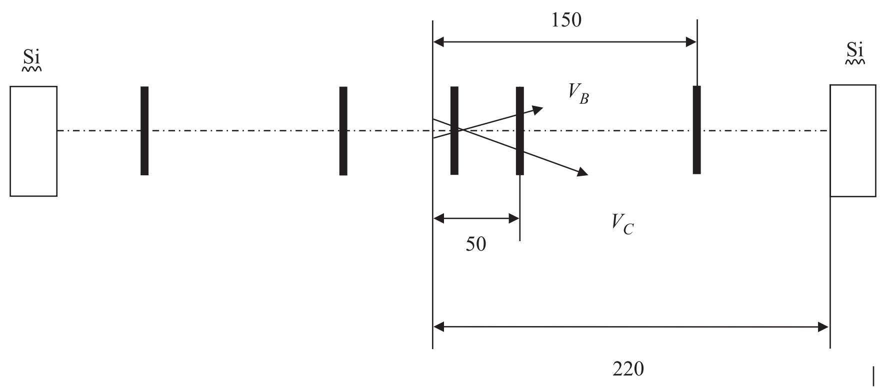

Fig. 1. Scheme of the experimental setup. See the text for details

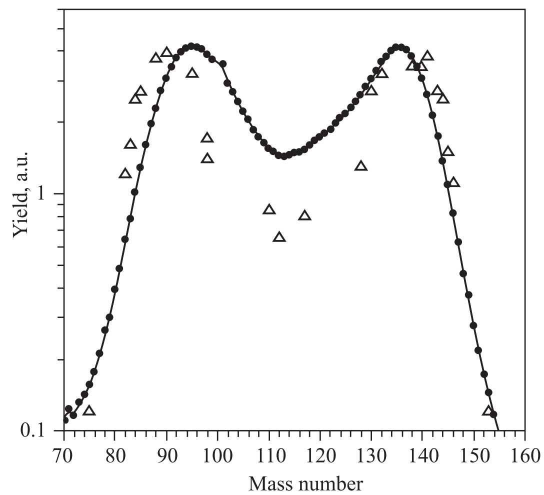

Fig. 2. Comparison of M_{te} spectra obtained in this work (circles) and M_{te} spectra from the reaction $^{232}\mathrm{Th} + d$ (11.5 MeV) [6] (triangles). The latter were obtained by radio-chemical method

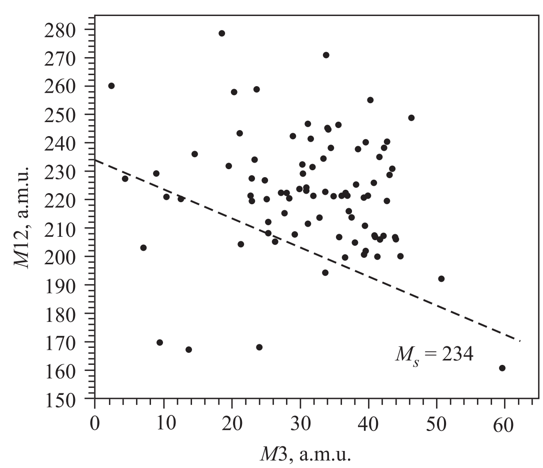

Fig. 3. Ternary events detected in the reaction $^{232}\mathrm{Th} + d$ (10 MeV). Here $M12 = M1 + M2$

Likely this is a reason of overestimated mass values obtained for ^{234}Pa* (approximately six mass units on total mass), while the FF M_{te} spectrum for ^{252}Cf (sf) is reproduced well.

All ternary events analyzed below were calibrated in the frame of «3-point» approach. For the sake of convenience the fragments in each ternary event were resorted in order of decreasing of fragment mass, namely, $M1$ is to be the heaviest, $M2$ is a middle one and $M3$ is the lightest. Ternary events detected are shown in Fig. 3. Their total yield is about $1.6 \cdot 10^{-5}$ per binary fission.

A bulk of points in the figure lies above the line $M_s = M1 + M2 = 234$ a.m.u., i.e., the mass of the compound nucleus. As was shown earlier [9], measured velocity of the less rapid fragment from the pair of fragments flying in one direction (Fig. 1) will be shifted due

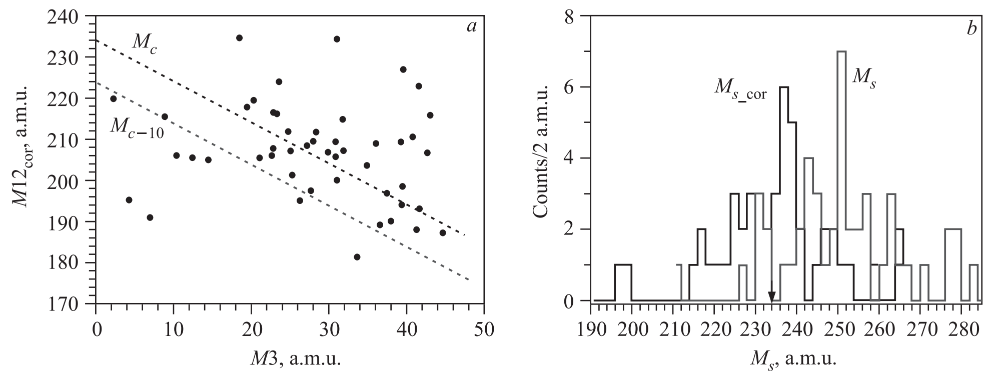

Fig. 4. *a*) Scatter plot of ternary events after correction of mass $M1$. The upper tilted line corresponds to the mass M_c of the compound nucleus. *b*) Comparison of the spectra of total masses of ternary decay products: initial one (M_s) and corrected (M_{s_cor}). The mass of compound nucleus is marked by the arrow

