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# THE BINARY DECAY OF HOT HEAVY NUCLEI: FISSION, EVAPORATION, AND ALSO FLOW ?

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# THE BINARY DECAY OF HOT HEAVY NUCLEI: FISSION, EVAPORATION, AND ALSO FLOW ?

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# 1 INTRODUCTION

Nuclear fission, appropriately characterized as "one of the most interesting processes of collective flow of nuclear matter" [1], is for a pretty large interval of excitation energy ($E^*$) the dominating decay mode of sufficiently intense heated heavy nuclei. This binary disintegration into two fission fragments (FF) of nearly equal mass ($M_F$) mainly competes with the emission of gamma-quanta, neutrons and — at temperatures higher than $T \approx 3$ MeV [2]) — light charged particles (LCP). Recently, a dynamical description of this complex interplay has been developped [3]. It should be well established now that fission represents an overdamped collective motion over a saddle in the hyperplane of potential energy to a considerably large-deformed scission configuration, and proceeds in a time scale of several units times $10^{-20}$ s [1]. The total kinetic energy (TKE) of the fragments is then defined by the Coulomb repulsion between the preformed FF at the scission point. A parametrization of the TKE has been given earlier by Viola et al. [4], considering that being governed explicitely by the Coulomb term $\frac{Z^2}{A^{\frac{1}{3}}}$ where $Z$ and $A$ denote the atomic number and the mass number of the fissioning nucleus, respectively. The consequence is a rather constant value of the mean relative velocity ($\approx 2.4\ \frac{cm}{ns}$) between the FF fairly well reproduced by the experimental observations.

The emission of light particles from a heated nucleus, as treated by the statistical model, is usually considered to be an evaporation process. The probability $P_{ev}$ is given by the level density which for a Fermi-gas takes the asymptotical form of a Bolzmann factor $\rho(E^*) \sim e^{2\cdot\sqrt{aE^*}}$ where the level density parameter is $a \sim A$. In the case of charged particles one has to account for their Coulomb barrier $B_C$ getting $P_{ev} \sim e^{2\cdot\sqrt{a(E^*-B_C)}}$. The characteristic time for particle evaporation then can be evaluated by $\tau_{ev} \sim \frac{1}{P_{ev}}$ keeping in mind the statistical nature of the decay. The inclusive spectrum of the particles is in a wide range of kinetic energy well described by a Maxwell distribution characterized by the temperature $T$ of the emitting nucleus. Of course, the nucleus is no heat bath, but cooles down during particle emission what has to be accounted for. The combined dynamical-statistical model of fission [3] mentioned above is, by the way, an attempt to take into account namely this feed-back on the fission-evaporation competition. Considering again the evaporation process, it is evident, that the kinetic energy of the emitted charged particles has the lower threshold corresponding to $B_C$.

The investigations of heavy-ion induced reactions at intermediate energies — in the so called Fermi-energy domain — which became possible in the 1980's, rather early showed that, besides LCP, also complex fragments of intermediate mass (IMF) are emitted. Somewhat arbitrarily one defined the IMF as being fragments of mass $4 < M_{IMF} < 20 \div 30$ — or $2 < Z_{IMF} < 10 \div 15$ — but, in any case, of mass between that of the evaporative LCP and the FF. They can have a very different origin (cf. e.g. Moretto et al. [5]). We consider for the present only such IMF emitted from an *equilibrated* (compound-like) source. The formation of an excited compound nucleus due to an incomplete fusion reaction characterized by only partial linear momentum transfer ($LMT < 1$) has been observed, e.g., by Charity et al. [6, 7].

From pure statistical considerations Moretto et al. [5] presumed that "fission and evaporation are the two particularly (but accidentally) obvious extremes of a single statistical decay process, the connection being provided in a very natural way by the mass asymmetry coordinate". The transition-state model of fission delivers for the fission probability $P_f \sim e^{2\cdot\sqrt{a^*(E^*-B_f)}}$, i.e. an expression of the same form as for evaporation. $B_f$ here is the (symmetric) fission barrier, the point of lowest potential energy on the saddle of the hyperplane spanned in the space of collective coordinates — the elongation and the mass asymmetry. At sufficiently high $E^*$ the fission yield should be only governed by the energetically allowed phase space flux over the "ridge line" [8], the line connecting the conditional saddle points for all possible mass splits.

