ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E7-99-253

Yu.V.Pyatkov[1], Yu.E.Penionzhkevich, O.I.Osetrov[2], A.A.Alexandrov, I.A.Alexandrova, V.F.Kushniruk, Yu.G.Sobolev, V.A.Maslov, Z.Radivojevic[3], W.H.Trzaska[2], S.V.Khlebnikov[2], V.G.Lyapin[2], V.A.Rubchenya[2], G.P.Tiourine[2], D.N.Vakhtin[3]

CLUSTER DECAY CHANNEL IN $^{238}U+^{40}Ar$ (243 MeV) REACTION

Submitted to «Nuclear Physics A»

[1]Moscow Engineering Physics Institute, Moscow, Russia
[2]Khlopin Radium Institute, St.Petersburg, Russia
[3]Accelerator Laboratory, Department of Physics of University of Jyväskylä, Jyväskylä, Finland

1999

Пятков Ю.В. и др. E7-99-253

Канал кластерного распада в реакции $^{238}U+^{40}Ar$ (243 МэВ)

Исследовалась реакция $^{238}U+^{40}Ar$ (E_{lab} = 243 МэВ). В массовом распределении продуктов распада ядерной системы $^{278}110$ с начальным возбуждением 60 МэВ впервые обнаружена хорошо выраженная тонкая структура (ТС) в виде отдельных пиков. Пики ТС расположены в окрестности массовых чисел A~70, 100, 130, характерных для магических ядер (кластеров) Ni, Ge, Zr, Sn, Sr. Пики ТС содержат события только с низкой энергией, обусловленные распадом очень удлиненных предразрывных конфигураций системы. Наблюдается также несколько событий, которые можно трактовать как тройной распад таких конфигураций с появлением двух одинаковых кластеров. Таким образом, предположительно реализуется канал коллинеарного тройного кластерного распада, наблюдавшийся ранее в спонтанном делении ядер ^{248}Cm и ^{252}Cf.

Работа выполнена в Лаборатории ядерных реакций им.Г.Н.Флерова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1999

Pyatkov Yu.V. et al. E7-99-253

Cluster Decay Channel in $^{238}U+^{40}Ar$ (243 MeV) Reaction

The reaction $^{238}U+^{40}Ar$ (E_{lab} = 243 MeV) was studied. For the first time a pronounced fine structure (FS) in the form of distinct peaks has been observed in the mass yields of the fragments of the $^{278}110$ nuclear system decay at the initial excitation of about 60 MeV. The FS peaks are located in the vicinity of the mass numbers A~70, 100, 130, which are specific for magic nuclei (clusters) of Ni, Ge, Zr, Sn, Sr. The FS peaks contain only low-energy events linked with the very elongated prescission configurations of the system. Some events are observed which can be treated as an indication of ternary fission via such configurations with the appearance of two equal clusters. Hence presumably the collinear cluster tripartition channel is realized observed earlier in the spontaneous fission of ^{248}Cm and ^{252}Cf nuclei.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 1999

Introduction

Some preliminary results of a study of the reaction ^{238}U+^{40}**Ar** at the beam energy E_{lab}=243 MeV are presented below. One of the goals of the experiment carried out was searching for and analyzing the manifestation of nuclear shells in the mass spectrum of the fragments. This question has a long-lived history. As was shown in a set of experiments (see for instance ref. 1,2) in the interaction of heavy nuclei with ions of A≥40 at intermediate energies the mass spectra exhibit peaks suggesting a preference for asymmetric fragmentation (A_1~90, A_2~200). It was proposed [1,2] that such peaks could be due to the doubly-closed ^{208}**Pb** shell, which manifests itself in the fission of a nuclear system close to statistical equilibrium. Later [3] a more trivial explanation was put forward based on the sequential fission origin of the peaks under discussion. Recent experiments on the synthesis of syperheavy elements gave rise to a new wave of interest to shell effects in this field.

In order to check out the alternative existing hypothesis we chose the reaction ^{238}**U**+^{40}**Ar,** which leads to the compound nucleus ^{278}**110,** which, by its composition, consist of the double magic nuclei of **Ni** and **Pb**. It is reasonable to expect shell effects to manifest themselves more pronouncedly in this case.

Experiment

The experiment was carried out at the **HENDES** (High Efficiency Neutron Detection System) set-up installed at the K-130 cyclotron at the University of Jyväskylä (Finland) [4].

