COMPARATIVE STUDY OF THE THRESHOLD MULTIFRAGMENTATION AND BINARY FISSION OF HEAVY NUCLEI BY 1 GeV PROTONS

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For experimental comparative study of the multifragmentation and binary fission of ^{238}U, ^{232}Th and ^{197}Au nuclei induced by 1 GeV protons, a double-arm time-of-flight spectrometer was used [1, 2]. The idea of the present experiment consisted in the registration of heavy products of the above-mentioned reactions in coincidence with one of the accompanying clusters (AC) and in the processing of experimental data with the use of fission parameters for the determination of multifragmentation ones [3]. A typical two-dimensional distribution of reaction products that were recorded by this spectrometer in the case when its arms were arranged collinearly in the direction orthogonal to the proton beam incident on a thin (80 μg/cm^2) ^{238}U target (collinear geometry) is shown schematically in Fig. 1 in terms of the velocity–momentum (V–P) coordinates for $V \geq 0.45$ cm/ns.

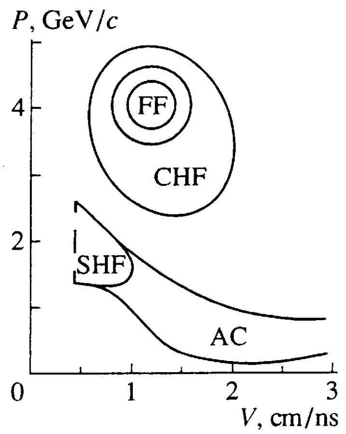

Fig. 1. Contour plot for the disintegration products of ^{238}U at the incident proton energy of 1 GeV. Notations: (FF) binary-fission fragments, (CHF) coincident heavy fragments, (SHF) single heavy fragments, and (AC) accompanying clusters (*i.e.*, clusters accompanying all types of heavy fragments). Selection criteria: $M_{FF} > 40$ amu, $E_{FF} > 35$ MeV, $(M_1 + M_2) > 163$ amu; $M_{CHF} > 40$ amu, $E_{CHF} > 35$ MeV, $(M_1 + M_2) < 163$ amu; where $M_{1,2}$ – coincident-fragment's masses; $M_{SHF} > 40$ amu, $E_{SHF} < 35$ MeV; $M_{AC} < 40$ amu, $E_{AC} < 50$ MeV

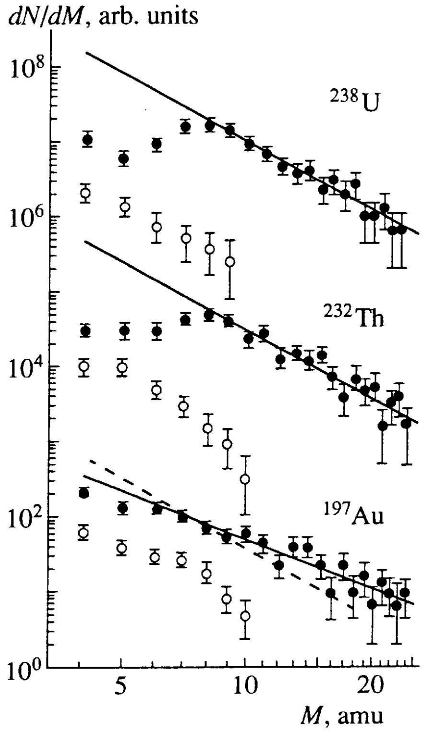

Fig. 2. Mass distributions of accompanying clusters in AC–SHF (closed circles) and AC–FF (open circles) events. The solid lines and dashed line represent, respectively, power-low approximations of these mass distributions and one for single clusters

We established that in the near-threshold energy region the multifragment breakup of nuclei results usually in the production of a single heavy fragment (SHF) accompanied by approximately ten smaller clusters and 30–40 free nucleons. For comparison: we measured that fission fragments (FF) at $E_p = 1$ GeV are accompanied, on the average, by 1.2 ± 0.2; 1.7 ± 0.2 and 2.6 ± 0.4 clusters for ^{238}U, ^{232}Th and ^{197}Au nuclei, accordingly, and by 10–15 released nucleons [3–6]. The mass distributions of AC accompanying SHF and FF are shown in Fig. 2. The corresponding mean masses of these AC, along with the most probable values of the single-heavy-fragment masses and fission-fragment ones which were recorded by the double-arm time-of-flight spectrometer in the collinear geometry, are quoted in the Table.

