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Spectroscopy of correlated fragments from the fission of hot nuclei performed at the FOBOS 4π - array

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SPECTROSCOPY OF CORRELATED FRAGMENTS FROM THE FISSION OF HOT NUCLEI PERFORMED AT THE FOBOS 4π - ARRAY [x]

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1. INTRODUCTION

A large amount of data concerning the fission process of hot nuclei has been collected up to now. Questions of the dynamics concerning the transition from the saddle to the scission point have been studied extensively. It is well known that this motion is overdamped. The time to reach the scission point can not become less than a certain limit if the primary excitation energy is increased. That is because the process is governed by a strong friction force. In the review article [1] , these problems have been studied mainly relying on experimental yields of pre- and post-scission particles. In most of these experiments mass splits of the fission fragments were not analyzed. Only few data are available for the asymmetric fragmentation (e.g. ref. [2] and [3]).

On the other hand, at low energies, total kinetic energy (TKE) and mass (M) distributions of binary heavy-ion induced reactions are essential for the understanding of the reaction mechanism. The "classical" reaction scenarios - the deep inelastic collision (DIC), the fusion-fission reaction and the quasifission - have been separated utilizing fragment spectroscopy [4]. The binary character of these reactions allows to directly determine the TKE and M from the measured velocity vectors applying the kinematic coincidences method [5].

The aim of our work was to measure TKE - M distributions for fission at higher excitation energies where very asymmetric mass splits occur. Pre- and post-scission components should be extracted from the spectra of light charged particles (LCP) and intermediate mass fragments (IMF) recorded in coincidence with two fission fragments (FF). Eventually, particles emitted from the neck region of the fissioning system, should be analyzed .

In heavy-ion reactions induced by projectiles of mass larger than ≈ 30 amu and with energies near the Fermi domain, one reaches excitation energies of many hundreds of MeV. There, however, the study of fission meets some principal problems, namely, it is difficult to separate the fission of an equilibrated compound-like system from DIC and quasifission. Compression phenomena and effects due to the transferred large angular momentum make the picture more complicate.

To avoid these problems we bombarded heavy targets (^{232}Th and ^{197}Au) with relatively light projectiles (^{7}Li and ^{14}N). In this case, nearly all fragments with mass heavier than that of the projectile arise from the decay of a compound-like system only.

2. EXPERIMENTS AND DATA ANALYSIS

The measurements were carried out on the 4π-facility FOBOS [6] at the Flerov Laboratory of Nuclear Reactions of the JINR Dubna.

We used the reactions ^{7}Li (43 AMeV) + ^{232}Th and ^{14}N (34 and 55 AMeV) + ^{197}Au. The velocities and the emission angles of FF pairs and coincident IMF were measured by position-sensitive avalanche counters, the energies and the Bragg peak-heights (Z) by axial ionization chambers. The data have been corrected for energy losses in penetrated detector materials. LCP were recorded by the CsI scintillator shell of FOBOS [7].

From the measured data FF and IMF masses were determined independently event-by-event. The sum mass and the mass split (mass ratio) of the FF as well as their TKE have been derived to construct TKE - M distributions in dependence on the transferred linear momentum (LMT). Correlations between FF and IMF as well as LCP have been analyzed. Since the data analysis is still in progress most of the results given in this work refer to the first reaction mentioned above.

3. RESULTS

3.1 Fission fragment momenta

The total FF momentum p_{tot} is the vector sum of the two single-fragment momenta. The transverse components of p_{tot} for the reaction ^{7}Li + ^{232}Th are shown in fig. 1. The width of the distribution is characterized by a FWHM = 700 ÷ 800 MeV/c [8]. It is larger by a factor of about 3.5 with respect to that of a ^{252}Cf(sf) calibration source where the $FWHM_{Cf}$ amounts to about 5 % of the single-fragment momentum.
The deflection of p_{tot} out of the beam axis can be explained by particle evaporation and the transverse momentum transfer at peripheral impacts. The transverse momentum vanishes at full LMT. In contrary, the deflection caused by neutron and LCP evaporation becomes more important at larger LMT.