A ^{238}**U** target 300 μg/cm^2 in thickness was prepared by evaporation onto a thin (65 μg/cm^2) backing. The target was located at 5 degrees relative to the beam axis (fig. 1) for minimizing the energy losses of the fragments. The reaction fragments were detected by a two armed time-of-flight spectrometer. A parallel plate avalanche counter (PPAC) and a position sensitive avalanche counter (PSAC) [5] delivered "start" and "stop" signals in each arm and were operated at 3.2 Torr of pentane vapour. Mylar foils 0.9 μm and 1.2 μm thick were used as entrance windows in the PPACs and PSACs, respectively. The cathode planes of the PSACs were fabricated from Mylar foil 1.2 μm thick with 40 μg/cm^2 Au layers evaporated on both surfaces. The PSACs with a sensitive region of 24.3 cm in diameter and a space resolution of 1.5 mm were placed at 24.7 (24.9 cm) from the target at 60^0 (70^0) to the beam axis. The time-of-flight bases of the arms equal to 21.0 cm (21.2 cm) were determined by the PSACs and the start detectors (PPACs) placed at 3.7 cm from the target. Four surface-barrier Si detectors ~30 cm^2 each were located behind the PSACs to measure the energy of the fragments. The laboratory angle range covered was 30^0 - 90^0 (40^0-100^0) in

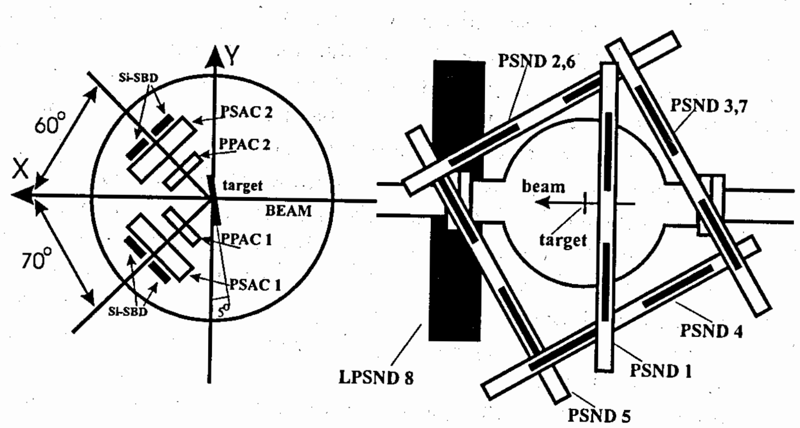

Fig.1 Experimental setup scheme.

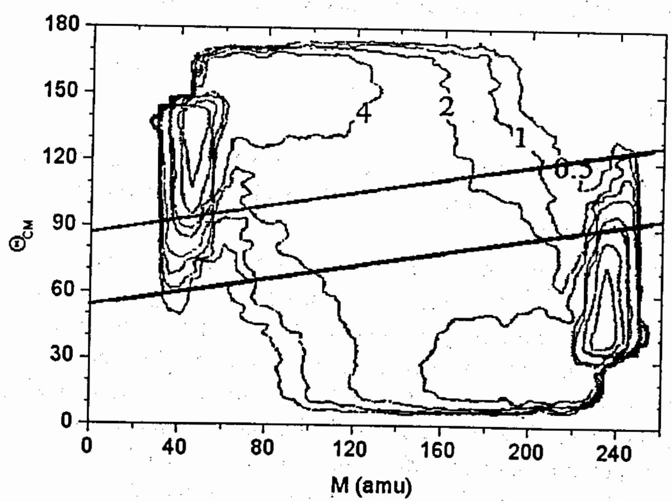

Fig.2. Contour plot of the double-differential cross section as a function of the center-of-mass scattering angle and the mass A for binary events, integrated over all values of the kinetic energy. $^{238}U+^{48}Ca$ (6AMeV) reaction, inverse kinematics [6]. The region between parallel lines is accessible to observation in our experiment.

the reaction plane and -30^0 - $+30^0$ out of the reaction plane. We were especially interested in the shell peculiarities in the fission channel. For extracting such events kinematically, the chosen angle-range seems to be close to optimal. It is clearly seen in fig. 2 that the yield of unequilibrated mass-drift modes is effectively suppressed in the chosen region. The velocity vectors of the fragments in the laboratory frame can be determined using the time-of -flight (TOF) and interaction point positions on the PSAC surface, measured for each fragment. The fragment mass and energy distributions were deduced using the equation

$$m_{1,2}=(M_p+M_t)(V_{2,1}\sin\theta_{2,1})/(V_1\sin\theta_1+V_2\sin\theta_2),$$

where $M_{p,t}$ - are the atomic masses of the beam particle and the target;
$V_{1,2}$ - are the fragment velocities;
$\theta_{1,2}$ - are the angles to the beam axis in the laboratory frame.
The measured velocities were corrected for the energy losses in the target, active layer and in all the foils of the start and stop detectors. The fragment detectors and the target were placed inside a thin stainless steel spherical reaction chamber of 0.8 m diameter.