Table

The comparison of the mean masses of heavy fragments and accompanying clusters produced in the nuclear reactions of multifragmentation and binary fission induced by 1 GeV protons

Targets	$\langle M_{SHF}\rangle$, amu	$\langle M_{AC}^{(SHF)}\rangle$, amu	$\langle M_{FF}\rangle$, amu	$\langle M_{AC}^{(FF)}\rangle$, amu
^{238}U	92 ± 2	9.5 ± 0.4	110.5 ± 1	4.0 ± 0.2
^{232}Th	86 ± 2	10.0 ± 0.4	106 ± 1	4.2 ± 0.2
^{197}Au	77 ± 2	7.2 ± 0.4	88 ± 1	3.8 ± 0.2

The ensemble of AC in each event is grouped near the direction opposite to that of the high linear momentum of SHF (on the average 1.5−1.8 GeV/c). That is, the emission of AC in events featuring SHF is anisotropic in the centre-of-mass frame of the residual nucleus; hence the breakup of nuclei is fast. The anisotropy of AC was found to be equal from 2.3 ± 0.2 for ^{197}Au to 3.5 ± 0.3 for ^{238}U [3–6]. The reason is that in an expanding nucleus undergoing fast disintegration the Coulomb repulsion from the SHF has a stronger effect than the repulsion of accompanying clusters one from another. As a result, at the freeze-out instant the SHF and the ensemble of AC are at opposite poles of the expanding nucleus. This entails the high recoil momentum of SHF, the anisotropy of a cluster emission, a comparatively high velocity of their centre of mass, and low relative velocities between large clusters. The latter effect, which is considered to be a key quantity in the multifragmentation, has been observed in our experiments [3–6], too. It proves a low freeze-out density of the expanding nucleus.

The power-low approximation's exponent τ of a cluster's mass distribution $N(M_{AC}) \propto M_{AC}^{-\tau}$ for ^{197}Au target proved to be less than the corresponding quantity in the reaction leading to the emission of single AC having the same mass. For ^{238}U and ^{232}Th nuclei a deviation from the power low in the region $M_{AC} \le 7$ amu has been found (see Fig. 2). We believe that this effect is of a threshold character and attribute it to the increase of the anisotropy with increasing cluster's masses and the decay of a part of small primary clusters in the course of a nucleon exchange process through the "gas" phase within an expanding nucleus and the corresponding increase of the dimensions of clusters with radii bigger than the critical size.

The mean excitation energy of ^{197}Au nuclei has been estimated through the average multiplicity of AC and the exponent in the power-low approximation τ of their mass distribution and turned out to be equal to around 500–600 MeV. Comparison of our experimental data for ^{197}Au with statistical-model simulations reveals that the calculated average mass of the SHF has been overestimated at this excitation energy [6]. The multifragmentation cross sections σ_{SHF} at E_p = 1 GeV are found to be 120 ± 40 mb for ^{238}U, 110 ± 30 mb for ^{232}Th, and 10 ± 5 mb for ^{197}Au. They were estimated for each target nucleus through the fission cross sections σ_f by using the relative method [6].

The fission-like multifragmentation (coincident heavy fragments (CHF) with nearly equal mean masses $\langle M_{CHF}\rangle$ = 74 ± 4 amu − that corresponds to filled deformed shells − in a company with 7–8 light charged particles (LCP, $\langle M_{LCP}\rangle \approx$ 4 amu) and some tens of released nucleons) is a more rare process. According to our measurements, the cross section for fission-like multifragmentation of ^{238}U is σ_{CHF} = 12 ± 2 mb [1, 5]. Like FF, the CHF have approximately opposite linear momenta of the same magnitude. The most probable azimuth angle between directions of CHF is $\langle\theta\rangle$ = 171° ± 1° (for comparison: all events of ^{238}U fission induced by 1 GeV protons are characterized by $\langle\theta\rangle$ = 174.7° ± 0.2°). The corresponding mean value of the longitudinal component of the linear momentum transferred from the incident proton to a homogeneous residual nucleus − the source of CHF − obtained from extrapolated folding-angle distribution for the CHF is $\langle P_{\parallel}^{(CHF)}\rangle$ = 700 ± 100 MeV/c (and for FF, respectively, $\langle P_{\parallel}^{(FF)}\rangle$ = 350 ± 30 MeV/c) [1]. At the same time, the transverse-momentum-imbalance distribution of the CHF is similar to the fission-fragment's one [1, 7]. It indicates to low-energy particles accompanying these CHF [1].

