SEARCH FOR AN EXPERIMENTAL DISTINCTION BETWEEN THE BINARY SEQUENTIAL DECAY AND THE PROMPT MULTIFRAGMENTATION OF HOT NUCLEAR SYSTEMS

K.Grotowski

Institute of Physics, Jagellonian University, Reymonta 4,

and H.Niewodniczański Institute of Nuclear Physics,

Cracow, Poland

Highly excited nuclear systems can disintegrate sequentially or promptly. Both scenarios characterize very short decay times, usually smaller than 10^{-20} sec. It seems that one can find a distinction between them, investigating charged particle correlations. Six different methods are discussed.

1. Introduction

In a beautiful although strenuous experiment Jacobsson et al. [1] investigated multifragmentation events in reactions induced by oxygen ions. Tracks of charged fragments were observed in nuclear emulsions which were used as a target containing the silver nuclei. It was found that the multiplicity of charged particles grows up quite rapidly with the collision energy (Fig.1). It is up to 6 for 15 MeV/u, up to 15 at 45 MeV/u, and at 2100 MeV/u reaches 56, what indicates a complete disintegration into constituent nucleons.

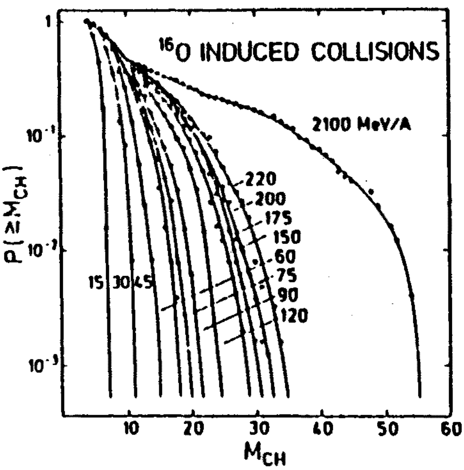


Fig.1

While low multiplicity nuclear decays are well known as a result of the direct reactions or as a statistical sequential evaporation from compound nuclei, the high multiplicity events could be produced in some new process which may be understood as an explosion-like simultaneous multifragmentation. A possibility of existence of such processes is exciting and a number of models have been proposed to explain them, as for example a liquid-gas phase transition [2].

Unfortunately, verification of the multifragmentation models by comparison with experimental data is difficult and frequently impossible. This is so because experiments cannot simply distinguish prompt multifragmentation (MULFRA) from a sequential break up (a chain of sequential binary decays (BINFRA)). Here we shall discuss some more complicated, exclusive measurements which can, probably, find a distinction between the BINFRA and MULFRA decay scenarios.

2.Decay modes of an excited nuclear system

We shall restrict discussion to central collisions producing hot nuclear systems with an excitation energy around the Fermi energy. A central collision is necessary in order to create a system with a well defined nuclear temperature. This is important, as it is the temperature (excitation) which governs a transition from BINFRA to MULFRA. Such a transition is expected around the Fermi energy [3].

If the incident energy is not to high, a central collision should produce a compound nucleus (CN) which is expected to have two decay modes: BINFRA and MULFRA. In principle a third decay mode proposed by Friedman [4] is also possible. In the model of Friedman a hot nucleus expands and undergoes sequential particle emission in a very short time which for a nucleus of mass 190 is less than 40 fm/c. We shall discuss here some possible experimental distinctions between BINFRA and MULFRA. The third decay mode of Friedman will be only mentioned.

Fig.2 presents some features of BINFRA. For lower excitation energies ($E^{*}/A \simeq$ 2MeV) the compound nucleus decays by sequential evaporation of light particles. The mass (or charge) spectrum shows a well separated group of heavy evaporation residues (E.R.). For higher excitation energies, e.g. 5 MeV/u, the compound nucleus evaporates sequentially some number of intermediate mass fragments, IMF, which also may undergo sequential evaporation of light particles. The final partition doesn't contain now a well defined evaporation residue. The