Position sensitive neutron detectors (PSND), filled with NE213 liquid scintillator, were located outside the chamber at about 120 cm from the target. Each PSND had a 1 m active length and 1.4 ns time resolution and 10-20 cm position resolution; depending on neutron energy. Neutrons were identified using two parameters, namely TOF and the fast- to slow- component relation of the scintillator signal.

Results and discussion

The mass-total kinetic energy (M-TKE) distribution of the fragments obtained is shown in fig. 3. No corrections for geometrical efficiency as a function of the emission angle of the fragments were introduced into this distribution. The mean TKE value is sufficiently lower (~180 MeV) than that predicted by the systematics for syperheavy nuclei (~217 MeV) [2]. It is not due to a calibration shift because we had the correct TKE values for elastic scattering peaks. This difference may partially be due to the angle range covered by the time-of-flight arms. As can be inferred from fig. 4, the sharp decrease of the yield starts at ~137^0 (just at the value of the laboratory folding angle corresponding to TKE=217 MeV). So the high energy part of the fragment spectrum is suppressed due to kinematical reasons. The integral mass spectrum is presented in fig.5. This smooth function without any visible structures looks like the akin spectra obtained at close excitations in previous works [3,7,8]. Fig. 6 depicts the TOF-TOF correlations of the fragments. As is known [3,9], the measured fission yield for reactions on actinide targets contains three components.The first

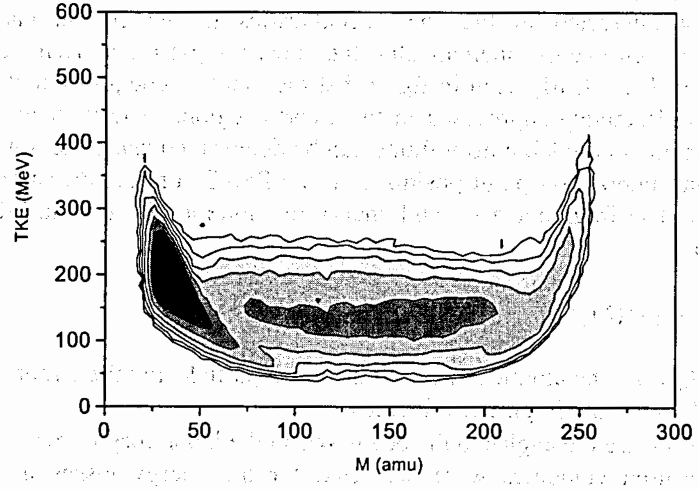

Fig.3. Mass-TKE correlations of fragments.

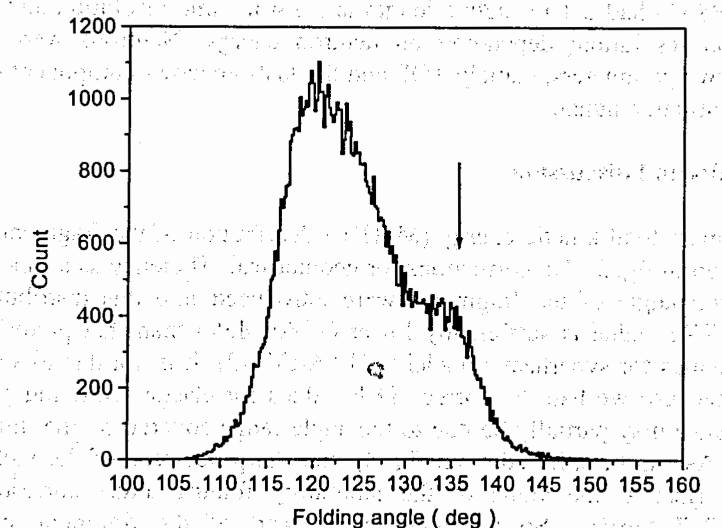

Fig.4. Laboratory folding angle spectrum.

