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The FOBOS collaboration

FISSION OF HOT HEAVY NUCLEI INVESTIGATED AT THE FOBOS 4π - ARRAY*

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ABSTRACT

Fission of hot nuclei after incomplete fusion in asymmetric heavy-ion collisions has been investigated at the 4π-array FOBOS. Binary decay as well as ternary intermediate mass fragment (IMF) accompanied fission has been observed. The broadening of the fragment mass distribution with increasing excitation energy is associated with the occurrence of very asymmetric mass splits consisting of IMF and heavy residues (HR). Correlations of fission fragments (FF) with IMF as well as light charged particles (LCP) have been studied. The results obtained up to now are discussed in terms of time scales and fission dynamics.

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1. INTRODUCTION

The decay mechanism of an excited heavy nucleus essentially changes with increasing excitation energy E* . At low E*, asymmetric fission influenced by shell effects and competing with neutron evaporation is observed. Symmetric fission is preferred by the lowest barrier and dominates at slightly higher excitations (≈ 0.2 – 0.6 AMeV) on a time scale of $\approx 10^{-20}$ s [ref. [1]]. The further increase of E* opens de-excitation channels with higher barriers, i.e. more asymmetric fragmentations with large fragment mass ratios (A_H / A_L) become energetically allowed. This asymmetric fission proceeds with a decreased characteristic disintegration time. In ref. [2], a change of (A_H / A_L) from 1.0 to 4.8 is found to be associated with a variation of the scission times from $\tau_{sc} \approx 1 \cdot 10^{-20}$ s to $\tau_{sc} \approx 5 \cdot 10^{-22}$ s. Finally, crossing the fragmentation barrier for higher-fold disintegrations, a multi-body decay mechanism is expected. The evolution of this scenario from binary decay to multifragmentation is accompanied by the change of the fragment mass spectrum from a double-humped shape via a single-humped to a significantly broader mass distribution.

Moreover, the de-excitation process of a hot nucleus always includes the evaporation cascade of light particles. This process leads to a mass and energy loss of the remnant nucleus and, consequently, changes the corresponding decay probabilities. At sufficient high excitation energy, the masses of the evaporated particles can achieve the so-called intermediate mass region - in the present work defined as $4 \leq m_{IMF} \leq 30$.

An attempt to describe the dynamics and the interaction of the two decay processes within a consistent picture was proposed in ref. [3], combining the dynamical-statistical model of fission with the pre-scission light particle evaporation . This formalism does not take into consideration the mass-asymmetry degree of freedom and the emission of more complex particles, so far. But, recent experimental data show an increasing probability of such decay chances with increasing E*. The more detailed understanding of the decay of hot nuclei requires, therefore , further experimental and theoretical efforts including the study of asymmetric decay channels.

In order to produce highly excited nuclei, heavy-ion reactions are widely used with projectile energies in the Fermi energy domain. In this energy region, incomplete fusion is the dominating reaction channel. At large projectile masses, the investigation of fission of an equilibrated composite system is complicated by the superposition of fast reaction mechanisms like deep inelastic collisions (DIC) or quasifission. However, by using light projectiles in asymmetric reactions, these difficulties are strongly reduced.

2. THE EXPERIMENTAL SET-UP

The measurements have been performed at the 4π-array FOBOS at the U-400M ion beam of the FLNR at the JINR in Dubna. By using the reactions ^{7}Li (43 AMeV) + ^{232}Th and ^{14}N (34 and 52.5 AMeV) + ^{197}Au, composite systems with $E^* \approx 150 - 600$ MeV were produced by incomplete fusion.

The FOBOS array is a logarithmic detector device consisting of position-sensitive avalanche counters (PSAC), axial ionization chambers (BIC) and CsI(Tl) scintillation detectors and covers a substantial part of the solid angle 4π [ref. [4,5]].

Triggering on two-fold fragment coincidences, for each fragment the time-of-flight (TOF), the emission angles (ϑ,φ) and the residual energy E_f have been measured. The atomic number Z can be identified up to ≈ 25 by Bragg-peak spectroscopy. The fragment masses m_f and their linear momenta p_f were determined after correction for energy loss in the detector materials. Penetrating particles reaching the CsI crystals were identified by use of the pulse-shape analysis ($Z \leq 3$) or the ΔE-E method. In the ^{14}N (52.5 AMeV) + ^{197}Au experiment, an additional PSAC was placed to cover the polar angles $\vartheta \approx 9^\circ - 19^\circ$ for the detection of heavy residues.