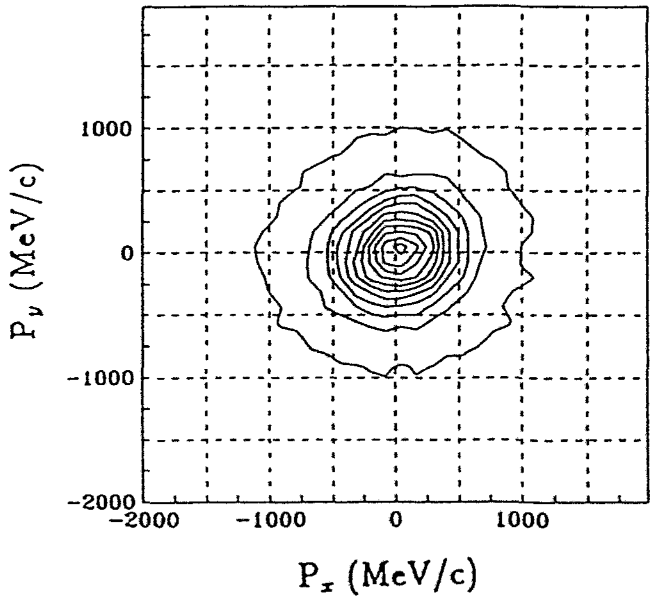

Fig. 1 Transverse components of the total FF momentum in the reaction ^{7}Li (43 AMeV) + ^{232}Th.

3.2 Coplanarity

While the fission folding angle distribution is sensitive to the LMT, the coplanarity is almost not influenced by the longitudinal velocity of the fissioning nucleus. The mean value of the difference of the FF azimuths is $\varphi_1 - \varphi_2 = 180^{\circ}$. A suitable observable for studying the transverse component of motion is the distribution of this difference. The width of this "coplanarity distribution" is a measure for the transverse deflection of the fissioning nucleus. Besides particle evaporation, other effects contribute to the broadening of the coplanarity distribution, e.g., the transverse momentum transfer due to incomplete fusion and the FF angular straggling within the target layer.

Agreement with the measured distributions could be achieved in simulations by only varying the number of evaporated neutrons (N_n) as a fit parameter. Values of $N_n = 18$ (fig. 2) and $N_n = 33$ have been deduced for the fission at the mean recoil velocities of the fissioning system of $v_{c.m.} = 0.12$ cm/ns and $v_{c.m.} = 0.24$ cm/ns corresponding to about 45 % and 90 % of LMT, respectively.

For comparison, the number of neutrons with mean kinetic energy of 6 MeV emitted during an evaporation cascade has been estimated from the balance of the binding, kinetic and excitation energies according to the systematics of ref. [9]. This procedure results in corresponding values of $N_n = 11$ and $N_n = 18$. Despite the significant discrepancy for the absolute N_n numbers at common $v_{c.m.}$, the trend of increasing neutron evaporation with higher LMT is reproduced rather well.

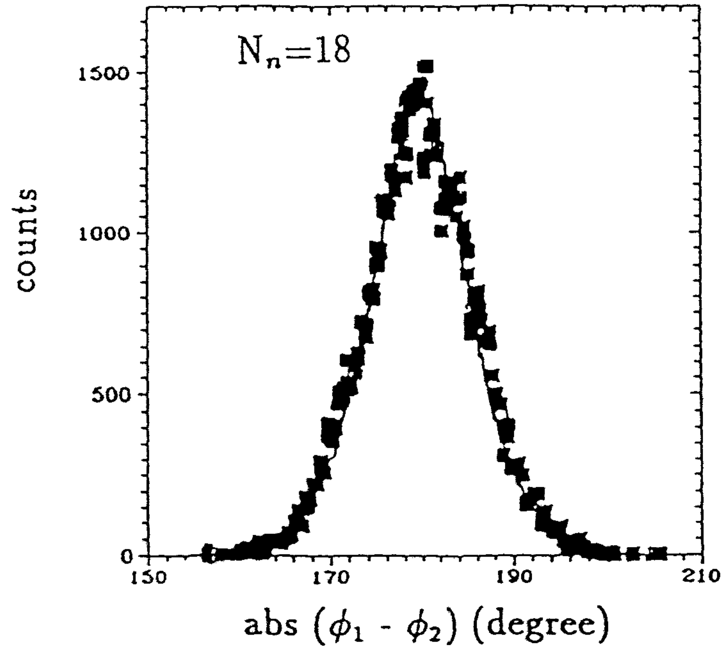

Fig. 2 Measured (line) and simulated (symbols) coplanarity distributions of the FF pairs for the reaction ^{7}Li (43 AMeV) + ^{232}Th. at 45 % LMT.

