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W. Wagner, H.-G. Ortlepp, C.-M. Herbach, P. Gippner, A. Matthies, Yu.E. Penionzhkevich, G. Renz, K.D. Schilling, O.V. Strekalovsky and V.E. Zhuchko

Fission and emission of intermediate mass fragments in asymmetric heavy - ion collisions investigated at the FOBOS 4π - array

Forschungszentrum Rossendorf e.V.
Postfach 51 01 19 · D-01314 Dresden
Bundesrepublik Deutschland

Telefon (0351) 260 3127
Telefax (0351) 260 3700
E-Mail schilling@fz-rossendorf.de

The FOBOS collaboration

FISSION AND EMISSION OF INTERMEDIATE MASS FRAGMENTS IN ASYMMETRIC HEAVY - ION COLLISIONS INVESTIGATED AT THE FOBOS 4π - ARRAY [x]

W. Wagner , H.-G. Ortlepp , C.-M. Herbach ,
P. Gippner , A. Matthies , Yu.E. Penionzhkevich [1] , G. Renz ,
K.D. Schilling , O.V. Strekalovsky [1] , V.E. Zhuchko [1]

Research Center Rossendorf Inc., POBox 51 01 19 , 01314 Dresden , Germany
[1] *Joint Institute for Nuclear Research, 141980 Dubna (Moscow Region) , Russia*

ABSTRACT

The decay of hot heavy nuclei has been studied at the 4π- array FOBOS using the reactions ^{7}Li (43 AMeV) + ^{232}Th and ^{14}N (34 and 52.5 AMeV) + ^{197}Au. After incomplete fusion , the intermediate system can be excited up to energies of 200–500 MeV. Fission accompanied by the emission of intermediate mass fragments as well as light charged particles has been studied. At higher excitation energies, very asymmetric mass splits have been observed thus pointing out that dynamical effects dominate the decay process.

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1. INTRODUCTION

The dynamics of the collective motion of nuclear matter leading to fission of nuclei is a field of investigation during the whole period since the discovery of fission. Recently, theoretical as well as experimental efforts were directed to a deeper understanding of the fission of relatively hot (heavy) nuclei, where a complicate interplay with particle evaporation has been observed. With increasing excitation energy (E*) of the nucleus, one observes not only an increasing number of evaporated neutrons and light charged particles (LCP), but also emission of intermediate mass fragments (IMF, $Z \approx 3-10$) prior to scission, which take away a considerable amount of the initial energy and mass. As a consequence, the residual lighter remnant, with a generally much higher fission barrier, can subsequently undergo fission or will remain after particle evaporation as a heavy residual nucleus (HR).

On the other hand, more asymmetric fragmentation becomes probable at higher E* leading - together with thermal effects - to a broadening of the mass distribution of the fission fragments (FF). Up to now, there are no consistent descriptions of such processes taking into consideration all degrees of freedom of the decaying nucleus. The most promising approach seems to be the combined dynamical-statistical model of fission and particle evaporation prior to scission applying the Langevin formalism to simulate the decay of hot nuclei[1)] - but, the emission of more complex particles as well as the mass-asymmetry degree of freedom are not considered so far.

With the aim to study the fission of hot nuclei, we measured TKE-mass distributions in dependence on E* and yields of particle accompanied fission using the reactions ^{7}Li (43 AMeV) + ^{232}Th and ^{14}N (34 and 52.5 AMeV) + ^{197}Au. Such asymmetric projectile-target combinations have some advantages, because incomplete fusion becomes a dominant reaction channel at energies near the Fermi domain. Indeed, with projectiles of mass heavier than about 30 amu, excitation energies E* of some hundreds of MeV are realized, but it turns out to be a rather difficult problem to separate fission of an equilibrated composite system from deep inelastic collisions and quasifission. Furthermore, compression phenomena and large transferred angular momenta make the picture more complex. In our case, almost all fragments heavier than the projectile arise from the decay of the composite system.