to the fact that the faster one gives «start» signal. This shift in the velocity gives too high corresponding mass value. Thus, the events lying above the tilted line in Fig. 3 could be due to this effect. The proper velocity V^{emis} of slower fragment B having experimental velocity V^{exp} can be calculated according to the formula:

$$V_B^{\mathrm{emis}} = \frac{22}{(17/V_B^{\mathrm{exp}}) + (5/V_C)}, \tag{1}$$

where V_C is the velocity of the faster partner in the pair.

In all ternary events where decay partners with the masses $M1$ and $M3$ fly in one direction we observe positive difference $V3$–$V1$. The scatter plot of these events after correction of mass $M1$ (the slower fragment) is presented in Fig. 4, a. Figure 4, b demonstrates the difference in spectrum of total mass before and after correction, respectively. Position of the main peak in the corrected spectrum is a little bit shifted, namely, $M_{s\_\mathrm{cor}} \approx 237$ a.m.u. It could be connected with the fact that experimental velocities were used for calculations within formula (1) instead of unknown proper velocity values which have the fragments on the flight path «target-start detector» (Fig. 1).

A «shoulder» of main peak from the left side (Fig. 4, b) is likely due to missing of forth fragment of mass ~ 10 a.m.u. (see the bottom line in Fig. 4, a).

Similar procedure of mass correction was applied to ternary events where the fragments of ranks «2» and «3» fly in the same direction (approximately half of all events). All of them show overestimated total mass values even after correction. We suppose a following scenario lies behind. Dinuclear system (molecule) formed after scission of the initial nucleus knocks out ^{12}C ion from the target backing. At the same time, this inelastic scattering destroys the molecule. As a result, three ions fly in the same direction and ^{12}C ion is the fastest among them. Thus, both $V3$ and $V2$ velocities must be corrected according to formula (1) what leads to increasing of corresponding masses $M3$ and $M2$. Quantitative testing convinced us that such a scenario is absolutely realistic. Unfortunately, true energy of the scattered ^{12}C ion is unknown in each event under analysis preventing one in making proper correction.

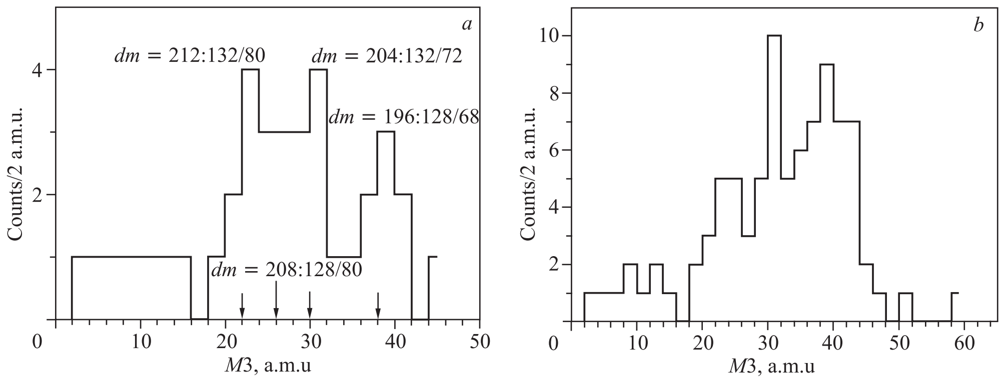

Fig. 5. *a*) Mass spectrum of the lightest fragments in each detected triplet of fragments under condition $M_s < 242$ a.m.u. (see Fig. 4, *b*). *b*) Similar spectrum for all ternary events detected. The arrows in the figure mark the partitions based on pairs of known magic nuclei of Ni, Ge, Sn

Mass spectrum $Y(M3)$ of the lightest fragments in each detected triplet of fragments under condition $M_s < 242$ a.m.u. (right border of the main peak in spectrum of M_{s_cor} in Fig. 4, *b*) is shown in Fig. 5, a. Similar spectrum for all ternary events detected is presented in Fig. 5, b. Comparing the spectra one comes to the conclusion that the latter could be transformed to the first one due to «swap» of counts from heavier to lighter masses. It is precisely the tendency predicted by the scenario above linked with knockout of fast ^{12}C ions.