3.3 Recoil velocity distribution

The longitudinal component of $v_{c.m.}$ has been deduced from the two measured FF polar angles $\vartheta_1 + \vartheta_2$ (folding angle). Under the assumptions of symmetric fission and fixed relative fragment velocity one can use equation (1) [10] :

$$v_{c.m.} = 1/2 \cdot v_f \cdot (- K \cdot T \; / \; (1 - K \cdot T / 4))^{1/2} \qquad (1)$$

with

$$K = 1 / \tan(\vartheta_1) + 1 / \tan(\vartheta_2)$$
$$T = \tan(\vartheta_1 + \vartheta_2)$$
$$v_f = 1.2 \text{ cm / ns} \qquad \text{(fission fragment velocity).}$$

The acceptance corrected distribution of $v_{c.m.}$ for a detector combination which covers the whole possible range of LMT is shown in fig. 3. A considerable part of the distribution extends to higher velocities and exceeds the reaction limit of 0.27 cm/ns for complete LMT. This behavior is caused by the deflection effects discussed above.

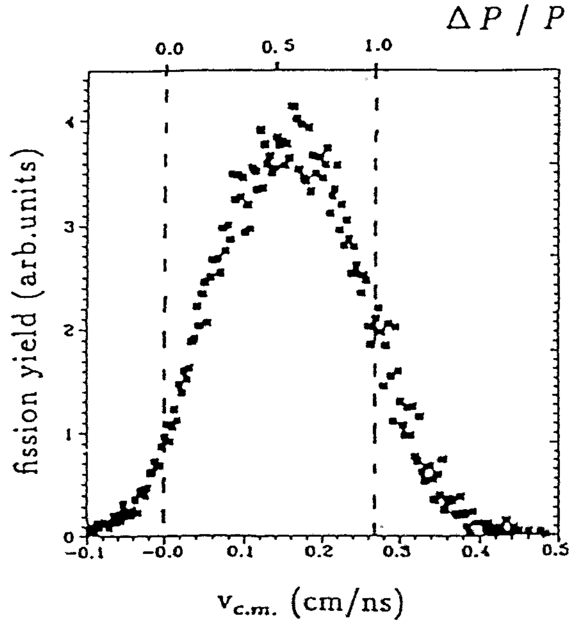

Fig. 3 Recoil velocity distribution deduced from the FF momenta for the reaction ^{7}Li (43 AMeV) + ^{232}Th..

The $v_{c.m.}$ spectrum for reactions induced by heavier projectiles at intermediate energies is usually characterized by a double-humped structure. The two maxima, at low and at high LMT, correspond to fission after incomplete and complete fusion, respectively. In our case, the data of the reaction ^{7}Li (43 AMeV) + ^{232}Th show a smooth transition from slower to faster composite systems. The maximum is located at $v_{c.m.} \approx 0.15$ cm/ns. This value corresponds to ≈ 55% of the projectile momentum, i.e. an absolute value of 1100 MeV/c. Referring to the predictions made for the most probable LMT in central collisions at intermediate energies [11], this result agrees fairly well with the value of 160 ÷ 180 MeV/c per projectile nucleon.

3.4 Fission fragment masses

Reminding the definition of LMT being the ratio of the total FF momentum to the linear momentum of the projectile, the dependence of the mean single FF mass $< m_f >$ on this parameter has been analyzed. The dependence of the $< m_f >$ values on LMT for the reaction ^{7}Li (43 AMeV) + ^{232}Th is shown in fig. 4. A difference of about 12 amu has been found between $< m_f >$ for low and high LMT.