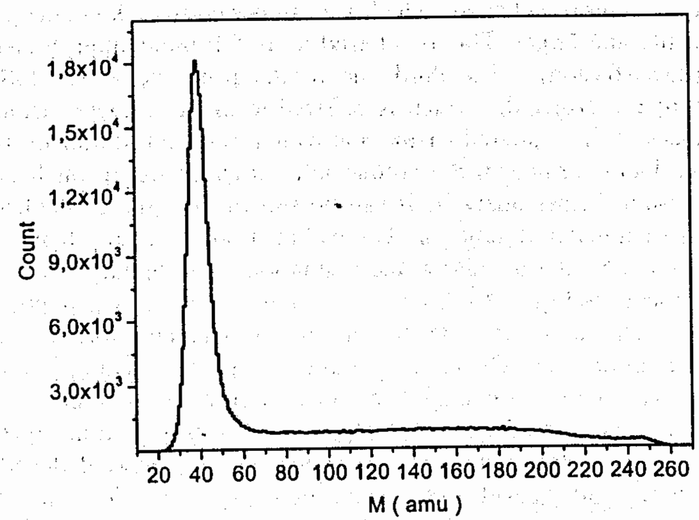

Fig.5. Total mass spectrum of fragments.

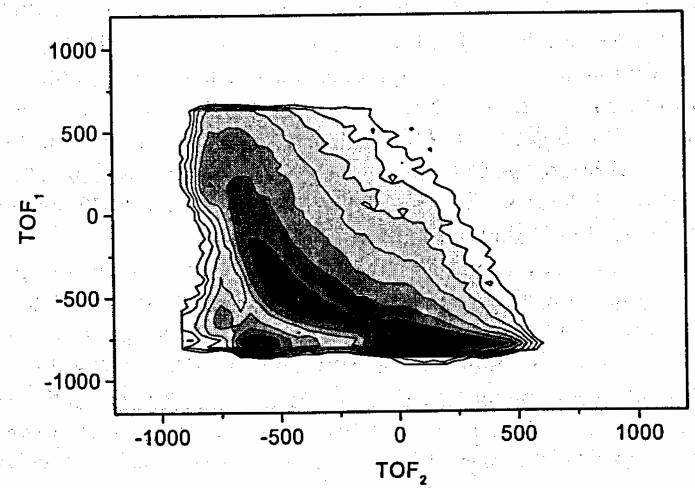

Fig.6. TOF-TOF correlations of fragments.

results from the fission of targetlike nuclei, which occurs due to excitation over the fission barrier during transfer reactions, in grazing collisions. The second is due to more central collisions, which lead to the more or less amalgamation of the projectile and target. This is referred to as full momentum transfer (**FMT**) fission (quasi-fission). The third one results from the fusion following the break-up of the projectile, which is referred to as incomplete fusion. Random coincidences of the scattered Ar-like ion with a fragment of transfer fission give rise to the locus located in the bottom left corner of fig. 6. Such events were excluded from further analysis. It can be shown that true coincidences of the fragments of transfer fission are also excluded due to PSAC being capable of detecting the very sharp angle of their emission from the target (the fragments lose too much energy). So the two reaction channels, which prove to be a hindrance background for the fission events searched for, are sufficiently suppressed in our case. The next "cleaning" used for extracting fission events is connected with the experimental determination of the two components $\mathbf{V_{perp}}$-$\mathbf{V_{par}}$ of the velocity vector of each fissioning nucleus as proposed in [9] (fig. 7). The component in the beam direction , denoted by V_{par}, was deduced from the folding angle and the velocities of the two fragments. The other component $\mathbf{V_{perp}}$ is in the plane perpendicular to the beam, and is perpendicular to the projection of the scission axis onto this plane. It was determined from the azimuthal folding angle and the projection of the measured fragment velocities onto this plane. The **FMT** fission events lie, following [9], at the centre of fig. 7 and should be involved in analysis. The events which satisfy both the $\mathbf{V_{par}}$-$\mathbf{V_{perp}}$ selection criteria and coincide with the neutrons detected in the **PSND,** located at the backward angles out of the reaction plane, are shown in fig.8. The laboratory folding angle of the fragments was chosen as a variable close to **TKE** but measured with better resolution and free from systematic errors. The latter arise when one calculates the **TKE** values for the nuclear system that appeared, for instance, after incomplete fusion. There appears to be four components on the map of fig. 8 (S1-S4). The mass distributions for the **FMT** events (set1, and set1+set2 in fig. 8) are shown in fig. 9.