3. RESULTS

3.1 The Fragment Masses

In figs. 1a and 1b, the first and the second moments of the fission fragment mass distributions from the reaction ^{7}Li (43 AMeV) + ^{232}Th are drawn in dependence on the linear momentum transfer (LMT). The LMT, deduced from the ratio of the total FF momentum to the incident momentum of the projectile, has been calculated from the two single-fragment momenta. Within the frame of the massive-transfer model (MTM), the E* can be estimated by the expression $E^* \approx E_{c.m.} \cdot \mathrm{LMT}$, where $E_{c.m.}$ is the available center-of-mass energy.

The linear decrease of the mean fragment mass $< m_f >$ with LMT is a hint at the applicability of the simple MTM for such asymmetric collision system at this incident energy. In any case, more nucleons are evaporated than captured by incomplete fusion. The difference of the $< m_f >$ for low and high LMT of about 12 amu is in accordance with the expected mass loss due to light particle evaporation.

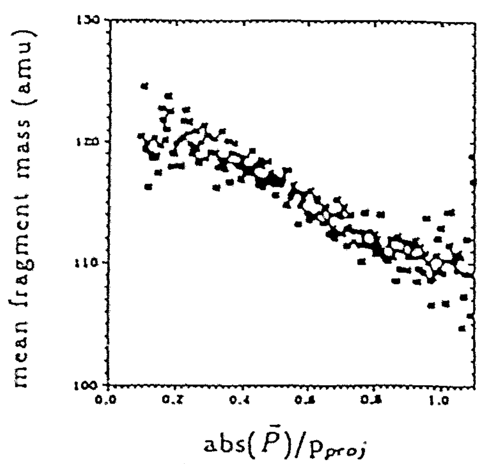

Fig. 1a Mean FF mass in dependence on the LMT.

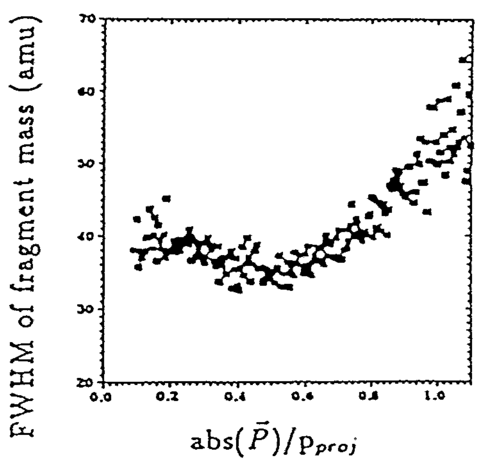

Fig. 1b Width of the FF mass distribution in dependence on the LMT.

The width of the mass distribution ($FWHM_{mf}$) varies between 35 and 50 amu, what is significantly larger than the experimental mass resolution ($\sigma_{mf} \approx 1.5$ amu for light and $\sigma_{mf} \approx 6$ amu for heavy FF, respectively). The minimum of $FWHM_{mf}$ is found at

LMT ≈ 55 %. The increase towards lower LMT can be explained by contributions from asymmetric fission of a heavy nucleus in the vicinity of ^{232}Th at low E*. A smooth increase of the width up to about 50 amu is observed for increasing LMT (respectively T).

The statistical transition state model of fission (TSM) predicts a proportionality for the squared variance of the mass distribution to the temperature : $\sigma_{mf}^2 \sim T$ [ref. [6]]. The measured width (Fig. 1b) is slightly smaller than the TSM predictions of $FWHM_{mf} \approx$ 38 amu at medium E* ≈ 0.5 AMeV. By using the excitation energy E_f^* residing in the fragments - which is expected to be $E_f^* \approx 0.3$ AMeV according to the systematics in ref. [1] - a width of the FF mass distribution of 31 amu is predicted by the TSM. Obviously, the mass distribution is formed well before scission at a T, which is lower than the initial temperature of the composite system. The nucleus permanently cools down due to particle emission on the fission path over the saddle point towards scission.