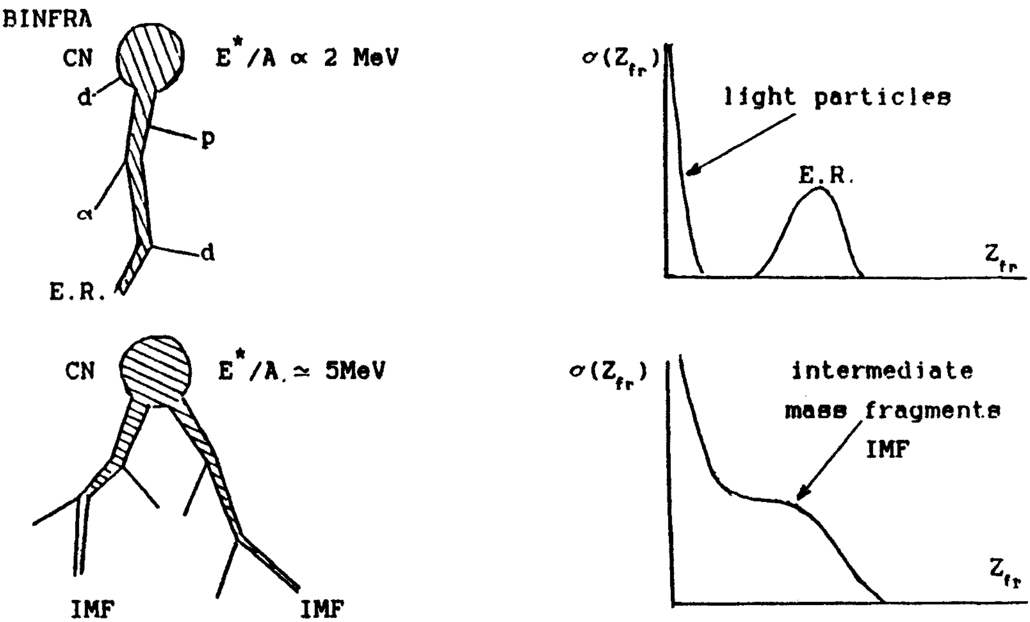
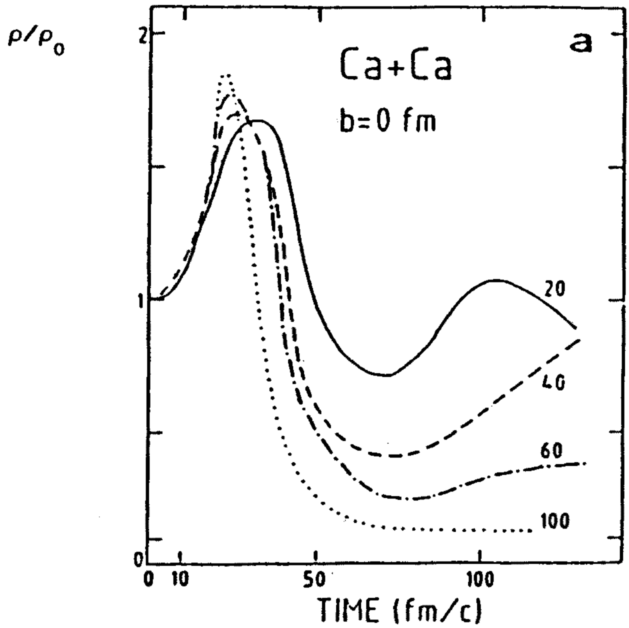


Fig.2

contribution of intermediate mass fragments, as compared to light particles, increases with the collision energy, and extends up to the symmetric fission region [5]. Heavy nuclei may fission also at low energy.

In head-on collisions nuclear density varies with time (see Fig.3). We present here a prediction of the Landau-Vlasov calculation [6] performed for the ^{40}Ca + ^{40}Ca head-on collision at 20, 40, 60, and 100 MeV/u. At a low collision energy nuclear matter density oscillates as a damped oscillator. After some very short time the oscillation energy dissipates to heat and the system may decay sequentially. For some higher collision energy (its exact value depends upon the value of the compressibility modulus) the system never comes back to the normal nuclear density and breaks up into some number of clusters and nucleons. At that moment fragments are contained inside the so called freeze-out volume and the system immediately explodes due to the Coulomb repulsion. This is the MULFRA decay mode. For heavy systems the expected MULFRA explosion time is shorter then 300 fm/c (10^{-21}sec) [7] and for Ca + Ca is about 2÷3 ⊗ 10^{-22}sec (see Fig.3)



Jouan et al. [6].

Landau-Vlasov calculations

$^{40}Ca + ^{40}Ca$

collision energy:

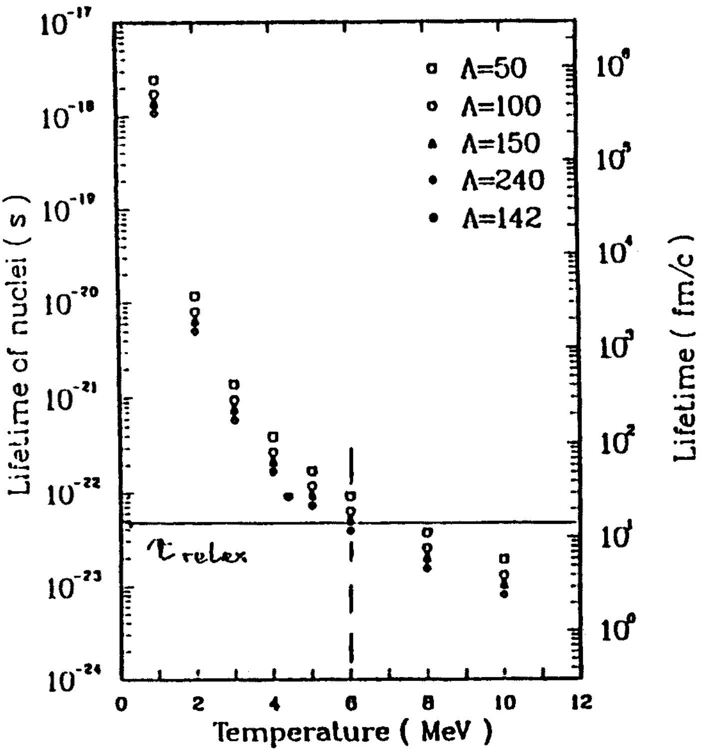
20, 40, 60, 100 MeV/u

1fm/c = 1/3 ⊗ 10^{-23}sec

FIG.3

According to Borderie [7] the life-time of nuclei for the sequential emission of the first neutron rapidly decreases with the increasing nuclear temperature. This is shown in Fig.4 for a number of nuclei with mass numbers from A=50 to A=240. Predictions of Borderie agree with the earlier prediction of the hot nucleus life-time obtained from the statistical theory (A=142, T=4.4 MeV), which properly reproduces the observed small-angle charged particle correlations in the reaction 680 MeV ^{40}Ar + Ag [8]. The horizontal line indicates the relaxation time for the formation of a compound nucleus. From the crossing with the lifetime curve one can estimate the value of the maximum possible temperature of the compound nucleus (about 6 MeV).