The statistical approach treating the decay of an excited nucleus as being controlled by the phase space only, of course, does not account for any dynamical effects, but considers the decay channels as "having equal rights" within their statistical weight. The transient times of fission caused by the influence of the nuclear viscosity on the decay mechanism [1], on the other hand, document the presence of dynamical hindrance effects. It is, therefore, an interesting and up to now open question, do they, and if "yes," in which way do they modify the mass distribution or other observables.
With other words: Where do dynamical quantities come into play ? Where does the transition from evaporation to fission happen?

Empirically it is clear that one has to investigate the dependence of suitable quantities of the decay process on the mass asymmetry coordinate. We tacitly presuppose here the binary character of the decay, but the validity of this assumption holds up to considerably high $E^*$ [9, 10]. In a first attempt, we analyzed the $M - TKE$ distribution of binary fragments measured for the reaction $^{14}N\,(34\,AMeV) + {}^{197}Au$ [11].

# 2 THE EXPERIMENTAL METHOD

The measurement has been carried out at the heavy-ion beam of the U-400M cyclotron of the FLNR JINR Dubna using the $4\pi$-fragment-spectrometer FOBOS[1] [12]. This multi-detector array consists of 30 combined detector modules mounted on the facettes of a truncated icosahedron, representing a so called logarithmic detector device. Three shells of i) position-sensitive avalanche counters, ii) axial field (Bragg-) ionization chambers, and iii) CsI(Tl) scintillators measure the coordinates $(\vartheta, \varphi)$, the time-of-flight $(TOF)$, the residual energy $(E)$, and the Bragg-peak height $(BPH \sim Z)$ of the fragments, as well as scintillator signals suited for the LCP identification by use of the pulse-shape analysis method [13].

From the measured quantities the individual fragment masses $(M_f)$ and the momentum vectors $(\vec{p_f})$ can be derived applying the $TOF - E$ method event-by-event without any kinematical assumption [14]. The sums $\Sigma M_f$ and $\Sigma \vec{p_f}$ were checked to select events of large $LMT \approx 0.8$. The $LMT$ has been used as a rough measure of $E^*$ of the composite system. A large value of $\Sigma M_f$ together with a limited deviation of the direction of the vector $\Sigma \vec{p_f}$ from the beam direction - corresponding to a value $\leq 500 MeV/C$ of the transversal component - were used as criteria for the selection of coplanar binary decays. At energies $E^* \approx 400\, MeV$ reached by the hot system in the reaction chosen, the amount of three-body decays with an additional IMF emitted before or during fission is yet $< 1\%$ [15], and the bulk of the data is due to binary disintegrations of the excited composite system. We must emphasize here that in the very asymmetric reaction induced by the light projectile, fragments heavier than $^{14}N$ should originate only from the *decay of a compound-like system*, and deep-inelastic or fast-fission components are excluded. In reactions induced by heavier projectiles (like $^{40}Ar$, $^{27}Al$, etc., cf. Ref. [9, 16]) this is in general not the case, and the picture becomes more complicate.

# 3 EXPERIMENTAL RESULTS

## 3.1 The M-TKE distribution at large linear momentum transfer

Binary events fulfilling the requests formulated above are figured in an $M - TKE$ contour plot (Fig. 1). To show the large full width of the distribution in mass and energy, and to illustrate the resolution obtained due to the application of the $TOF - E$ method we chose a logrithmic scale. The main yield is due to "normal symmetric" multi-chance fission of a hot equilibrated system, but very asymmetric decays extend to fragments usually classified by their $M_f$ as IMF and heavy residues,