The large $FWHM_{mf} \approx 50$ amu at LMT ≥ 0.8 (corresponding to E* ≈ 1 AMeV) cannot be explained by thermal effects only. Hence, with increasing E*, there should be an additional enhancement of asymmetric mass splits, further broadening the m_f distribution and successively filling the gap between FF and IMF. This is illustrated in fig. 2 showing a Bragg-peak height vs. energy scatterplot. The FF are measured in the reaction ^{14}N (52.5 AMeV) + ^{197}Au at folding angles $\Theta_f = \vartheta_1 + \vartheta_2 \approx (100 \pm 25)°$ and identified by their relative velocity $v_{rel} = 2 - 3$ cm/ns. Since the symmetric fission component is kinematically suppressed, only asymmetric fission events are recorded. The light fragments are spread over a wide Z-range, and their binary heavy partners have very low energies. The A_H / A_L ratio reaches values of ≥ 10.

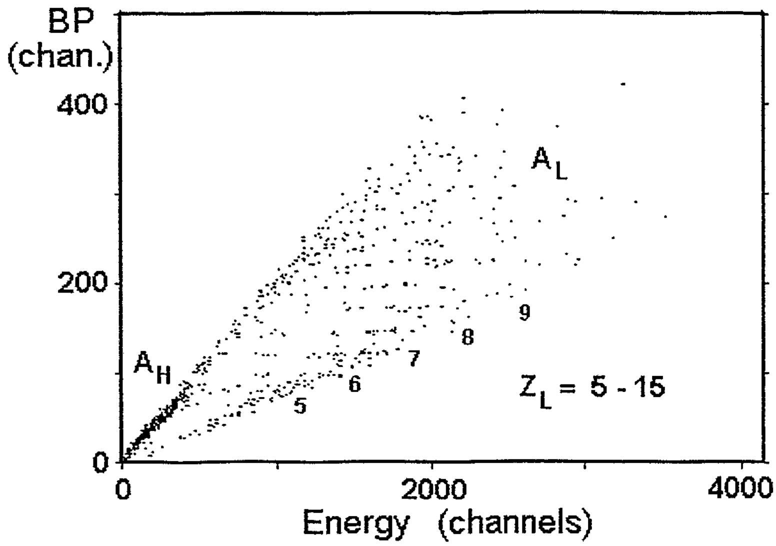

Fig. 2 Bragg-peak height vs. energy scatterplot of FF with a large A_H / A_L ratio.

Since asymmetric fission proceeds faster than symmetric [2)], it should be less influenced by dynamical hindrance effects. Hence, one could expect that the FF in asymmetric fission are more excited than in symmetric fission.

In order to proof such a hypothesis, we measured FF in coincidence with light charged particles (LCP) in the experiments ^{14}N (34 and 52.5 AMeV) + ^{197}Au. The aim is to separate the pre- and post-scission components (cf. 3.3) and to deduce E_f^* and τ_{sc} from measurements of LCP in coincidence with FF up to $A_H / A_L \approx 10$.

3.2 Heavy Residue Production

The de-excitation of the hot nucleus is associated with light-particle emission. At higher E*, more complex evaporated particles can occur taking away a considerable part of energy and mass and a remnant of less fissility remains.

In the present work, yields of IMF-accompanied fission in dependence on LMT have been measured. A preliminary result for the ratio of ternary decay to binary fission in dependence on E* is given in fig. 3 including our data of ref. [7].

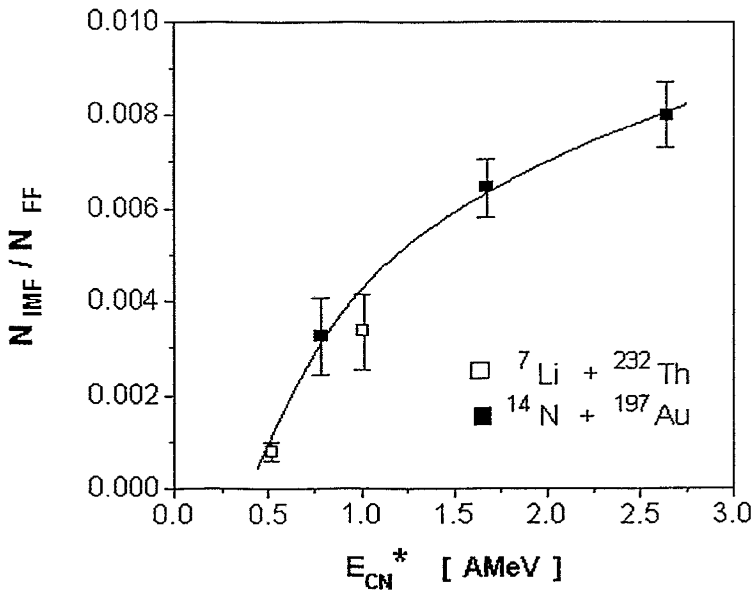

Fig. 3 Dependence of the ratio of ternary decay to binary fission on the excitation energy.