As mentioned before, hot nuclei deexcite emitting light particles, IMF's, and fission fragments. Fission and IMF emission can be treated as the two extremes of a single mode of decay, connected by the mass asymmetry degree of freedom [5]. Measurements of the pre-scission neutron multiplicities performed over a large set of the projectiletarget combinations [7], suggest for a symmetric fission after fusion, decay times in the range of $3.5 \pm 1.5 \cdot 10^{-20}$ sec. For the increasing mass-



statistical evaporation of neutrons

Borderie [7]

Fig.4

asymmetry of the fission fragments the decay-time is reduced [9], showing a smooth transition to the value characteristic for the neutron evaporation. The emission times for the IMF's don't change to much in the collision energy range 18÷84 MeV/u.

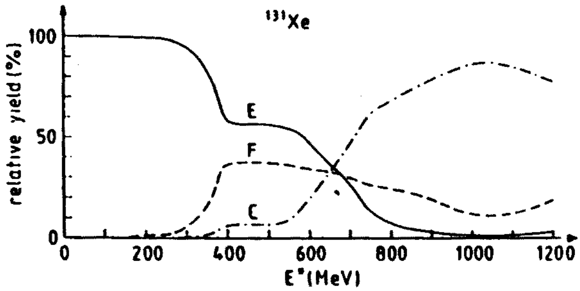
The life-time for emission of nucleons, and for emission of IMF's can be simply parameterized [10]:

$$\tau = 2 \exp(13/T)\exp(A/8) \text{ [fm/c]},$$

where T is the nuclear temperature, and A is the mass of the emitted fragments.

3.The distinction between multifragmentation MULFRA and sequential binary decay BINFRA

Statistical calculations of nuclear disassembly [11], presented in Fig.5, predict a transition from the sequential evaporation at a low excitation energy to the fission and sequential evaporation as energy increases, and finally at much higher excitation to cracking (MULFRA).



Statistical calculations Gross,Massmann [11]

E - evaporation
F - fission
C - cracking

Fig.5

How to distinguish experimentally between

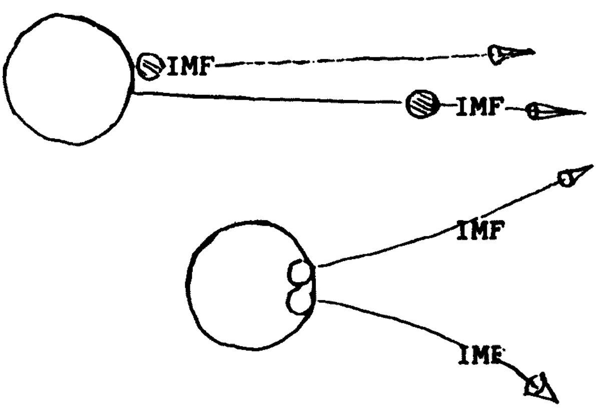
the prompt multifragmentation,

and the sequential binary decay ?

The inclusive data are rather insensitive to the CN decay scenario. E.g. $\sigma(A_{fr})$ and $\sigma(Z_{fr})$ predicted by different models are similar for BINFRA and MULFRA [12].

More hope: exclusive data based on the particle-particle correlations.

i.IMF-IMF correlations ; small relative angles.

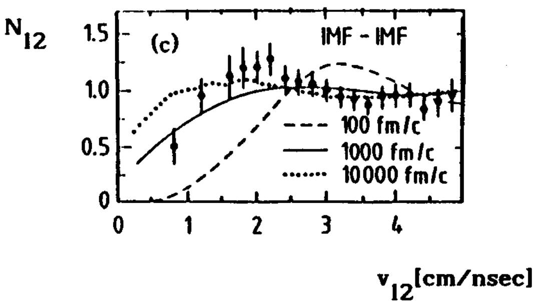


Sequential emission

Simultaneous emission

Fig.6

It is expected, that distributions of the relative velocity between the intermediate mass fragments, measured atsmallrelative angles, are determined by the interaction between them. Since such interaction is mainly the mutual Coulomb repulsion,the shape of the relative velocity distribution should depend on the distance (in space as well as in time) between fragments (see Fig.6). In line with conventional nuclear interferometry studies [13] that effect has been used to select slow binary sequential processes [14]. Fig.7 displays the measured and calculated relative velocity correlations of intermediate mass fragments observed in the ^{18}O + ^{197}Au reaction at 84 MeV/u. Due to the repulsive Coulomb interaction the two IMF's can't



^{18}O + ^{197}Au 84 MeV/u
(central collisions were not selected)
Trockel et al. [14]
Conclusion: $\tau \simeq$ 1000 fm/c
The BINFRA scenario.

Fig.7

be to close to each other in the relative velocity space, depending on the value of the CN decay constant. As one can see the minimum in the correlation function has the proper size for $\tau \simeq$ 1000 fm/c, a value expected for the BINFRA scenario. As central collisions were not selected in the experiment, this result can be treated only as an average over all possible values of the impact parameter.

ii.IMF-IMF correlations ; relative angles close to 180^0.