[1]Supported by the BMBF, Germany, under contract No.: 06 DR 671

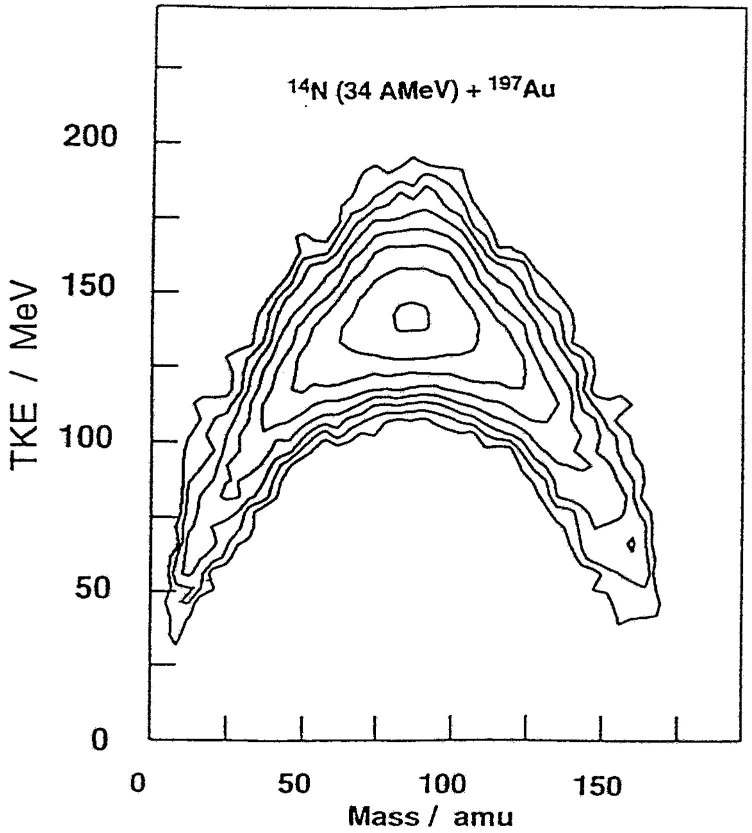


Figure 1: Contour plot of the $M - TKE$ distribution for binary decays of the hot compound system formed after incomplete fusion ($LMT \approx 0.8$) in the reaction $^{14}N\,(34\,AMeV) + {}^{197}Au$. The contour spacing is equidistant in a logarithmic scale.

respectively. The mean value of the sums of fragment masses $\langle \sum M_f \rangle$ amounting to 175 a.m.u. corresponds to an average mass-loss of 36 a.m.u. due to pre-compound particle emission (incomplete fusion) as well as pre- and post-scission evaporation. The branch of the heavier fragment is slightly broader than that of the lighter one because of the larger corrections for energy losses in the detector window materials and, therefore, larger uncertainties in the mass determination.

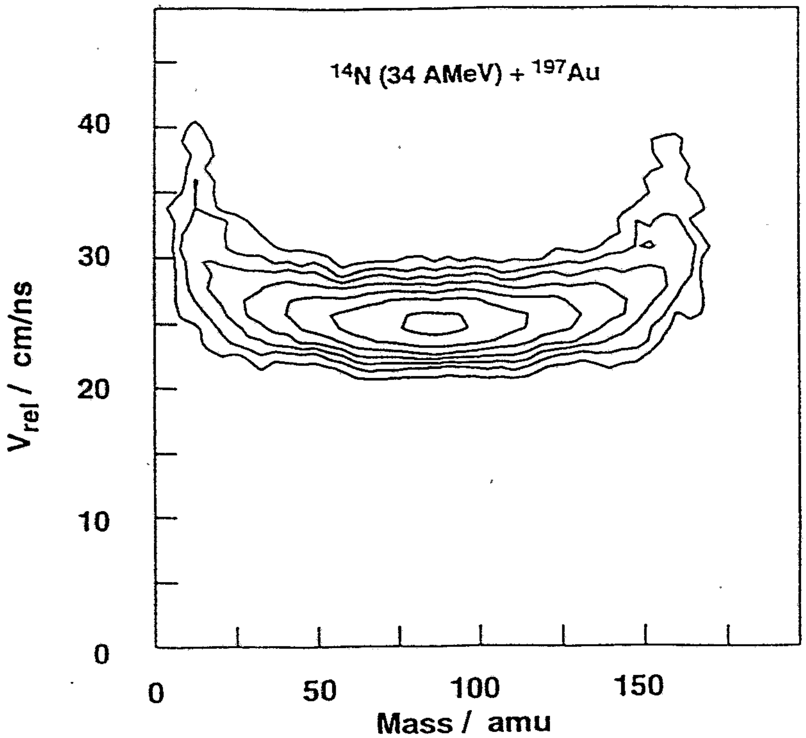


Figure 2: Contour plot of the $M - v_{rel}$ distribution for binary decays of the hot compound system formed after incomplete fusion ($LMT \approx 0.8$) in the reaction $^{14}N\,(34\,AMeV) + {}^{197}Au$. The contour spacing is equidistant in a logarithmic scale.