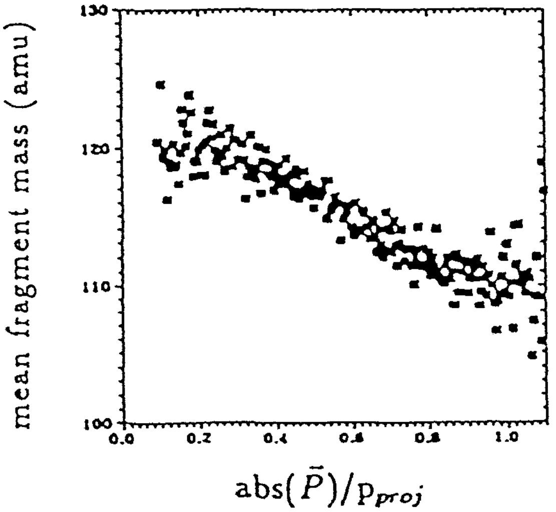

Fig. 4 Mean single-fragment mass as a function of LMT.

The $FWHM_{mf}$ of the m_f-distribution as a function of LMT is shown in fig. 5. It varies between 35 and 50 amu what is significantly larger than the experimental mass resolution of FWHM ≈16 amu for FF estimated from the calibration with a ^{252}Cf source.
The minimum of $FWHM_{mf}$ is found nearly the most probable LMT of 55 %. The increase towards lower LMT can be explained by contributions from asymmetric fission at low excitation energy (E_{CN}*) of the fissioning nucleus. A smooth increase of the width up to about 50 amu is observed for increasing LMT (i.e., within the frame of the massive-transfer model, for increasing E_{CN}* respective temperature T of the composite system).

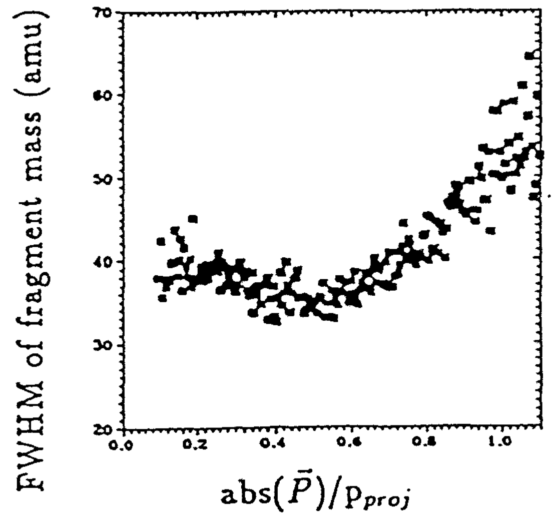

Fig. 5 Width of the single-fragment mass distribution as a function of LMT.

The simple proportionality for the variance of the mass distribution $\sigma_M^2 \sim T$, as it follows from the statistical approach to fission using the transition state model (TSM) [12], does not explain the observed behavior quantitatively.

At medium E_{CN}* ≈ 0.5 AMeV the measured width is slightly smaller than the TSM predictions of ≈ 38 amu. This means that the temperature determining the $FWHM_{mf}$ is lower than the initial temperature of the composite system (E_{CN}*). On the other hand, for such an estimation one can use the excitation energy residing in the fragments (E_f*). According to the systematics derived in ref. [13], one expects E_f* ≈ 0.3 AMeV. In this case the prediction from the TSM of ≈ 31 amu is to small. Obviously, the mass distribution is formed well before scission.

The large $FWHM_{mf}$ of the m_f distribution at LMT ≥ 0.8 (E_{CN}* ≈ 1 AMeV) cannot be explained by only thermal effects. Therefore, with increasing E_{CN}* there should be an enhanced probability for asymmetric mass splits governed by the dynamics of the fission process. The mass-asymmetric fission proceeds faster than the symmetric fission [2] and, therefore, should be less influenced by dynamical hindrance effects.

The problem has to be analyzed more in detail in the framework of the combined dynamical-statistical model for fission of hot nuclei accompanied with the pre-scission emission of light particles [14] including the mass-asymmetry degree of freedom into the consideration. The shape dependence of nuclear friction, possibly, should be a decisive factor.

To investigate FF - LCP correlations more precisely aiming to select the pre- and post-scission LCP components, measurements of the reaction ^{14}N + ^{197}Au have recently been carried out at projectile energies of 34 AMeV and 55 AMeV. For qualitative illustration, a LCP pulse-shape discrimination scatterplot measured by a CsI detector of the FOBOS scintillator shell is given in fig. 6.