The angular correlation looks different when two coincident IMF's are emitted into opposite hemispheres. For the BINFRA scenario the relative velocity of IMF's should be approximately twice the value of the individual emissions from the heavy evaporation residue (Fig.8). The Coulomb recoil energy should be reduced if the breakup occurs out of an expanded state, as expected for MULFRA. Consequently, the relative velocity should be smaller, and $\Delta(v_{12})_{MULFRA} < \Delta(v_{12})_{BINFRA}$. Results of such experiment are presented in Fig.9. The measured relative

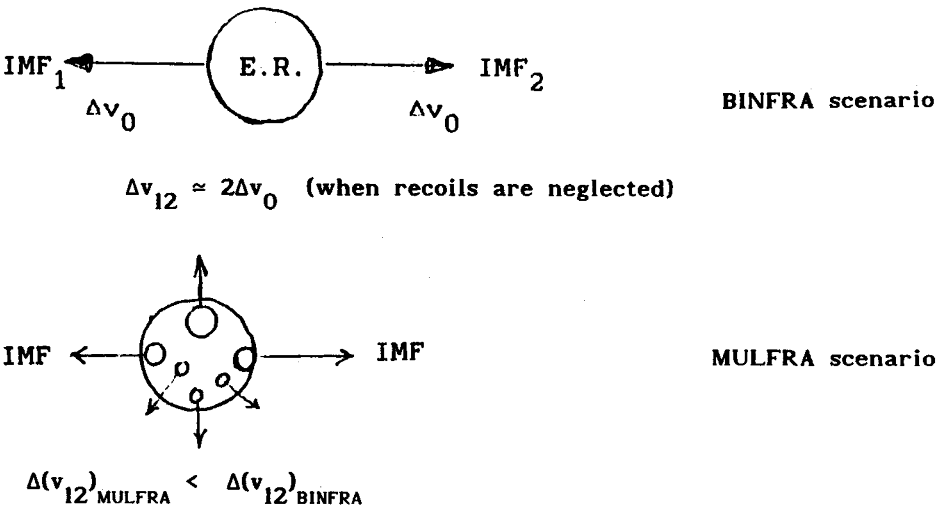
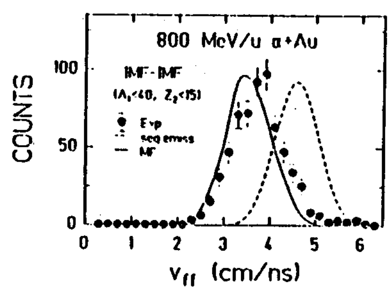


Fig.8

velocity distributions are in agreement with predictions of a MULFRA Monte Carlo model [15]. The authors performed the intra-nuclear cascade calculations in order to define the CN mass and atomic number (A=184, Z=74), and other parameters necessary to perform the LAB to CM



$\alpha + {}^{197}Au$; 800 MeV/u
Gross et al. [15]
(central collisions were not selected)
CN = ${}^{184}_{74}W$ (intra-nuclear cascade calculations)
Conclusion:MULFRA scenario.

Fig.9

transformation. The same data were analyzed by Pochodzalla et al. [16]. According to their opinion Gross et al. overestimated the CN mass and in consequence the calculated relative velocities were to large. Pochodzalla et al. maintain that the experimental data agree well with the BINFRA picture.

iii.Average recoil momentum of the heaviest fragment (E.R.).

Recently a recursion relation has been derived by Cole et al.[17] which relates the mean square momenta of the sequentially emitted light particles and of the final residue. It appears, that in the case of BINFRA

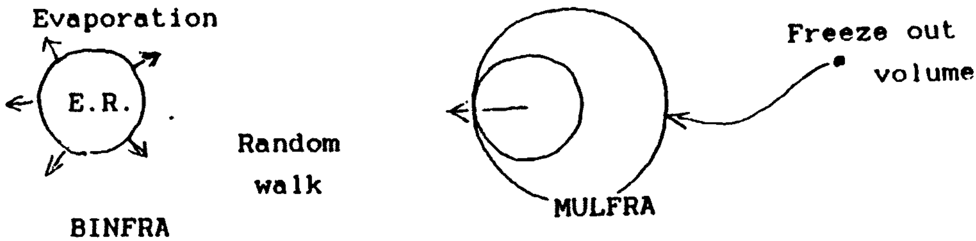


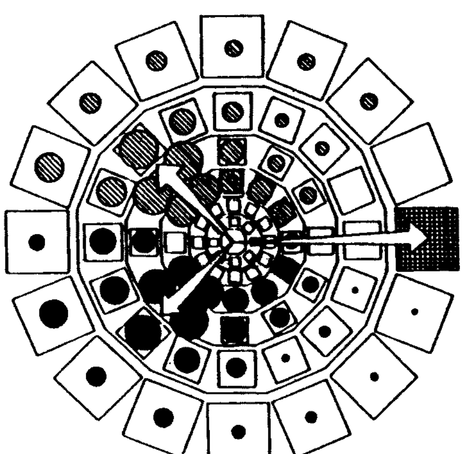
Fig.10

random recoils transmitted to the evaporation residue by evaporating particles almost cancel each other. In a MULFRA decay a collective "kick" received by the heaviest fragment from the rest of the nucleus is much larger (see Fig.10). The obvious suggestion:

$$\langle p^2 \rangle_{BINFRA} \ll \langle p^2 \rangle_{MULFRA} \quad \text{for the heaviest fragment.}$$

One could argue that such kind of a measurement is an inclusive one. It is not true, as one has to record all fragments in order to select the heaviest one.

iv.Azimuthal correlation of particles.