2. EXPERIMENTAL SET-UP

The measurements have been carried out at the U-400M beam of the FLNR at the JINR in Dubna. The FOBOS array is a logarithmic detector device consisting of position-sensitive avalanche counters (PSAC), axial ionization chambers (BIC) and CsI(Tl) scintillation detectors covering a substantial part of the solid angle 4π [ref. [2,3]].

Triggering on two-fold fragment coincidences, for each fragment the time-of-flight (TOF), the emission angles (ϑ,φ) and the energy E_f have been measured. The fragment masses and linear momenta were determined after correction for energy loss in detector materials. The atomic number Z can be defined up to about 25 by Bragg-peak spectroscopy. Penetrating particles reaching the CsI crystals were identified applying the pulse-shape analysis ($Z \leq 3$) or the ΔE-E method.

The sum mass and the mass split for FF pairs have been derived event by event. From the fragment momenta, the linear momentum transfer (LMT) has been calculated. Within the frame of the massive-transfer model (MTM), the excitation energy of the composite system can be estimated by the equation $E^* \approx E_{c.m.} \cdot LMT$, where $E_{c.m.}$ is the available center-of-mass energy and LMT is the ratio of the total FF momentum to that of the projectile. The LMT, therefore, has been used as a measure for the temperature (T) of the composite system.

3. RESULTS

3.1 The Recoil Velocities

Assuming symmetric fission, the longitudinal recoil velocity ($v_{c.m.}$) has been calculated for the reaction ^{7}Li (43 AMeV) + ^{232}Th from the folding angle of the FF. On the other hand, $v_{c.m.}$ has been derived directly from the determined FF masses and the momentum sum. The correlation between the two results is shown in fig. 1.

As the maximum for this reaction is $v_{c.m.} = 0.27$ cm/ns, higher values in the $v_{c.m.}$ distribution can be caused by fluctuations due to particle evaporation as well as by uncertainties in the mass determination. Nevertheless, the nearly linear correlation in a wide range of $v_{c.m.}$ confirms the reliability of the direct method, which becomes the only available one at higher E*, where more complex particles are emitted and the folding angle analysis fails.

In order to investigate the transversal $v_{c.m.}$-component, the coplanarity ($\varphi_{f1} - \varphi_{f2}$) has been simulated assuming isotropic evaporation of neutrons with a kinetic energy of 6 MeV. Satisfactory agreement with the measured distribution (fig. 2) could be achieved for the neutron numbers $N_n = 18$ and $N_n = 33$ at $v_{c.m.} = 0.12$ cm/ns and $v_{c.m.} = 0.24$ cm/ns, respectively.

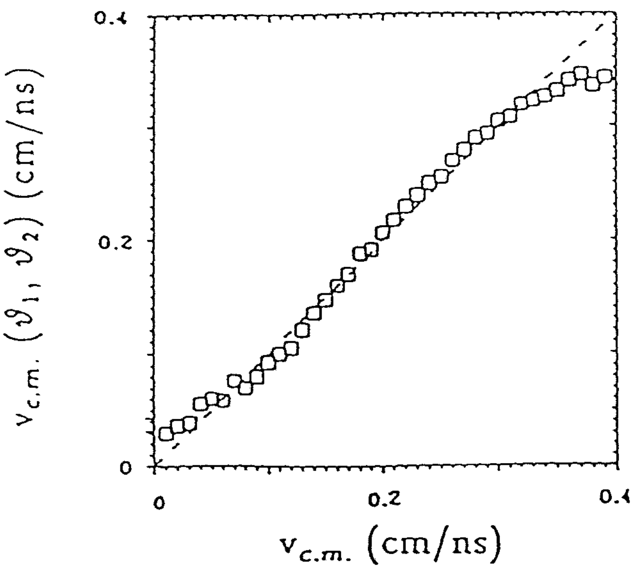

Fig. 1 Correlation between the recoil velocities independently determined from the folding angle and from the FF parameters directly.