The fine structure (**FS**) of the spectra in the form of distinct peaks attracts attention. Similar but less pronounced structures were observed in [10] for the same reaction at 247 MeV of the ^{40}**Ar** beam. The **FS** peaks are located in the vicinity of the mass numbers A~70, 100, 130, which are specific for spherical and deformed magic nuclei (clusters) of **Ni, Ge, Zr, Sn, Sr. TKE** and velocity in the center of mass ($\mathbf{V_{CM}}$) distributions for the events selected from the spectra of fig. 9 are displayed in figs. 10,11. It should be emphasized that the **FS** peaks contain only low-energy events linked with the very elongated prescission configurations of the system.

The physical origin of the **FS** considered seems to be very close to that observed recently in the spontaneous fission of ^{248}**Cm** and ^{252}**Cf** nuclei [11]. The quoted experiments aimed at searching for the true ternary fission of ^{248}**Cm**

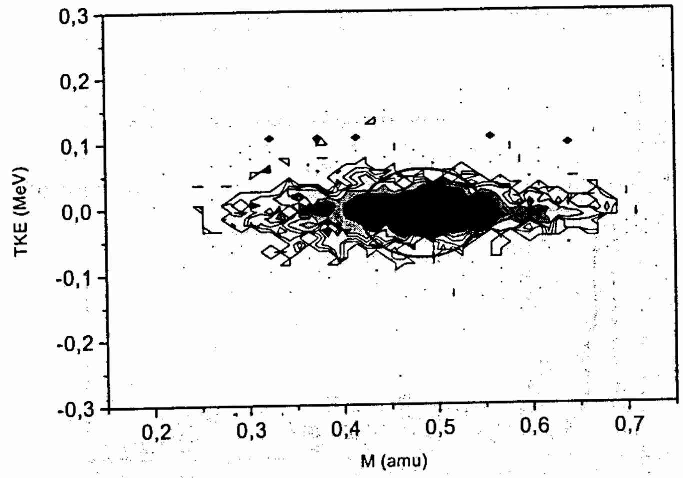

Fig.7. Experimentally determined velocity components of the fissioning nuclei V_{par} and V_{perp} (see the text for definitions). The central circle is a selection region for FMT binary events.

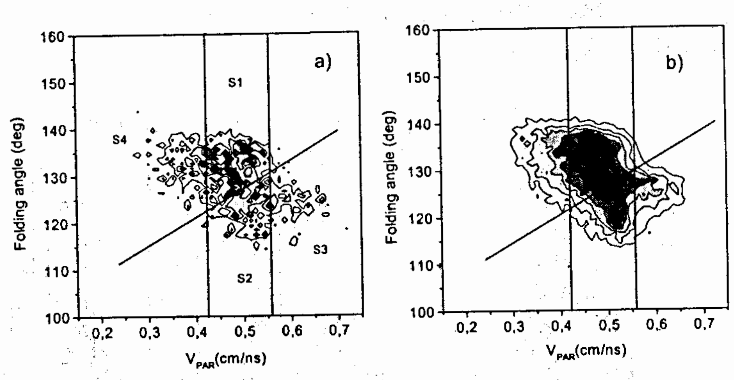

Fig.8. Laboratory folding angle as a function of V_{par} at the condition that neutron was detected: a) in PSND1 (backward angles), b) in PSND8 (forward angles).

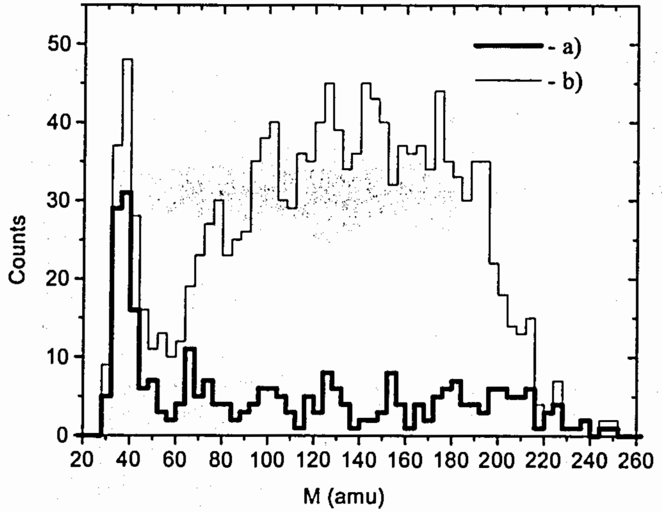

Fig.9. Mass spectra of fragments for events satisfied three selection criteria: coincidence with neutrons detected in PSND1, V_{par}-V_{perp} gate (fig.7), Set1-gate (fig. 8)-a), Set1+Set2 gate (fig. 8)-b).