^{32}S + ^{58}Ni ; 26 MeV/u
Multidetector system
ARGUS, HMI Berlin
Sourell et al. [18]
A>4 particles
recorded in coinc.
with IMF's at $\theta=29^0$

Fig.11

As suggested by Gross (see Fig.5), for higher excitation energies of the system, evaporation is being replaced by fission and than by cracking (prompt multifragmentation). The multifragmentation should begin from some kind of tri-partition. For such a reaction an average distribution of fragments is expected to show a 120^0 periodicity in the azimuthal angle. Some kind of such correlation was apparently observed by Sourell et al. [18]. They have studied the ^{32}S + ^{58}Ni reaction at **26 MeV/u** using the **multidetector system ARGUS** of **HMI** in **Berlin**. The front wall of the system seen from the target (beam direction in the center) is presented in Fig.11. One of the phoswich detectors was replaced by a solid-state telescope identifying intermediate mass fragments. The circles represent the distribution over the array for the A>4 particles (black and hatched, respectively) recorded simultaneously in coincidence with the IMF (the solid-state telescope). The authors suggest here the MULFRA reaction picture. Here also central collisions were not selected.

v.Coulomb focusing by the field of the two heaviest fragments.

The initial configuration of the MULFRA reaction picture, just before the Coulomb explosion, contains some number of clusters and nucleons confined in the freeze-out volume. Computer simulations show [10] that the two heaviest fragments participating in disintegration take a large part of the charge of the system. They are emitted almost back to back and at the beginning create an axial very strong Coulomb field

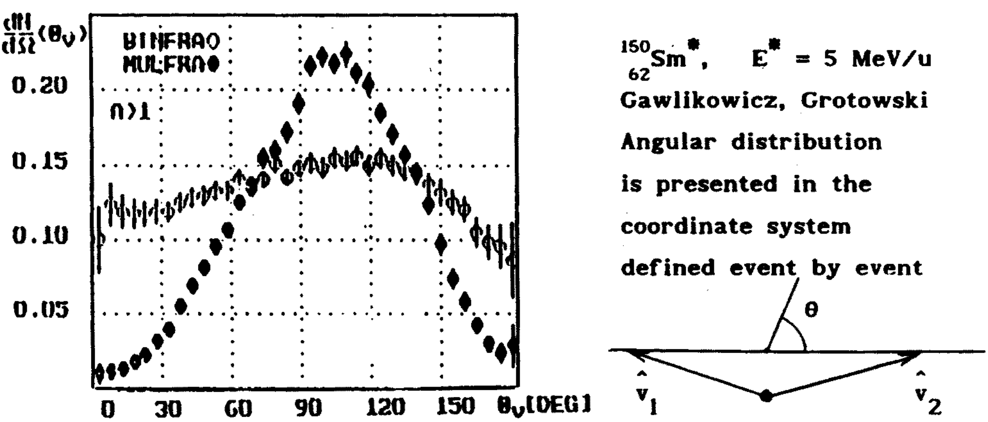


Fig.12

which focuses velocities of the other intermediate mass fragments. The focusing may be observed in a coordinate system oriented by the relative velocity of the two heaviest fragments, (1) and (2). Fig.12 presents an example of such Coulomb focusing of IMF's for prompt multifragmentation of the excited $^{150}_{62}Sm^*$ compound nucleus [10].

In the same coordinate system the velocity distribution of IMF's from the sequential binary fragmentation of the hot system is nearly isotropic.

vi.Event-shape analysis

- was proposed for multifragment reactions in 1982 (**Gyulassy et al.** [19], **Fai & Randrup**[20]). It was applied to the problem of the time scale of the fragmentation process by **López and Randrup** [21]. **For each event in the CM system** one can define the kinetic-flow tensor:

$$F_{ij} = \sum \frac{p_i^{(n)} p_j^{(n)}}{2m_n} \qquad \text{where}$$

$p_i^{(n)}$ **is the** i^{th} **Cartesian component of the momentum of the** n^{th} **fragment with the** m_n **mass.** For $t_1<t_2<t_3$ **-(the ordered eigenvectors of F)** - one can define **the reduced quantities**

$$q_i = \frac{t_i^2}{\sum_{j=1}^{3} t_j^2}$$

and introduce

the sphericity $S = \frac{3}{2}(1 - q_3)$, and

the coplanarity $C = \frac{1}{2}\sqrt{3}\,(q_2 - q_1)$.

S and C describe the shape of the energy flow surface.

As an example lets look on the **C** versus **S** plot (Fig.13) for the case of the $^{150}_{62}Sm^*$ compound nucleus excited to the energy of **5 MeV/u.**

The consecutive decays of the compound nucleus were simulated event by event for both the BINFRA and the MULFRA scenarios [21].