## 3.2 The relative velocities between binary fragment pairs

The large $TOF$ path of the FOBOS array (50 cm), and the fast timing properties of the position-sensitive avalanche counters allow an accurate measurement of the fragment velocities. The derived relative velocities ($v_{rel}$) between binary fragment pairs are drawn in dependence on $M_f$ in the contour plot of Fig. 2.

The mean value at symmetric fission is well reproduced by the systematics of Viola et al. [4]. By scaling of their $TKE$ formula with the asymmety factor $\frac{4 \cdot M_{f1} \cdot M_{f2}}{(M_{f1}+M_{f2})^2}$, accordance of the experimental mean $v_{rel}$ with the evaluated values is observed for asymmetric mass splits down to about $1:3$. At larger mass asymmetry of the decay the $v_{rel}$ deviate considerably, as can be directly seen in Fig. 2. A similar deviation of measured mean $v_{rel}$ from a Coulomb calculation has already been observed for binary decays induced by the reaction $^{139}La\,(18\,AMeV) + {}^{12}C$ (cf. Fig. 23 in Ref. [5]). There, the $v_{rel}$ are found to be increasingly larger than the calculated values with decreasing atomic number of the fragments starting at $Z < 20$. Our observations considerably well agree with this set-in of some deviation.

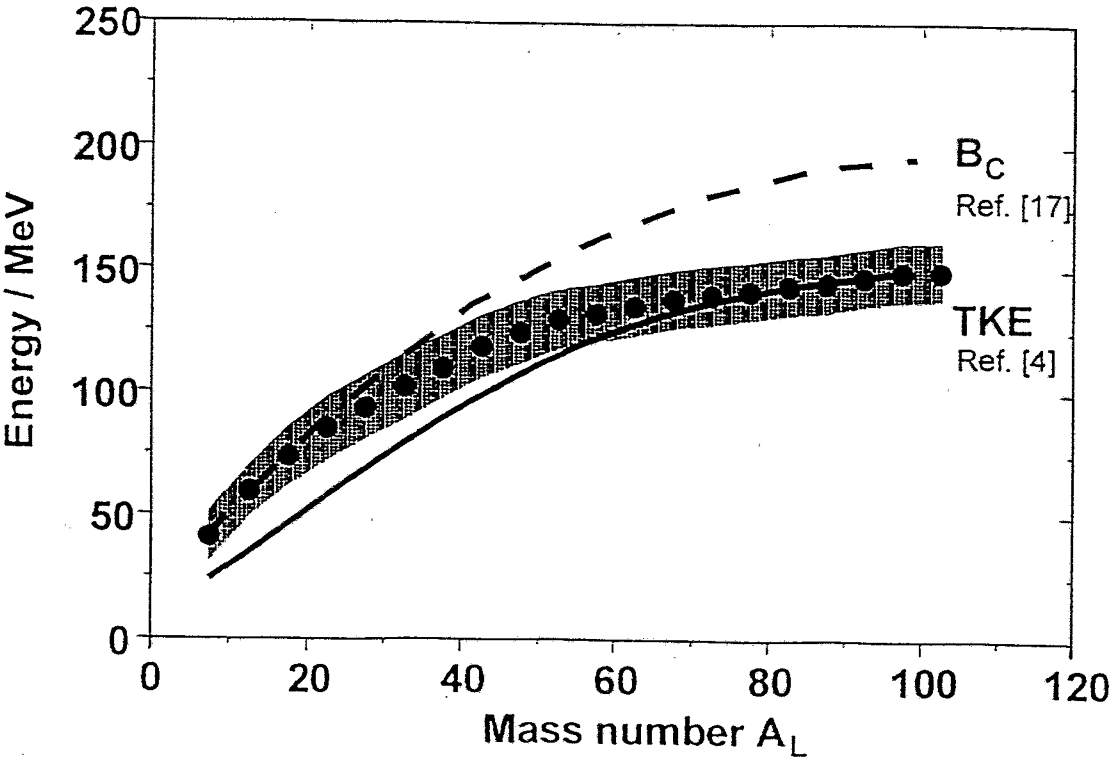


Figure 3: Measured $< TKE_M >$ (full circles) versus the fragment mass. The hatched corridor corresponds to $\pm\,\sigma_{TKE_M}$. The full line is calculated by use of the $TKE$ formula, the dotted line represents a $B_C$ calculation.