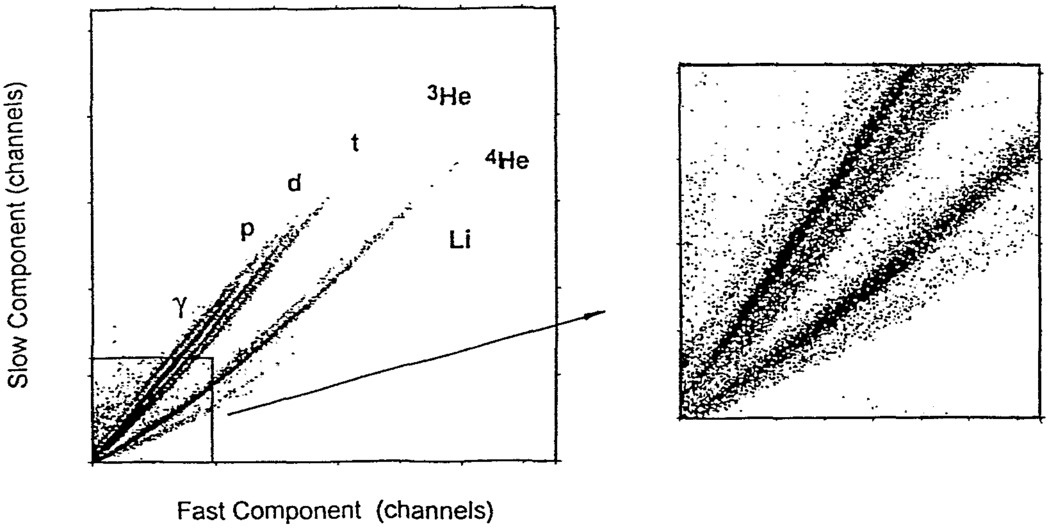

Fig. 6 Scatterplot of pulse-shape discrimination for LCP spectroscopy by a CsI detector.

3.5 Intermediate mass fragment accompanied fission

First results of our investigations of the ratio of ternary ($\mathrm{IMF}_{Z=3+8}$ +FF+FF) to binary (FF+FF) decay yields for the reaction ^{7}Li (43 AMeV) + ^{232}Th have already been published [15]. Especially, evidence for an IMF neck-emission component has been found.

Summarizing the measured data for the reactions ^{7}Li (43 AMeV) + ^{232}Th and ^{14}N (34 and 55 AMeV) + ^{197}Au a preliminary systematics for this ratio with regard to the excitation energy of the composite system E_{CN}* (estimated by use of the massive-transfer model approximation) is given in fig. 7. The data have been corrected for the geometrical acceptance of the FOBOS detector configuration.

The order of magnitude of the IMF accompanied fission probability has been found to be 10^{-3}. Considering the IMF production cross-section given for similar systems in ref. [16], it follows that fission after IMF emission is markedly suppressed. The reason could be obvious. The IMF, and most likely further light particles, take away a considerable part of E_{CN}* as well as of mass and the fission of the remaining residue becomes improbable. In other words, IMF emission of hot nuclei favours the survival of a heavy (evaporation) residue (HR) and the binary character of the decay holds. The HR's, of course, are mainly forward directed. An energy-over-TOF scatterplot measured for the reaction ^{14}N (34 AMeV) + ^{197}Au by a FOBOS module placed at $\vartheta = 37.6^{\circ}$ with respect to the beam axis is shown in fig. 8. In coincidence with a backward emitted IMF, a large amount of slow (heavy) fragments has been observed.

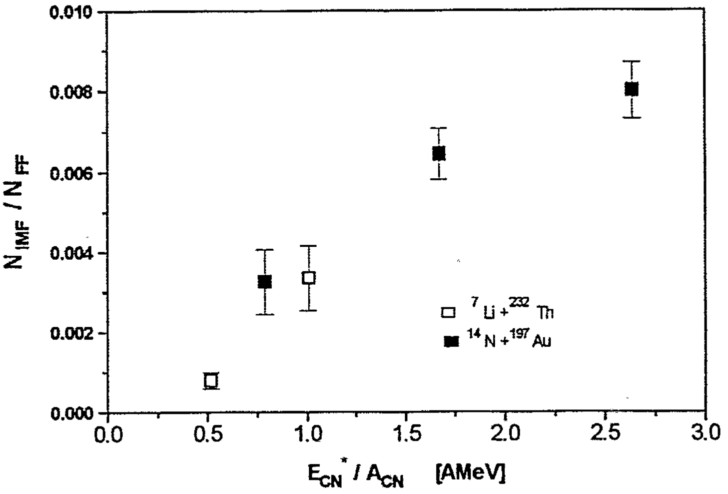

Fig. 7 Yield ratio of ternary to binary decay in dependence on the excitation energy of the composite system.