2. DISCUSSION

In our works [4, 5] the island of high yields of the CCT events (two-dimensional bump) in the mass–mass distribution of the FF from ^{252}Cf (sf) and ^{235}U(n_{th}, f) is discussed. In both cases the bump shows the same internal structure consisting of the ridges $M_s = \mathrm{const}$. While the masses of initial decaying systems differ on 16 a.m.u., positions of the ridges stay in the range 200–212 a.m.u. We supposed that the pairs of magic nuclei (light plus heavy one) of Ni, Ge and Sn stand behind this permanency. Here we observe directly light fragments calculated in the cited works as «missing» masses added the total masses of pairs of magic clusters to the mass of mother system. *It seems to be very clear physics rules over the effect. As in known heavy ion radioactivity (cluster decay) the double magic Pb cluster plays a key role, pair of magic clusters does the same in the CCT mode under discussion.*

The idea put forward is confirmed as well by the results obtained by M. L. Muga and coworkers [10]. Mass spectra obtained in this work for the lightest fragment and the one published by M. L. Muga are compared in Fig. 6.

As can be referred from the figure the confines of the gross peaks in the spectrum for ^{234}U* and that shown in Fig. 5, b are in good agreement. We observe as well the tendency similar to this revealed in our previous data, namely, gross peak in mass spectrum of lightest fragments changes its position following the mass of compound nucleus. Really, the sharp rise of the yield in all three spectra presented in Fig. 6 starts at the partitions (marked by the triangles) corresponding to the same value of difference $M_c - M3 = 212$ a.m.u. presumably linked with total mass of magic clusters of ^{132}Sn and ^{80}Ge.

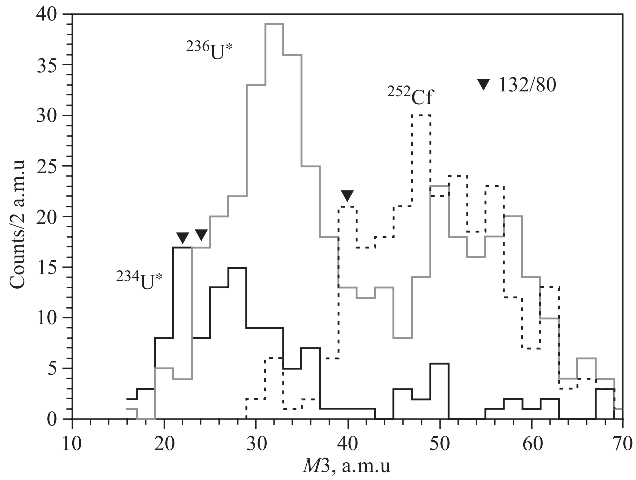

Fig. 6. Mass spectra of the lightest fragment in ternary fission of three different fissioning systems [10]. Triangles mark the partitions corresponding to the fixed difference $M_c - M3 = 212$ a.m.u. presumably linked with total mass of magic clusters of ^{132}Sn and ^{80}Ge

Ternary decays were detected in [8] by three Si semiconductor detectors placed at 120° to each other. Estimated yield did not exceed 10^{-6}/binary fission. The effect for ^{234}Pa* is observed at the level of 10^{-5}/binary fission, but these values can be hardly compared due to absolutely different geometry of the experiments. Total angular distribution of the ternary decay partners is also unknown for the moment. We can only remind that in the events identified as ternary decays in the frame of the missing mass approach two detected fragments fly in the opposite directions (i.e., at 180° to each other) within angular resolution to be less than 2° [4, 5]. Experimental angular spread of the fragments originated from the ternary decay of ^{234}Pa* flying in one direction can range from 1 up to 20°. Thus, measuring of both angular distribution of partners of ternary decay under discussion and its yield stays an actual goal of special forthcoming experiments.

Due to peculiarities of the FF energy calibration used we lack opportunity to analyze accurately mass–energy correlations of ternary decay products in the wide range of masses and energies. By its nature the calibration works well only in the vicinity of three points on the E–M plane chosen as reference points. Just imperfection of the calibration forces us to treat the results as «preliminary».

CONCLUSIONS

Basing on direct detection of three coincident reaction products we declare first observation of true ternary fission of ^{234}Pa* from the reaction $^{232}\mathrm{Th} + d$ (10 MeV). The yield of the effect being dependent on the geometry of the experiment is about 10^{-5} per binary fission. Experimental angular spread of the ternary decay products flying in one direction can range from 1 up to 20°. Mass spectrum of the lightest fragments in each detected triplet of fragments shows gross peak in the range of 20–40 a.m.u. The spectrum agrees with this followed from our previous experiments aimed at searching for collinear ternary decays performed in the frame of missing mass approach [4, 5]. It is in good agreement as well with the similar spectrum obtained by Muga et al. for ^{234}U* [10].

Available data confirm our hypotheses put forward earlier [4] that the lightest among the ternary decay partners adds total mass of pair of magic clusters Ni/Sn or Ge/Sn forming magic «core» up to the total mass of fissioning system. It is reasonable to suppose that as in heavy ion radioactivity (cluster decay) the double magic Pb cluster plays a key role, pair of magic clusters does the same in the CCT mode under discussion. Decisive role of magic pairs of Ni/Sn and Ge/Sn in ternary decay seems to be expectable bearing in mind that they govern in the main conventional binary fission as well [11–14].

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