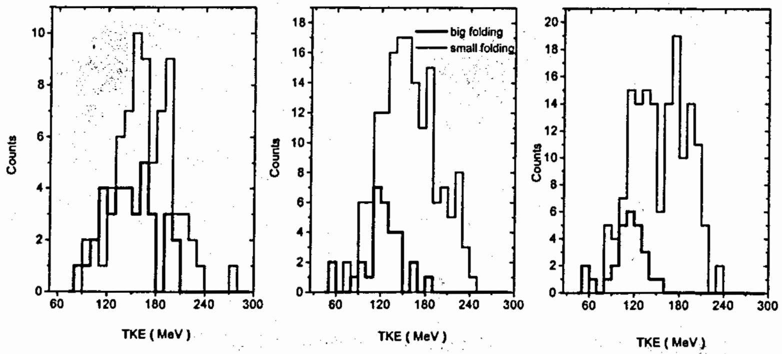

Fig.10. TKE spectra of fragments linked with peaks in fig. 9a.

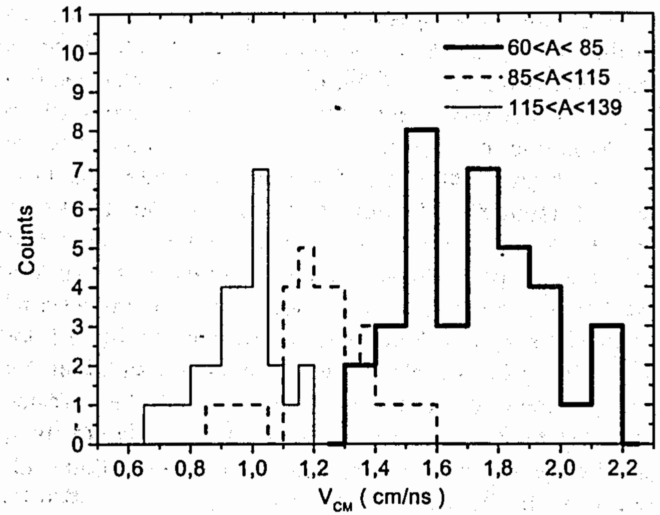

Fig.11. V_{CM} spectra of fragments linked with peaks in fig. 9a.

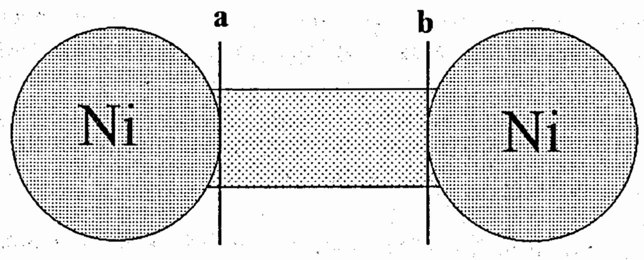

Fig.12. Presumable prescission shape of the fissioning system in the frame of the cluster mode linked with the FS in the mass yields.

and ^{252}**Cf** nuclei, were carried out at the 4π-spectrometer of charged fragments **FOBOS**, installed at the FLNR , Dubna [12]. Of the 10^7 spontaneous fission events observed for each nucleus under study some events were detected in the frame of the time-of-flight – energy (**TOF-E**) method in which the total mass of the two fragments was about 30% smaller than the mass of the fissioning nucleous. The fragments corresponding to the group of rare events are concentrated in the vicinity of the mass-numbers A~72, 82, 88, 96, which are specific for magic nuclei (clusters) of **Ni, Ge, Se, Sr**. An analysis of the mass-energy correlations for the rare events (the total yield is about 10^{-5} relative to binary fission) allows one to associate them with the fission of the system via very elongated and highly deformed di-cluster configurations [13] with an excitation energy of about 80-120 Mev at the scission point. The preliminary results noted have been interpreted as an indication of a new mode of the multicluster decay of heavy actinide nuclei. Taking into consideration the results mentioned above, we have tried to check out the hypothesis whether the prescission shape of the system looks like as sketched in fig. 12 and whether there were any triple fission events caused by two-fold simultaneous ruptures that occurred at the interface of the clusters (fig. 12). As a result, the two fragments at the extreme left and extreme right positions should fly apart along the chain axis whereas the middle fragment should stay almost in rest. The expected velocities of the fragments would be a little bit less than those in the binary fission of such a configuration with the emergence of only one cluster-just the events which give rise to the **FS** peaks in fig. 9. The velocities of the clusters in binary decay seem to be known (fig. 11). Summarizing, one should search for fragments with approximately equal velocities and unrealistically high **TOF-TOF** energies (i.e. the energies calculated in the frame of the **TOF-TOF** method) due to the wrong mass of the compound nucleus used for the calculation. Really, the **TOF-TOF** method is out of law for triple events.