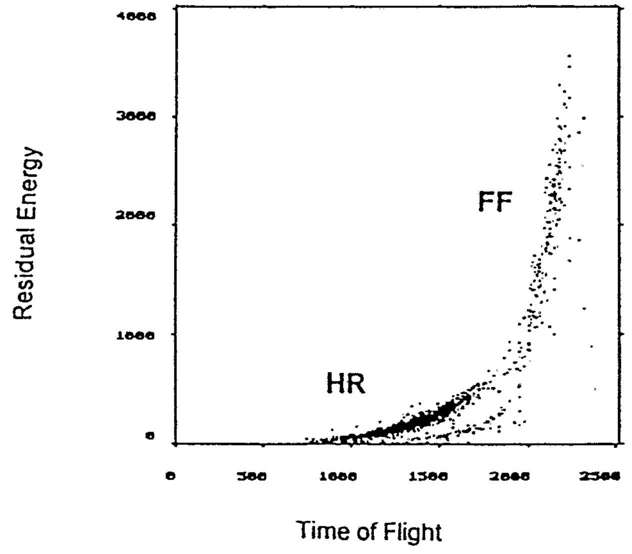

Fig. 8 Energy-over-TOF scatterplot of a FOBOS detector module for fragments of the reaction ^{14}N (34 AMeV) + ^{197}Au (the time-of-flight counts from channel 2300 to the left; all a.u.).

The increasing importance of dynamical effects on the fission process with increasing E_{CN}*, especially the dynamical hindrance of fission and the appropriate enhancement of particle emission, has been discussed very instructively in ref. [1]. A considerable deviation (increase) from the predictions of statistical model calculations for the HR production cross - section is observed for temperatures of the composite system higher than ≈ 1.5 MeV. The necessity to measure simultaneously FF/HR and light particles has already been outlined in ref. [1]. Concerning LCP, this has been done for the reaction ^{14}N (55 AMeV) + ^{197}Au in our last measurement the data analysis of which is just in progress.

4. Summary

Investigations of the decay of hot nuclei with mass A ≈ 200 at excitation energies of 200 ÷ 600 AMeV are presently carried out at the 4π- facility FOBOS at JINR Dubna. Main efforts are directed to the spectroscopy of correlated fragments from fission accompanied with the emission of intermediate mass fragments and light charged particles. The low registration threshold of the detector array allows registration of masses up to heavy residues. From the independent measurement of the fragment momenta the transferred linear momentum can be determined. It is a considerable good measure for the excitation energy of the composite system after the incomplete fusion reaction.

At high excitation very asymmetric mass splits have been observed resulting in a successive broadening of the fragment mass distribution with increasing transferred linear momentum. Since dynamical effects in this context lead to a hindrance of fission and an enhanced production of heavy residues accompanied with particle evaporation, the large rise of asymmetric fragmentation yields at higher excitation could be a further manifestation of the same physical phenomenon. More theoretical investigation of the interplay of particle emission and fission is necessary. The combined dynamical-statistical model for fission of hot nuclei and pre-scission particle evaporation seems to be the most suitable approach to this problem. The mass-asymmetry degree of freedom and the emission of more complex particles have to be included into consideration. Further information about nuclear dissipation is expected. The relation between asymmetric and symmetric fragmentation should contain information about time scales of the disintegration process.

The relative yield of ternary IMF accompanied fission to binary fission is an increasing function of the excitation energy. Fission after IMF emission is suppressed by about one order of magnitude in the energy range considered. An interesting task for the future is the further investigation of the interplay between binary and ternary decay modes. The FOBOS array is a very suitable tool for such experiments.

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