The measured ratio is of the order of 10^{-3} . By comparing the total cross sections of fission and IMF emission in a comparable mass and energy region [8], the ratio σ_{IMF} / σ_f can be estimated to be about 10^{-2}. Obviously, fission after IMF emission is suppressed by about one order of magnitude. As a result, the heavy remnant survives as an HR.

Figs. 4a and 4b show TOF vs. energy scatterplots of fragments measured by a FOBOS detector module in forward direction (ϑ = 37.4 °) in coincidence with an IMF detected in backward direction at ϑ = 100.8° for the reaction ^{14}N (34 AMeV) + ^{197}Au. In order to discriminate between binary and higher-fold events, the data shown in fig.4 have been collected with (4a) and without (4b) a special TOF-TOF gate, respectively. The

HR produced by binary decay (fig. 4a) have very low velocities and v_{rel} is typical for a binary decay into an IMF and a HR.

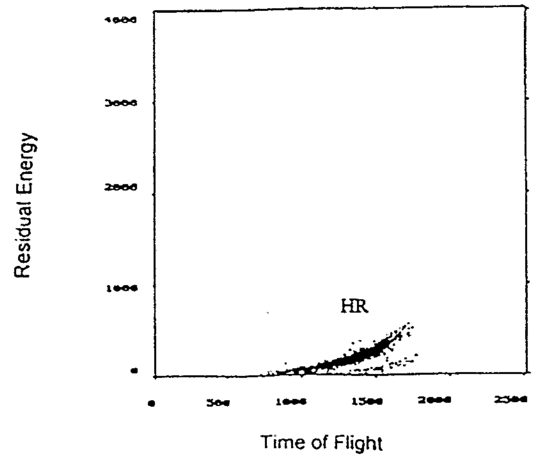

Fig. 4a TOF vs. energy scatterplot of the detector module positioned at $\vartheta = 37.4°$.

In fig. 4b - in addition to the binary events - FF from the ternary IMF-accompanied fission can be observed.

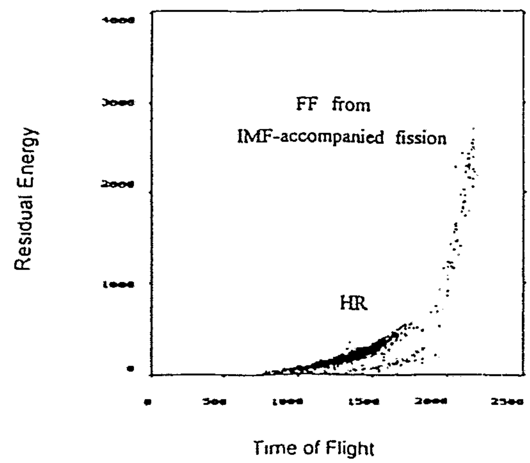

Fig. 4b TOF vs. energy scatterplot as in fig. 4a but without the time gate.

It seems that for most of the backward emitted IMF the partner is a HR. For quantitative conclusions, however, acceptance corrections have to be included. Nevertheless, the present data confirm that the decay of the heavy hot nuclei up to $E^* \approx 2$ AMeV is mainly binary (cf. also ref. [9]).

The TOF spectrum of fragments recorded in the reaction ^{14}N (52.5 AMeV) + ^{197}Au by the HR detector (at $\vartheta = 9° - 19°$, 30 cm from the target) in coincidence with a second particle detected at backward directions is shown in fig. 5.