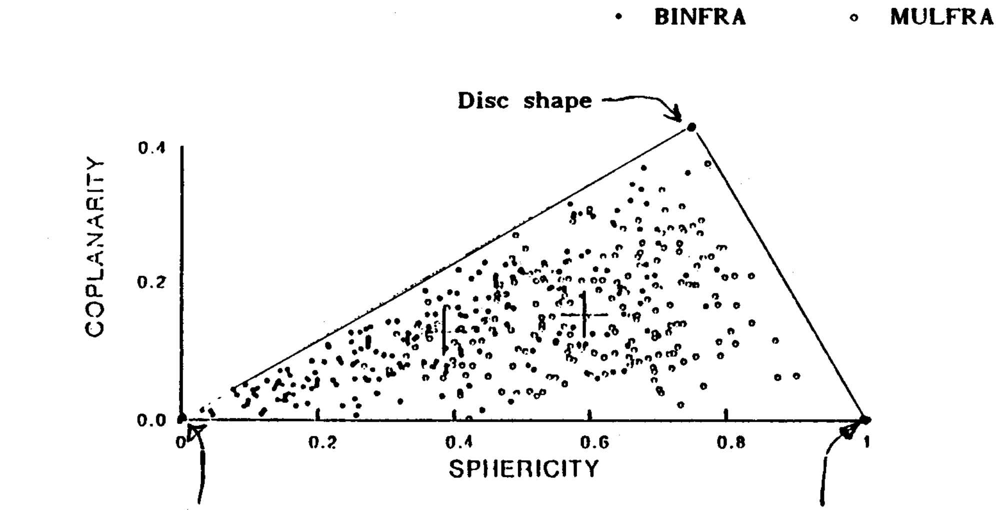


Fig.13

Crosses in Fig.13 show the average sphericity and coplanarity for the BINFRA (left cross) and for the MULFRA (right cross). As one can see, the MULFRA eventsare more spherical in shape, the BINFRA events are more disc-like, but the average difference is not tremendous. The event shape analysis was applied by the Michigan State University group [22] to the central collisions, $^{40}Ar + {}^{51}V$, investigated at a number of energies between 35 MeV/u and 85 MeV/u.

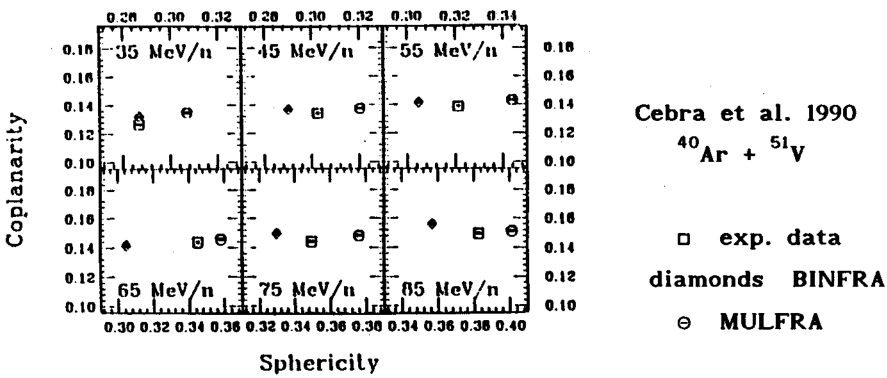


Fig.14.

As suggested by the average C and S values (Fig.14) BINFRA dominates at 35 MeV/u. As the collision energy increases up to 65 MeV/u there is a progression from BINFRA towards MULFRA. For higher collision energies the picture is less clear.

4.Computer simulation of the BINFRA and MULFRA scenarios.

In the preceding pages we frequently recall results of simulations for the hot nucleus decay. We are interested in the kinematic difference between the two extreme scenarios: the binary sequential decay and the prompt multifragmentation. We shall show now how such simulation can be performed in a relatively simple way. With some modifications we follow here the suggestion of **López & Randrup** [21]. For details see Gawlikowicz and Grotowski [10].

Lets begin with some hot system (compound nucleus) with an initial excitation energy E_0^*. It may disassemble promptly or sequentially. For each disintegration event it is assumed that the final mass (charge) spectrum of the fragments as well as the final total kinetic energy are the same for the BINFRA and MULFRA alternatives. Therefore, in both cases the BINFRA Monte Carlo code is used to calculate the mass (charge) partition of fragments. The BINFRA code provides also the value of the final total kinetic energy of fragments. In the MULFRA alternative nuclear fragments of the initial configuration may have some initial excitation energy. They are confined just after multifragmentation in some initial freeze-out volume and accelerated next in the Coulomb field of other participants. The initial mass and charge partition of MULFRA is also provided by the BINFRA code. It is illustrated by Fig.15. Now one can calculate

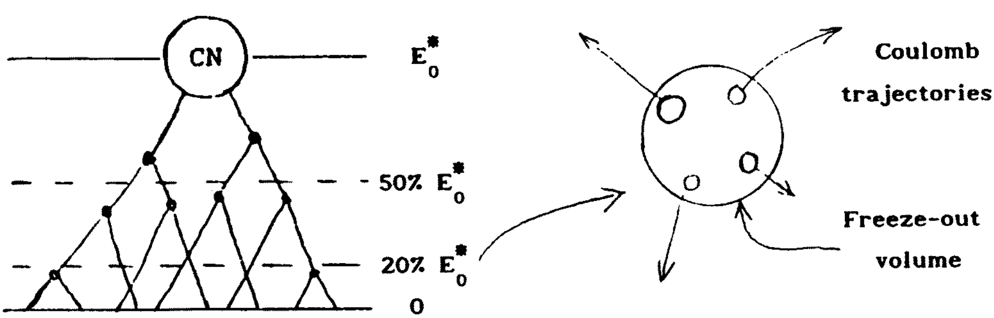


Fig.15

trajectories of the MULFRA and BINFRA particles accelerated in the Coulomb field of other participants, and at some effectively infinite distance from the initial hot system one can compare the velocity distributions of fragments for the two alternatives. The comparison at infinity is made for cold, deexcited fragments. The sequential binary decay proceeds according to some time scale. The time-constants governing consecutive partitioning should depend on the excitation energy, asymmetry of splitting and other factors. In the case of prompt multifragmentation it is reasonable to assume that one observes a simultaneous break-upinto a setof pre-formed excited fragments which move in themutual Coulomb field and deexcite under way. Deexcitation takes place mainly by the sequential evaporation of particles and should proceed with the corresponding time-constants. It can be done for each fragment by switching on the BINFRA Monte Carlo code.