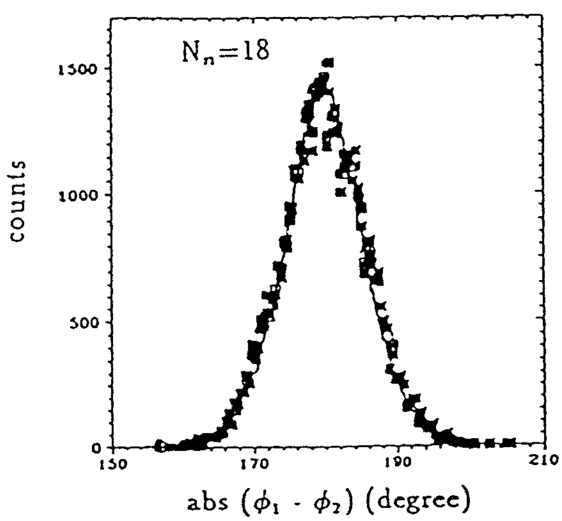

Fig. 2 Measured and simulated coplanarity distributions for FF from the reaction ^{7}Li (43 AMeV) + ^{232}Th.

These numbers are considerably higher than those expected from the balance of binding, kinetic and excitation energies (N_n = 11 and N_n = 18) according to the systematics of ref. [4]. This means that other effects like fluctuations from complex particle evaporation and transversal momentum transfer during incomplete fusion become essential. Nevertheless, the trend of increasing neutron evaporation with increasing LMT is reproduced correctly. It can be concluded that the method of independent momentum balance works rather well.

3.2. The Fission Fragment Masses

One of the crucial technological problems of FOBOS was to minimize the foil thickness of the large-area PSAC and BIC windows for reducing the detection thresholds as far as possible. Nevertheless, the foils have to endure the gas pressure and to guarantee sufficiently low gas diffusion rates. In any case, heavy fragments lose a considerable part of their kinetic energy (≥ 50 %) and the measured E_f has to be corrected for. Using the E_f, TOF (ΔTOF ≈ 1 ns) and (ϑ,φ) informations, the primary fragment energies can be determined rather well applying an iterative correction method [5], what results in a fragment mass resolution of $\sigma_{mf} \approx 1.5 - 6$ amu for light and heavy FF, respectively.

In figs. 3a and 3b, the first and the second moments of the FF mass distributions from the reaction ^{7}Li (43 AMeV) + ^{232}Th are shown in dependence on the LMT. The linear decrease of the mean fragment mass with LMT supports the applicability of the rather simple MTM for such an asymmetric system at this bombarding energy. The difference of the $< m_f >$ for low and high LMT is found to be about 12 amu, in accordance with the expected mass decrease resulting from light particle evaporation.

The width of the mass distribution ($FWHM_{mf}$) varies between 35 and 50 amu, what is significantly larger than the experimental mass resolution. The minimum of $FWHM_{mf}$ is observed at LMT ≈ 55 %. The increase towards lower LMT can be explained by contributions from asymmetric fission at low E* of the heavy fissioning nucleus. A smooth increase of the width up to about 50 amu is observed with increasing LMT (i.e. for increasing E* resp. temperature T of the composite system).

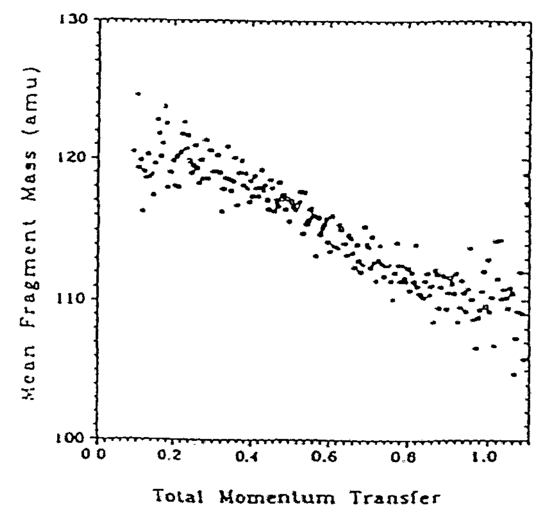

Fig. 3a Mean FF mass in dependence on the LMT.