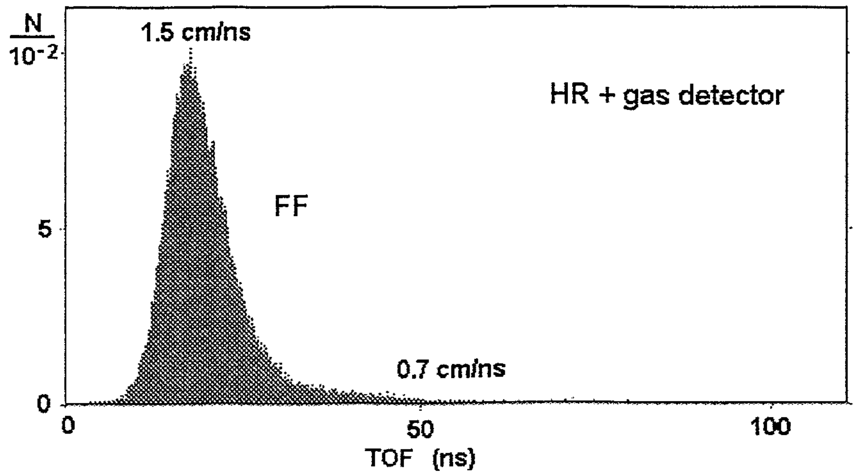

Fig. 5 TOF spectrum of the HR detector in coincidence with a second fragment.

Fragments with velocities down to ≈ 0.4 cm/ns occur. To investigate the origin of the long tail in fig. 5, the TOF spectrum of the HR detector is analysed in coincidence with evaporated LCP (fig. 6) and IMF emitted into backward directions (fig. 7). Three components can be identified in fig. 6, namely FF at $v_f \approx 1.5$ cm/ns, HR at $v_{HR} \approx 0.7$ cm/ns what approaches the $v_{c.m.}$, and a component at $v_{p.c.} \approx 0.4$ cm/ns probably resulting from peripheral collisions (PC).

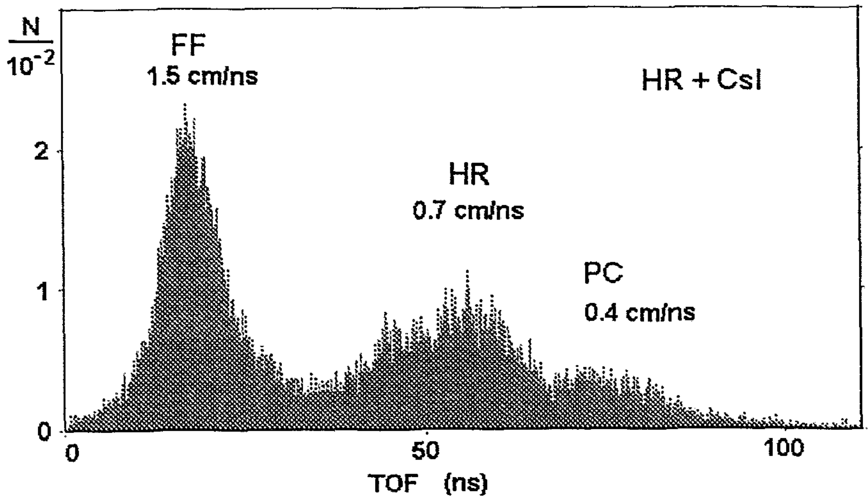

Fig. 6 TOF spectrum of the HR detector in coincidence with evaporated particles.

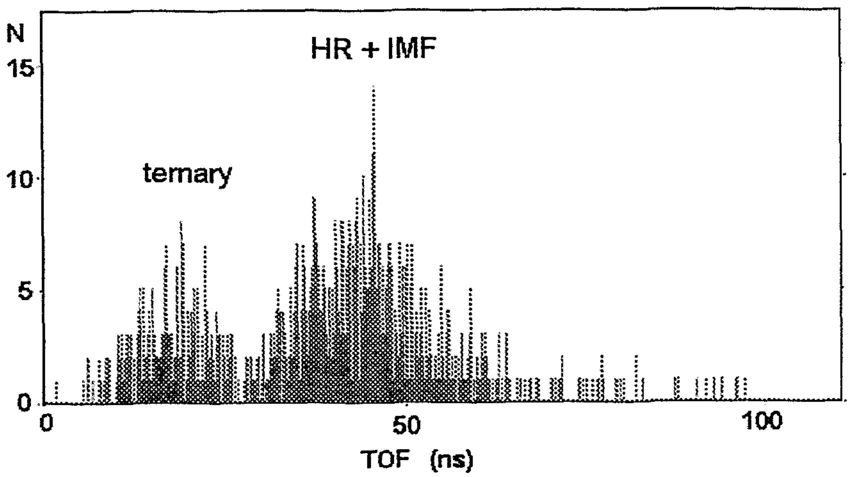

Fig. 7 TOF spectrum of the HR detector in coincidence with an IMF.