As an example we shall now present calculations performed for the central heavy ion collisions : $^{40}Ca + ^{40}Ca$ at 35 MeV/u (Gawlikowicz, Planeta [23]). The **Landau-Vlasov** [24] and **Boltzmann-Uehling-Uhlenbeck** calculations [25] performed for this reaction predict $^{70}Se^{*}$ as a compound nucleus, with the excitation energy $E^{*}=420$ MeV and the expansion energy $E_{expansion}=100$ MeV. We shall compare for this case the BINFRA and MULFRA disintegration scenarios and look for some particle correlations mentioned in Section 3.

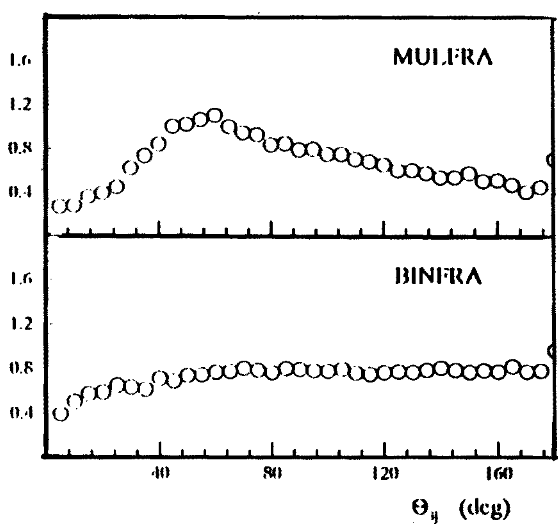
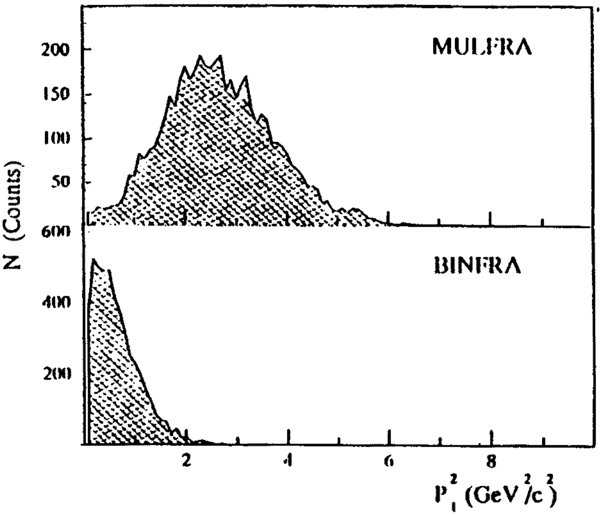


Fig.16

IMF-IMF correlation. Number of events vs relative angle θ_{ij}.

BINFRA: In the sequential emission fragments are separated in time. The distribution is uniform, with some reduction at very small relative angles.

MULFRA:In a simultaneous "explosion" of the system fragments are not separated in space and time. Small angles are excluded by the Coulomb repulsion. A diminution at large angles may be explained by the Coulomb focusing.



Distribution of the squared momentum P_1^2 of the heaviest fragment.

The most probable values of P_1^2:
BINFRA $\simeq$ 1/4 GeV^2/c^2
MULFRA $\simeq$ 2.5 GeV^2/c^2

Fig.17

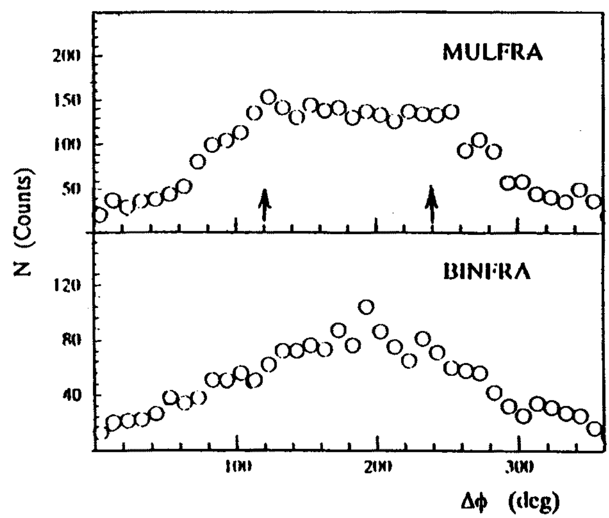


Fig.18

Azimuthal correlation of particles.

MULFRA: One can see some concentration of events around 120^o and 240^o.

BINFRA: A concentration of events in the vicinity of 180^o may be observed in agreement with the binary reaction picture (focusing of fragments in the vicinity of the reaction plane).