# 4 DATA ANALYSIS

## 4.1 The TKE spectra

On the base of the data presented in Fig. 1 and Fig. 2 we analyzed the $TKE$ spectra for mass bins of $\Delta M_f = 5\,a.m.u.$. The spectra have a symmetric shape except for the smallest fragment masses at $M_f < 25\,a.m.u.$. The mean values $< TKE_M >$ of these spectra determined within intervals of width $\pm 3 \cdot \sigma_{TKE_M}$ are drawn versus the mean values of the mass bins in Fig. 3. The $\sigma_{TKE_M}$ are the standard deviations of Gauss distributions fitted to the spectra within intervals of $\pm 3 \cdot \sigma_{TKE_M}$. The hatched corridor in Fig. 3 corresponds to $\pm\,\sigma_{TKE_M}$. For comparison we also drawed the $TKE$ calculated corresponding to Viola et al. [4] with account for the asymmetry factor, and the $B_C$ calculated using the formula of Bass [17].

Starting from symmetric fission, one observes that the $< TKE_M >$, being the "most probable" $TKE$ value for the mass bin considered, at first follows the line

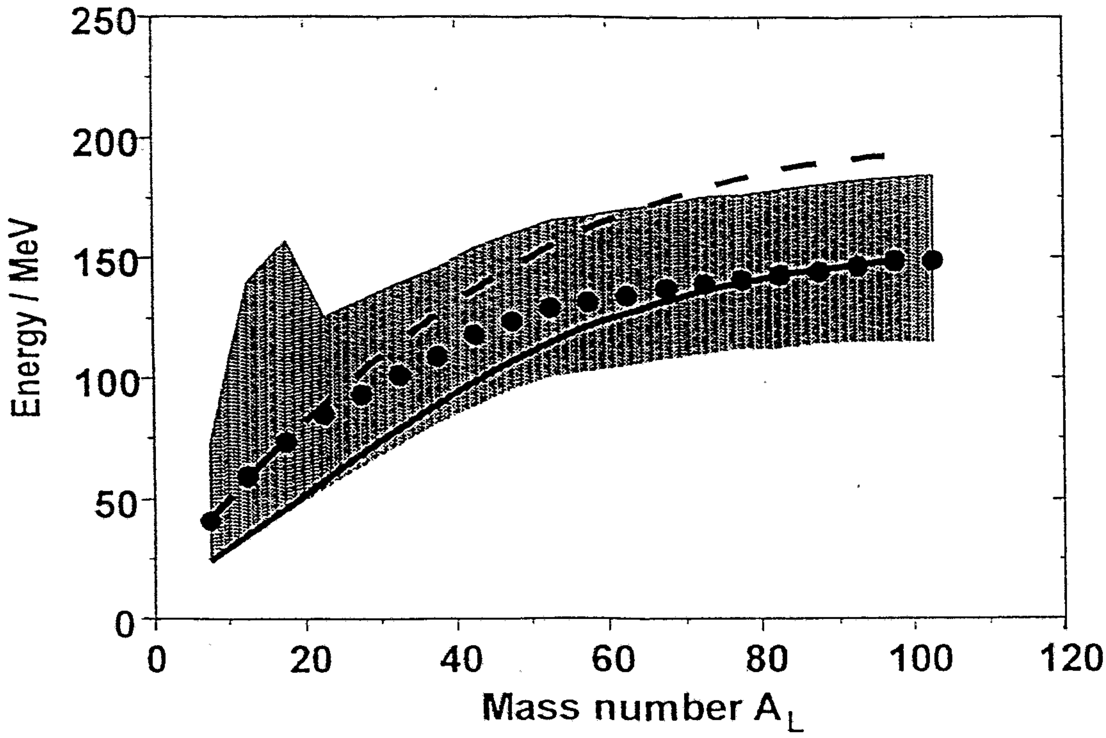


Figure 4: The same as shown in Fig. 3 but the hatched corridor shows the region where the yields exceed 1% of the maximum for a given $M_f$.

calculated by use of the $TKE$ formula, and then smoothly approaches to the $B_C$ line. On a confidence level of one $\sigma_{TKE_M}$ the deviation from the $TKE$ curve sets in at $M_f \approx 50\,a.m.u.$, and below $M_f \approx 25 \div 30\,a.m.u.$ the $< TKE_M >$ are well reproduced by $B_C$.