The mean relative velocity of CHF, which is equal to $\langle V_1 + V_2\rangle$ = 3.0 ± 0.1 cm/ns (for FF: 2.4 ± 0.1 cm/ns), is consistent with that touching spherical fragments of mass 74 amu would acquire as a result of the mutual Coulomb repulsion in case they had equal numbers of protons and neutrons[1, 7].

For ^{238}U, the cross section σ_{CHF} increases by up to one order of magnitude between the incident proton energies E_p = 1 GeV and E_p = 11.5 GeV, while σ_{FF} decreases in this energy region by around half a magnitude. The energy balance of the former nuclear reaction becomes realistic in the presence of an internal energy of the residual nucleus higher than 500 MeV.

The multifragmentation of ^{197}Au nuclei induced by 1 GeV protons proved to be a rare phenomenon: its cross section σ_{SHF} is less than 3% of the total cross section of inelastic interaction $\sigma_{in.}$ For actinides, however, we obtained $\sigma_{SHF} \approx 7\%$ of σ_{in}. In all probability, this is because actinide nuclei are rather loosely bound. Under the effect of a branched fast cascade, they readily break up into clusters and fragments as soon as this becomes allowed by their internal energy. In our opinion, this looseness is due to their large nuclear charges and dimensions.

To our thinking, a momentary reduction of the nuclear binding energy on the branched intra-nuclear-cascade stage may be the starting mechanism of the heavy-nuclei's multifragmentation in the near-threshold energy region. It results in fast breakup of the highly excited nuclei by joint forces of the Coulomb repulsion and the thermal pressure. A partial transformation of a chaotic thermal motion of nucleons into an ordered radial flow as well as the possible emission of nucleons and LCP at early stages of the residual-nucleus expansion reduce the excitation energy of this nucleus to such an extent that large clusters begin to grow at the expense of the disappearance of smaller ones. This process ends up in the formation of one or two especially large fragments accompanied by a few clusters. In this case, the freeze-out of CHF becomes possible under two conditions: not only must these fragments be near the ground state but it is also required that their binding energy is maximal.

The fact that the cross section for the reaction under study depends strongly on the charge of the target nucleus and that the emission of clusters is anisotropic in the c.m. frame of the residual nucleus allows to suggest that the Coulomb repulsion plays a key role in the near-threshold multifragmentation of heavy nuclei.

References

[1] B.Yu.Sokolovsky, Candidate of Sciences (Phys.-Math.) Dissertation, PNPI, 2002. 130 p. (unpublished).

[2] Yu.A.Chestnov and B.Yu.Sokolovsky, Preprint PNPI-2314, Gatchina, 1999, 40 p.

[3] Yu.A.Chestnov and B.Yu.Sokolovsky, Izvestiya Akademii Nauk **66,** 685 (2002).

[4] Yu.A.Chestnov and B.Yu.Sokolovsky, in *Theses LI Meet. Nucl. Spectr. Nucl. Struct., Sarov,* 2001. p.218.

[5] Yu.A.Chestnov and B.Yu.Sokolovsky, Yad. Fiz. **64**, 1541 (2001) [Phys. At. Nucl., **64**, 1464 (2001)].

[6] Yu.A.Chestnov and B.Yu.Sokolovsky, Preprint PNPI-2350, Gatchina, 2000, 49 p.

[7] Yu.A.Chestnov and B.Yu.Sokolovsky, Yad. Fiz. **60**, 822 (1997) [Phys. At. Nucl. **60**, 720 (1997)].