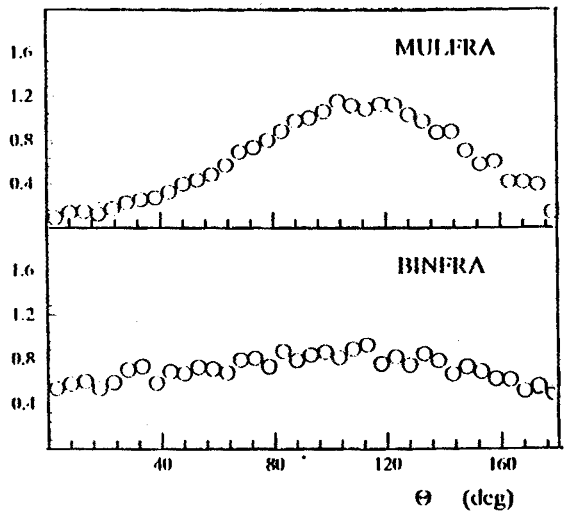


Fig.19

MULFRA:
Coulomb focusing of IMF's by the field of the two heaviest fragments, presented in the coordinate system defined event by event by v_1-v_2.
BINFRA:
the distribution of IMF's presented in the same coordinate system is nearly isotropic.

In order to select "complete events" corresponding to the central collisions one has to use in eventual experiments the 4π multidetector systems. To reduce kinematic distortionsof the angular and of the energy distributions the detector energy thresholds should be as low as possible.

All simulations presented in Figs.16-19 were performed in the CM system of the compound nucleus $^{70}Se^*$. In order to display results in a real experimental environmentone has to make transformation into the LAB system and apply to the simulation data a "filter" of a 4π multidetector system to be used in the experiment. The "filter" will induce experimental effects as e.g. energy thresholds and angular "granularity" of detectors. Now one can transform "the data" back to the CM system and look for a signature of the BINFRA or MULFRA scenario.

5.Final remarks.

We have discussed six different particle correlation methods which may help in searching differences between the sequential and the prompt multifragmentation of hot nuclear systems. All of them are based on the kinematic differences between the multi-fragment events produced according to a particular reaction scenario. The differences are related to the time-scales involved in the multi-fragment emission and to the geometric structure of the initial system. Generally speaking BINFRA is characterized by a relatively long decay-time and an isotropic (or 90^{o}_{CM} · symmetric) angular distribution. The prompt MULFRA has a much shorter time-scale and a highly unisotropic configuration of fragments inside the freeze-out volume. And so, e.g. for the IMF-IMF correlation at small relative angles the main difference between the MULFRA and the BINFRA scenario is caused by the different time-scales (see Figs.7 and 16). Because of that, in the Friedman sequential very fast decay scenario, the correlation picture will be probably similar to that of MULFRA. On the other hand, the most probable value of the squared momentum, P_1^2, of the heaviest fragment will be probably very small for the Friedman mechanism, similarly as for BINFRA and contrary to MULFRA, due to different initial configurations (see Figs.10 and 17).

Four out of the six methods presented here were used for different experimental data and the results are frequently inconsistent or controversial. It may be useful to apply all six methods to the one set of data and to compare results.

It will be also important to find such two different incident reaction energy regions where the sequential decay and the prompt multifragmentation could be individually investigated.

Acknowledgements

I wish to thank my colleagues A.J.Cole from I.S.N. Grenoble, and A.Budzanowski, W.Gawlikowicz, S.Micek, R.Płaneta, and Z.Sosin from the Jagellonian University, Cracow for sharing interest in the problems discussed here.

References

1.B.Jakobsson et al.,Physica Scripta, Vol.38(1988)132.

2.See e.g.B.Friedman, and V.R.Pandharipande, Nucl.Phys.A361(1981)502.

3.See e.g.J.P.Bondorf et al. Phys. Lett.150B(1985)57.

4.W.A.Friedman, Phys.Rev.Lett.60(1988)2125.

5.L.Moretto, Nucl.Phys. A247(1975)211.

6.D.Jouan et al.Z.Phys.A340(1991)63.

7.B.Borderie, Preprint, I.P.N. Orsay IPNO-DRE-92-03.

8.A.Elmaani et al.Phys.Rev.C43(1991)2474.

9.D.J.Hinde et al.Hahn-Meitner-Institut, Berlin, Rep.Anu-1094.

10.W.Gawlikowicz and K.Grotowski, Acta Physica Polonica B22(1991)885; Nucl.Phys., accepted for publication.

11.D.H.E.Gross and Massmann, Nucl.Phys.A471(1987)339c.

12.J.Richert and P.Wagner, Nucl.Phys.A519(1990)203c.

13.See e.g.W.Bauer, Nucl.Phys.A545 (1992)369c.

14.R.Trockel et al.Phys.Rev.Lett.59(1987)2844.

15.D.H.E.Gross et al. Phys.Lett.B224(1989)29.

16.J.Pochodzalla et al.Phys.Rev.Lett.64(1990)2246.

17.A.J.Cole et al. Preprint ISN Grenoble 1992.

18.A.Sourell et al.Preprint, Hahn-Meitner-Institut, Berlin, 1992.

19.M.Gyulassy et al., Berkeley, LBL-13379(1981).

20.G.Fai and J.Randrup, Nucl.Phys.A404(1983)551.

21.J.A.López and J.Randrup, Nucl.Phys.A491(1989)477.

22.D.A.Cebra et al.Phys.Rev.Lett.64(1990)2246.

23.W.Gawlikowicz and R.Płaneta, 1992 (unpublished).

24.K.Sneppen and L.Vinet, Nucl.Phys.A480(1988)342

25.K.Niita et al.,Nucl.Phys.A504(1989)391; H.M.Xu et al.,Phys.Rev.Lett.65(1990)843.