The structure at $v_{HR} \approx 0.7$ cm/ns in fig. 6 remains in fig.7. These events result from the binary decay into IMF + HR discussed above. The peak of FF originates from sequential IMF-accompanied fission.

3.3 Post-scission Light Charged Particles

Extensive investigations of the multiplicities of LCP detected in coincidence with fragments from the reaction ^{136}Xe (18.5 AMeV) + ^{48}Ti have been published in ref. [2] . The kinematic source analysis was used to separate LCP into pre- and post-scission components. Conclusions were made considering the dependence of the mean lifetime of the composite system on fission with respect to different mass asymmetries. These studies met two main difficulties. First, the occurrence of reaction products from DIC could not been excluded. Secondly, the limited detection efficiency for LCP led to low statistics.

The composite system after incomplete fusion in the reaction ^{14}N (52.5 AMeV) + ^{197}Au is slightly heavier than that produced in ref. [2] , but the asymmetric reaction allows to separate peripheral collision products from the decay of the equilibrated composite system. Furthermore, the 4π-geometry of FOBOS enables sensitive measurements of angular correlations and, additionally, the large solid angle of the scintillator shell of FOBOS [5] ($\Omega_{CsI} \approx 4$ sr) allows coincidence measurements with higher statistical accuracy. These features should be well suited for the study of the interplay of fission and LCP emission of hot nuclei.

A first attempt to investigate FF-LCP correlations has been made with respect to the separation of LCP emitted by different sources. In our case, LCP can be emitted by the hot composite system resulting in a nearly isotropic (in the center-of-mass frame) angular distribution originating from evaporation and a forward-peaked precompound component. Furthermore, the FF as well as the HR are de-excited by evaporation of LCP. The velocity spectra as well as the angular distributions of the LCP components are strongly influenced by the source velocities.

For the illustration of the FOBOS scintillator shell [5], a pulse-shape discrimination scatterplot of LCP measured by a CsI detector is shown in fig. 8.

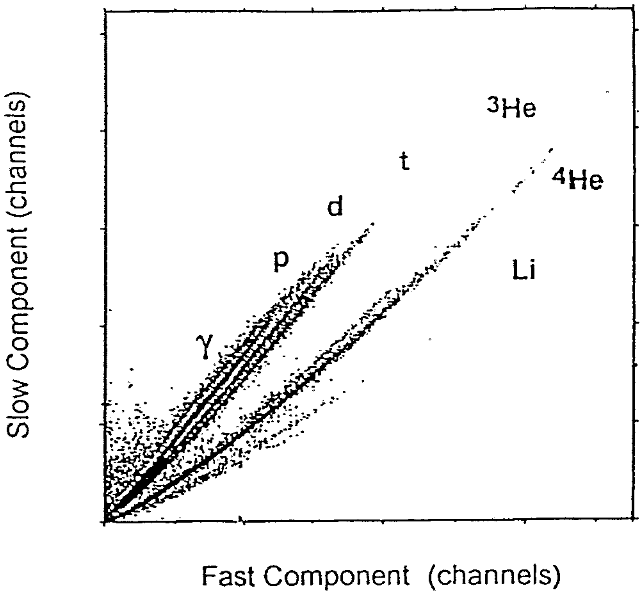

Fig. 8 Scatterplot of the LCP pulse-shape discrimination of a CsI - detector.

Spectra of alpha particles, measured at backward directions (ϑ) in coincidence with FF for different relative orientations of the fission axis (α) are shown in figs. 9 and 10.