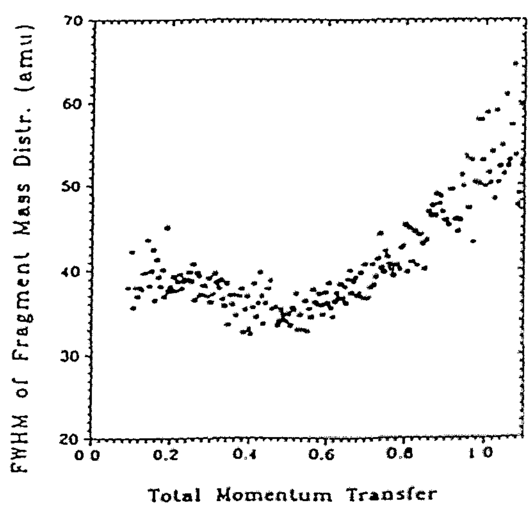

Fig. 3b Width of the FF mass distribution in dependence on the LMT.

The statistical transition state model of fission (TSM) predicts a proportionality for the squared variance of the mass distribution to the temperature : $\sigma_M^2 \sim T$ [ref. [6]]. However, it does not explain the observed behaviour quantitatively.
At medium energies $E^* \approx 0.5$ AMeV (corresponding to LMT = 55 %), the measured width in fig. 3b 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. 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. [7] - a width of the FF mass distribution of 31 amu is predicted by the TSM. Obviously, the mass distribution is formed well before scission.
The large $FWHM_{mf} \approx 50$ amu at $LMT \geq 0.8$ (corresponding to $E^* \approx 1$ AMeV) cannot be explained only by thermal effects within the TSM. Hence, with increasing E*, there should be an additional enhancement of asymmetric mass splits. Since asymmetric fission proceeds faster than symmetric [8], it should be less influenced by dynamical hindrance effects leading to the relatively large scission times in symmetric fission [7]. Of course, deeper understanding of the dependence of the nuclear viscosity (governing the dynamics of the fission process) on the nuclear shape and temperature is necessary. Furthermore, the evolution of the composite system has to be studied in more detail concerning the interplay of particle evaporation and collective motion.
Up to now, studies of the fission dynamics have mainly been carried out considering the amount of pre- and post-scission neutrons [7]. The neutron evaporation probability was used as a "clock" for the evolution towards scission. It is also a "thermometer" for the excited nucleus as well as for the fragments. Since FOBOS is not sensitive to neutrons, FF - LCP correlations have to be studied. Recently, we carried out such measurements using the reactions ^{14}N (34 and 52.5 AMeV) + ^{197}Au. LCP were recorded by the FOBOS CsI-scintillator shell. The experiments aim to separate the different LCP components in order to make conclusions on the time scales of the fission process in dependence on the mass-asymmetry parameter. The data analysis is just in progress.

3.3 Intermediate Mass Fragment Accompanied Fission

From inclusive measurements, the cross section of IMF production for hot nuclei has been determined [9]. The branching ratio relative to fission has been found to be of the order of 10^{-2}.
We measured the ratio of IMF-accompanied fission to binary fission in dependence on the LMT. Summarizing the measured data for the reactions ^{7}Li (43 AMeV) + ^{232}Th and ^{14}N (34 and 52.5 AMeV) + ^{197}Au, a preliminary result for this ratio in dependence on E* is given in fig. 4. The order of magnitude of the IMF accompanied fis-

sion probability has been found to be 10^{-3}. This means that fission after IMF emission is remarkably suppressed and, on the other hand, the survival probability of a HR is increased. This is in accordance with the findings quoted in ref.[7]. For T ≥ 1.5 MeV, a considerable deviation for the HR production cross section from statistical model calculations has been found.

With higher E* , the IMF production rate should further increase. The chance for subsequent fission of the remaining HR should decrease with its mass and energy loss due to particle evaporation. This may be a qualitative explanation for the behaviour depicted in fig. 4.