To answer the question posed, the **TOF-TOF** energies and amplitudes in the Si-detector were compared for a set of events with roughly equal velocities (fig. 13,14). There are four sets of points on the map of fig. 14 with significantly different amplitudes in the **Si-detector** at the same value of the **TOF-TOF** energy.

Going from the upper part of fig. 14, sets of points are seen linked presumably with conventional binary symmetric fission events (the most populated family), the **Sn-Sn**, **Zr-Zr** (or/and **Sr-Sr**) and **Ni-Ni** modes respectively. The points linked with di-cluster modes are characterized, as expected, by high velocities (see the thick squares in fig. 13). Bearing in mind all that was said above about the fission events forming the **FS** peaks in the mass spectra (fig. 9), one can treat the data under analysis as an indication of the collinear (due to the chain-like prescission configuration) cluster tripartition of heavy nuclei around the ^{278}**110** system.

As for the manifestation of the double magic ^{208}**Pb** nucleus there is no peak

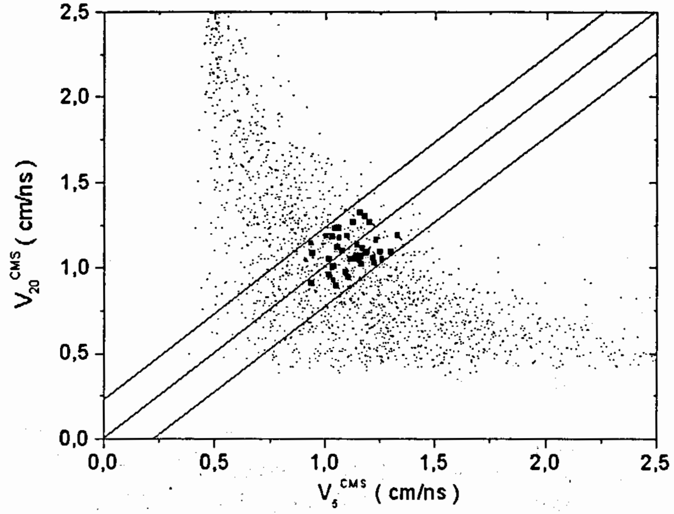

Fig.13. V_{CM} correlations of fragments. Events linked with three bottom lines in fig. 14 are marked by thick squares.

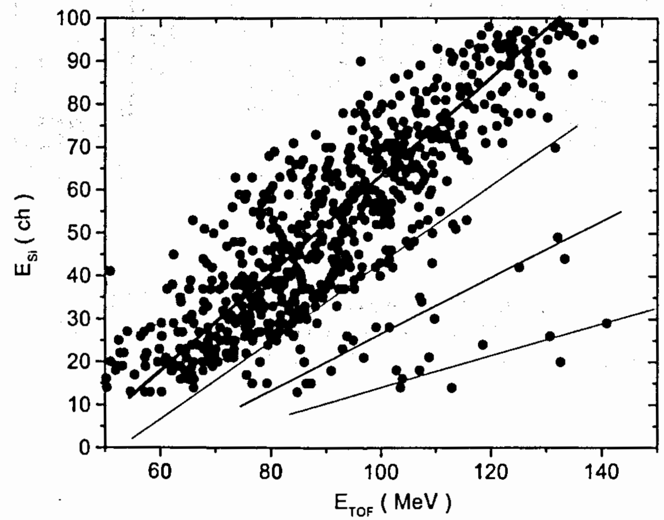

Fig.14. Fragment signal amplitude in Si detector as a function of TOF-TOF energy of the fragment.