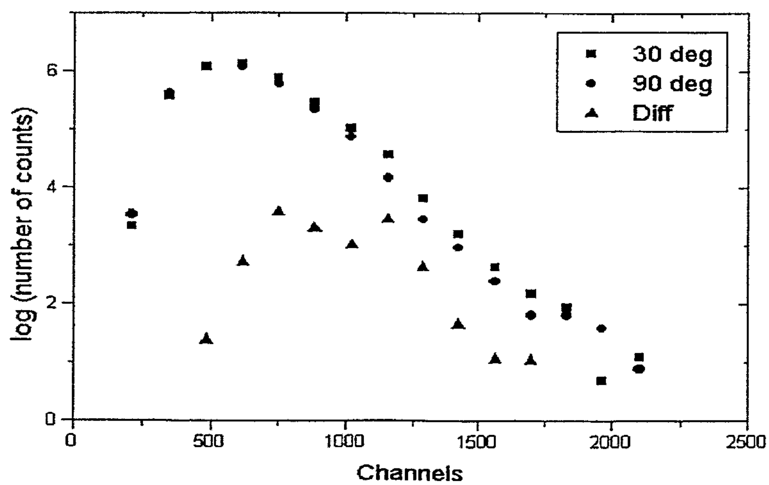

Fig. 9 Alpha particle spectra measured at $\vartheta = 143°$ for $\alpha \approx 30°$ and $90°$.

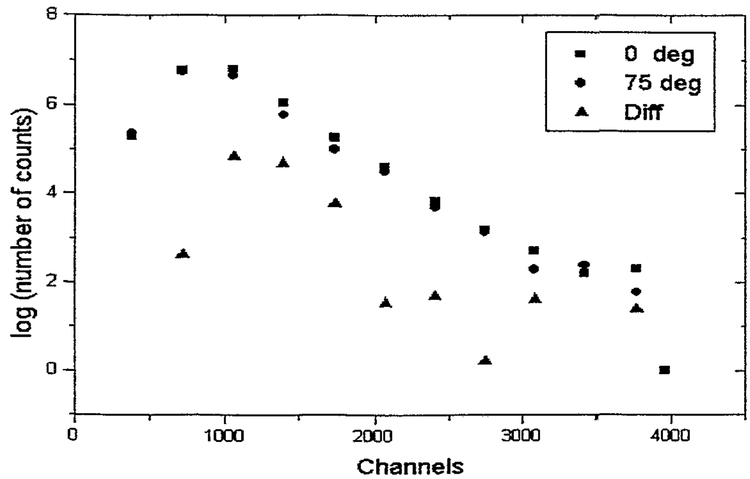

Fig. 10 Alpha particle spectra measured at $\vartheta = 101°$ for $\alpha \approx 0°$ and $75°$.

The FF were recorded by two detector combinations both covering the folding angle range $\Theta_f \approx 143° \pm 36°$ but differing in their azimuths by $72°$. The alpha particles were measured by CsI-scinillators placed at $\vartheta = 143°$ (fig. 9) and $\vartheta = 101°$ (fig. 10), respectively. The spectra correspond to mean emission angles $\alpha = 30°$ and $90°$ resp. $\alpha = 0°$ and $75°$ with respect to the fission axis . The overall shape of the spectra drawn in a logarithmic scale resembles to an evaporation spectrum from the composite system. To look for a post-scission component, we calculated the difference of the spectra corresponding to different α . For kinematical reasons, we expected - after this procedure - only such alpha particles, which were emitted by FF directed towards the alpha particle detector. The energies of these particles are, due to the FF velocity, at $\alpha < 45°$ higher than the energy in the maximum of the pre-scission spectrum. Indeed, the maxima observed in the difference spectra of fig. 9 and fig. 10 really appear at higher energy.

This preliminary result , in principle, indicated the chance to separate the pre- and post-scission LCP components in a more detailed analysis of the data, which is in progress now.

4. CONCLUSIONS

The decay of hot heavy nuclei is mainly a binary process in the considered energy range (0.5 - 3 AMeV). With increasing excitation energy of the composite system, the gap in the fragment mass distribution between the fission fragments and the products from evaporation successively disappears.

On the one hand, a large broadening of the width of the fission fragment mass distribution with increasing excitation has been observed.. On the other hand, the increasing emission of more complex fragments (IMF) is also connected with the production of heavy residues. This additional binary fragmentation process competes - depending on the excitation energy - with the symmetric fission decay channel.

To study the complexity of the decay mechanism, correlations of the fission fragments and heavy residues with light charged particles have further to be investigated. The decisive parameter might be the characteristic time scale of the decay of the composite system.

Considering IMF-accompanied fission, the study of the evolution from binary to ternary decay in terms of its time scales should give further insights into the mechanism of higher-fold disintegrations of hot nuclei with respect to its driving forces and other dynamical aspects. In this context, the investigation of *few-body* decays of hot *heavy* nuclei should be of fundamental interest for the understanding of the transition scenario towards multi-fragmentation.

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