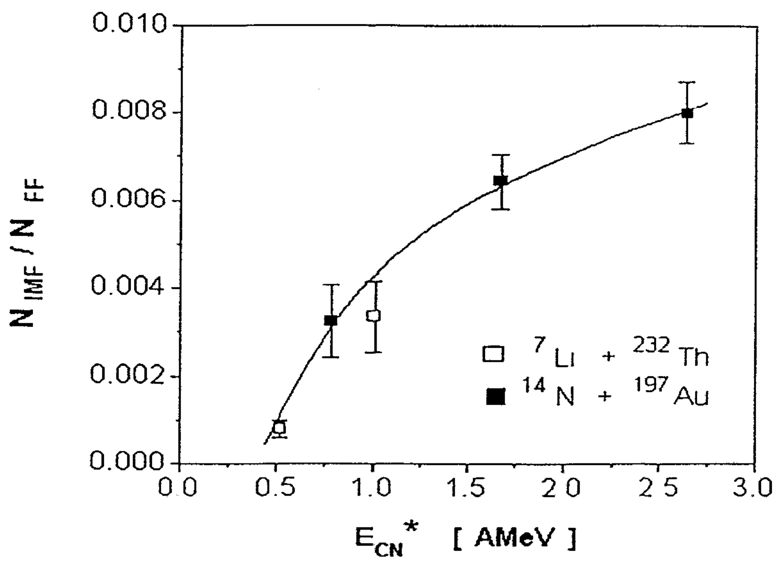

Fig. 4 Yield ratio of ternary decay to binary fission in dependence on the excitation energy of the composite system.

With increasing E* (or T), the ratio of ternary decay to binary fission increases slower. When, after the evaporation processes, the remaining HR moves to the Businaro-Galone point, the symmetric fission barrier increases and fission becomes less probable. Within such a scenario, we have a transition from IMF-accompanied fission to a sequential (multi-) fragmentation. The increasing width of the FF mass distribution with E* may be a further argument for such a behavior. With increasing E*, symmetric fission will be less probable and the mass distribution becomes broader, i.e. we observe more asymmetric fragmentation.

A pure statistical picture for the multiple decay of hot nuclei formed by incomplete fusion reactions at 60 AMeV has been developed in ref. [10]. The multi-body decay probabilities are reduced to a chain of binary sequential decays introducing an empirical set of sequential barriers and assuming the decay to be governed by the phase space only. Then, the ratio of the probabilities for n-fold to binary decay can be expressed by

$$\ln [P_n / P_2] \sim - (a / E^*)^{1/2} \cdot (B_n - B_2)$$

where a - is the Fermi gas level density parameter, B_i - are the fragmentation barriers and E* - is the excitation energy of the formed composite system in AMeV. Thus, plotting $\ln [P_n / P_2]$ versus $(E^*)^{-1/2}$ one should get a straight line.
This transformation of our data in fig. 4 is shown in fig. 5. Indeed, some linear dependence as predicted in ref. [10] can be recognized. The absolute ratios, however, are in crucial disagreement with that of ref. [10]. The reason may be that, for heavy nuclei, the low fission barriers play a dominant role, favouring fission against IMF emission.
While the emission of light particles is usually treated as an evaporation process, fission is not a pure statistical break-off, but a much more complicate collective motion of nuclear matter governed by an assembly of different forces and collective degrees of freedom, which proceeds on a dynamical time scale.