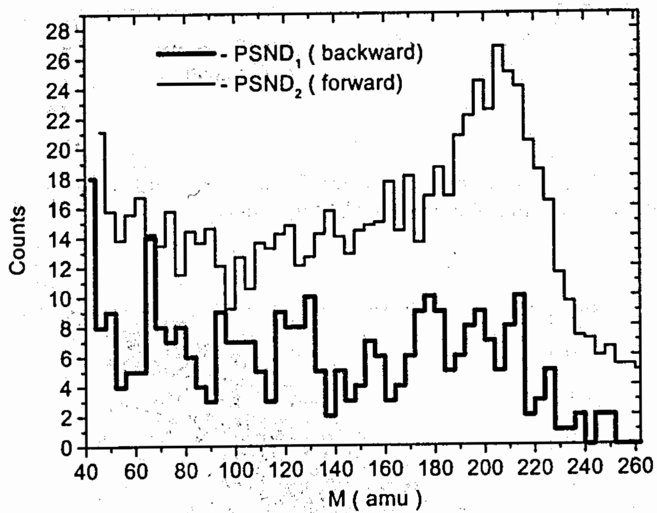

Fig.15. Mass spectra of fragments after selection as used for events in fig. 9. A selection window for coordinates of interaction points on the surface of PSACs is changed only.

at the appropriate position in the mass spectra which would show the most pronounced stuctures (fig. 9). In contrast to this, the peaks at A~200 and A~214 are observed (fig. 15) complimentary to ^{78}**Ni** and ^{64}**Ni** nuclei (fig. 15 differs from fig. 9 only in the range of the selection window for the coordinates of the interaction points on the surface of the **PSACs**). The mode based on the ^{208}**Pb** nucleus can manifest itself at the very high (~240 MeV) **TKE** values due to the compactness of the prescission shape (two magic spherical nuclei). This part of the spectrum was suppressed in our experiment due to kinematical reasons (the range of the folding angles covered by the **PSACs**).

Conclusion

For the first time a pronounced fine structure (**FS**) in the form of distinct peaks has been observed in the mass yields of the fragments of the ^{278}**110** nuclear system decay at the initial excitation of about 60 MeV. The **FS** peaks are located in the vicinity of the mass numbers **A** ~70, 100, 130, which are specific for spherical and deformed magic nuclei (clusters) of **Ni, Ge, Zr, Sn, Sr**. The **FS** peaks contain only low-energy events linked with the very elongated prescission configurations of the system.

Some events are observed which can be treated as an indication of ternary fission via the prescission configurations noted above with the appearance of two equal clusters. Hence presumably the collinear cluster tripartition channel is realized observed earlier in the spontaneous fission of ^{248}**Cm** and ^{252}**Cf** nuclei [11].

Further investigation of the ^{40}**Ar**+^{238}**U** reaction is of great interest and should be aimed at obtaining direct experimental evidence of the collinear cluster tripartition of the ^{278}**110** system.

We are grateful to Yu.P. Gangrsky, M.G. Itkis, V.V. Volkov, Yu.A. Muzychka, and V.V. Pashkevich for fruitful discussions.

References

[1] R.Kalpakchieva, Yu.Ts. Oganesian, Yu.E. Penionzhkevich et al. Z.Phys., A 283 (1977) 253.

[2] R.Kalpakchieva, V.G.Kartavenko, Yu.Ts.Oganessian et al. Nucleonika 24 (1979) 417.

[3] G. Guarino, A. Gobbi, K.D. Heldenbrand et al. Nucl. Phys. A 424 (1984) 157.

[4] W.H. Trzaska et al. In: Application of Accelerators in Research and Industry, ed. Duggan and I.L. Morgan, AIP Press, 1997, 1059.

[5] A.A.Alexandrov, I.A.Alexandrova, M.Andrassy et al. Prib. i Tekhn. Eksp. No 2, 1997, 27.

[6] M.G. Itkis, V.N. Okolovich, A.Ya. Rusanov et al. Int. School-seminar on Heavy Ion Physics, Dubna, JINR, 1993, v. 1, 213.
[7] J.Toke, R.Bock, G.X. Dai., et al. Nucl. Phys. A 440 (1985) 327.
[8] W.Q. Shen, J.Albinski, A. Gobbi et al.. Phys. Rev. C 36 (1987) 1158.
[9] D.J. Hinde, M. Dasgupta, J.R. Leigh et al. Phys. Rev. C 53 (1996) 1290.
[10] D.J. Hinde, D. Hilsher, H.Rossner et al. Phys. Rev. C 45 (1992) 1229.
[11] Yu,V. Pyatkov, V.V. Pashkevich, Yu.E. Penionzhkevich et al. preprint JINR p15-98-263, Dubna,1998.
[12] W.Wagner et al. (FOBOS collaboration) NIM A403 (1998) 65.
[13] Yu.V.Pyatkov, V.V. Pashkevich, Yu, E. Penionzhkevich et al. Nucl. Phys. (1997) 140.

Received by Publishing Department
on September 21, 1999.