In Fig. 4 the data of Fig. 3 are shown again, but the hatched corridor includes practically all observed events. Note that the tails of the $TKE$ spectra observed for $M_f < 25\,a.m.u.$ lead to asymmetric dispersions. Three additional informations are contained in this figure: i) The corridor is obviously connected with shape fluctuations of the scission configuration leading to a spread in the Coulomb repulsion. ii) The lowest $TKE$ value observed for small $M_f$ fairly well approaches to the $TKE$ curve. iii) The tails of the $TKE$ spectra at $M_f < 25\,a.m.u.$ extending to higher kinetic energies of these fragments could suggest an evaporation-like emission process, but the temperatures evaluated from the slope of the spectra are not consistent with any temperature of an equilibrated system.

## 4.2 What can one conclude from this observations ?

We want to make a first attempt of an interpretation of the experimental findings. The gross-behaviour of the $< TKE_M >$ (Fig. 3) points to a decreased damping of the motion of the excited system on some "trajectory" to a scission configuration with increasing mass asymmetry of the decay. Down to mass splits of about $1 : 3$ the $TKE$ formula scaled by the asymmetry factor describes the kinetics of the fission-like decay. Since the scaling factor can be taken as $\frac{4 \cdot M_{f1} \cdot M_{f2}}{(M_{f1}+M_{f2})^2}$ or $\frac{4 \cdot Z_{f1} \cdot Z_{f2}}{(Z_{f1}+Z_{f2})^2}$ it is obvious that it accounts only for the re-distribution of the charge of the fissioning nucleus between the preformed FF, and does not vary the shape of the scission configuration. This approximation does not hold for more asymmetric splits, and the average scission shapes for transitional asymmetries from about $1 : 3$ to $1 : 7$ should be more compact leading to an enhanced Coulomb repulsion and, therefore, larger $< TKE_M >$ values. In the framework of Moretto's theory [5] this reflects the approaching of the conditional scission points to the "ridge line" of conditional saddle points with increasing asymmetry of the binary decay. Furthermore, as the descent from the saddle to the scission point is responsible for a large amount of the fission transient time [1], this should be a hint that more asymmetric disintegrations proceed faster than symmetric fission. They are less damped !

The minimum $TKE$ at large mass asymmetries is realized when the heavier fragment is maximum deformed. This is the case of maximum energy transformed into collective degrees of freedom (or surface energy). The $B_C$ curve implicitely considers the scission configuration as being that of two touching spheres. A sufficiently small cluster being preformed in the vicinity of the surface of the hot nucleus and being rather compact — i.e. having no collective degrees of freedom — can in principle be escaped (or *evaporated*) if this is energetically possible. The probability of such a process is governed by the phase space, and the minimum kinetic energy of the cluster corresponds to the Coulomb barrier $B_C$. The recoil nucleus (or evaporation residue), being the partner in the binary decay and being a priori a *heavy* remnant, has intrinsic as well as collective degrees of freedom and, therefore, should be responsible for dissipative fluctuations.

At first sight one could conclude that with the unification of the saddle and the scission point we observe the transition from a fission-like to an evaporation-like decay mechanism claimed to be "the two extremes of a single statistical decay process." But possibly there is evidence of something more !

## 4.3 A new hypothesis

The statistical description of the decay implies an equilibrated (compound) system. If so, its temperature governs the spectrum of the evaporated particles (cf. also Ref. [8]). For very asymmetric mass splits, however, we observe $TKE$ values of twice the Coulomb barrier (Fig. 4). As the light fragments were recorded at backward angles ($\vartheta > 100^o$), such large $TKE$ can not be connected with deep inelastic processes. The $TKE$ in that case would approach to the $B_C$ value (in the $\vartheta - TKE$ Wilczynski plot). A possible scenario could be a fast (binary) break-up of the system *before reaching a full equilibration*, and that for "semi-central" impacts. In a BUU calculation using the code of Bauer et al. [18, 19] one observes for an early stage of the reaction (at about 150 $\frac{fm}{c}$) a dense zone being connected with the stopping of the *light projectile* inside the target nucleus. At semi-central impact we also expect considerably large transferred angular momentum (several tens of $\hbar$). A break-up of the system in this stage, i.e. at some time when the momentum spheres of the projectile and target nuclei begin to overlap, could be the origin of the effect observed. Consequently, it should appear at large mass asymmetry, and in very asymmetric heavy-ion reactions at intermediate energies only. This would represent a specific decay mechanism being reminiscent of some "local radial flow". The existence of such a process, of course, has yet to be proofed.

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