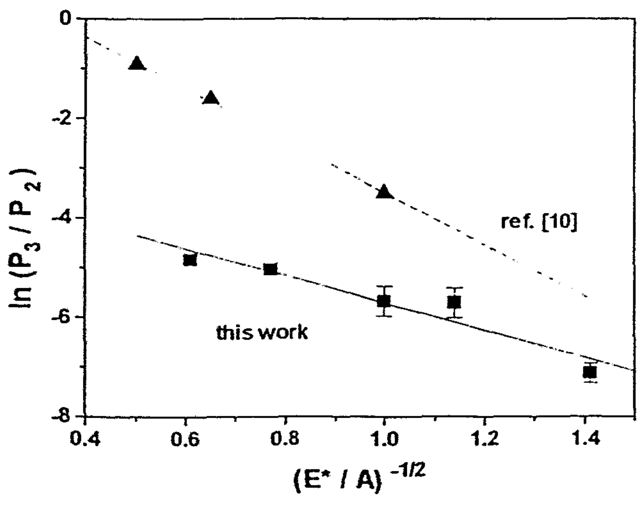

Fig. 5 Natural logarithm of the probability ratio for ternary decay to binary fission in dependence on the reciprocal square root of the excitation energy

Nevertheless, the scaling law seems to be preserved, although the mass split as well as the different time scales are not considered.

Assuming the IMF production probability as the product of the pre-formation and emission probabilities, a mass- and Z-dependence of the characteristic mean lifetimes (τ_{IMF}) of the composite system against IMF emission should be expected. However, the evaporation picture of the decay mechanism should meet some difficulties both with increasing mass and with decreasing E*. Supposing IMF emission is a very asymmetric fission, it should be associated with higher-order shape degrees of freedom of the composite system.
Up to now, the problem of the interplay of these decay mechanisms is far from a full understanding. With increasing E*, IMF emission as well as asymmetric fission yields increase. This leads to a successive filling of the valley in the fragment mass distribution between FF and IMF with increasing E* .
An estimate of the periods of mass-asymmetric collective vibration modes is given in ref. [6] ($\tau_{asym} \approx 10^{-21}$ s) . From pre-scission neutron evaporation measurements, the characteristic time for a symmetric fission has been determined to be $\approx 10^{-20}$ s [ref. [7]].The variation of the scission times τ_{sc} in dependence on the fragment mass ratio (A_H / A_L) has been deduced in ref. [11] . A change of (A_H / A_L) from 1.0 to 4.8 is found to be connected with a variation from $\tau_{sc} \approx 1 \cdot 10^{-20}$ s to $\tau_{sc} \approx 5 \cdot 10^{-22}$ s. To summarize, τ_{asym} and τ_{sc} become comparable with increasing E* and the fission path in direction towards asymmetric mass division is shorter than that for symmetric mass division. However, the barrier increases with larger values of (A_H / A_L) and asymmetric fission can only occur at sufficient high E*.
Within such a scenario, it could be speculated that, at intermediate E*-values, coherence effects decide the further fate of the remnant nucleus (HR) at the moment of IMF emission. Either the shape of the HR favours the Coulomb repulsion - what irreversibly leads to fission - or the HR remains. Nevertheless, further information is needed to make final conclusions.
In order to investigate the time scale between IMF emission and fission, the angular distributions of the IMF with respect to the fission axis have been analysed. In our recent measurements [12], we observed nearly isotropic IMF emission at E* ≈ 0.6 AMeV, but an enhancement of IMF emission towards angles perpendicular to the fission axis at E* ≈ 1 AMeV. Such an IMF component, which is characterized by a lower kinetic energy compared to the isotropic component, has been already observed by Fields et al.[13] . It was interpreted as a neck emission of IMF during scission.
The absolute yield of this component was found in the present experiment [12] to be larger than expected from the tripartition yields at low energy. Furthermore, the isotropic IMF component shows some decrease at small relative angles. In any case, the observed behaviour at E* ≈ 1 AMeV should be interpreted in terms of Coulomb proximity effects: With inreasing excitation energy E*, additional decay channels can open with similar

time scales for IMF emission and fission. Besides the sequential process of fission after IMF emission, ternary fragmentation becomes possible. The study of this evolution acquires the analysis of higher-order correlations between FF, IMF, HR and LCP in a suitable frame of variables and needs experiments with a sufficient high number of events.

A detailed investigation of the transition from binary to higher-fold decay modes with respect to the time scales of the different processes should , therefore, be of fundamental interest for the understanding of the de-excitation mechanism of hot nuclei.

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