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DISSIPATIVE ASPECTS OF INTERMEDIATE-MASS FRAGMENT EMISSION IN NUCLEAR COLLISIONS

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Abstract:

A sum-rule model (ESM) accounting for dissipative processes in heavy ion collisions is discussed and applied to the analyses of intermediate-mass fragment emission observed in light and heavy ion induced reactions. It reproduces the observed Z distributions of the complex fragments at low and intermediate energies and reveals the angular momentum localization of various contributing mechanisms.

ASPEKTE DER ENERGIE-DISSIPATION BEI DER EMISSION MITTELSCHWERER FRAGMENTE BEI NUKLEAREN STÖSSEN

Es wird ein Summenregel-Modell, das dissipative Prozesse in Schwerionenreaktionen berücksichtigt, diskutiert und in Analysen experimenteller Beobachtungen der Emission mittelschwerer Fragemente in Leicht- und Schwerionen induzierten Reaktionen angewandt. Das Modell gibt gut die Elementverteilung der komplexen Ejektile bei niederen und mittleren Projektilenergien wieder, und es zeigt die Lokalisation verschiedenartiger Mechanismen im Drehimpulsraum auf.

1. Introduction

The study of intermediate-mass fragment (IMF) emission in low- and intermediate-energy collisions has revealed interesting features of a reaction mechanism, which can be attributed neither to a direct reaction mode nor to the formation of a completly equilibrated compound nucleus. The general interest in details of the mechanism stems from potential information about the compression stages formed by the colliding nuclei. We observe :

- forward peaked angular distributions at the grazing angle, which characterize a fast process,
- linear dependence of the cross-sections on the groundstate Q-value, a typical feature of a statistical reaction mechanism,
- transfer of larger nucleon clusters between the reaction partners.

A concept introduced to describe the new, somehow hybrid reaction mechanism is the concept of *partial statistical equilibrium*, assuming that the system of colliding ions approaches a statistical equilibrium with respect to a subset of the degrees of freedom [1].

In the low energy region, the major part of particle emission can be attributed to incomplete fusion processes. Using the concept of partial statistical equilibrium [1], a sum-rule model was elaborated with a successful description of complete and incomplete fusion processes in the collisions of 140 MeV $^{14}N + ^{159}Tb$ [2]. The model, predicting a narrow localization in ℓ-space for the emission of different clusters, leads to a good agreement with the experimental Z distribution of the emitted complex fragments.

Assuming the formation of a strongly interacting dinuclear system, this *original sum-rule model* (OSM) has been based on following basic assumptions :

- the probability for emission through a partial statistical equilibrium is given by an exponential factor [1] :

$$P(i) = exp\left\{[Q_{gg}(i) - Q_c\ (i)] / T\right\} \tag{1}$$

  where T is the effective temperature, Q_c (i) is the charge transfer at the relative distance $R_c = r_{oc}\,(A_1^{1/3} + A_2^{1/3})$ and Q_{gg} is the ground-ground state value.

- the concept of a generalized critical angular momentum that allows the transfer of a cluster from the projectile to target (and inverse) only if the relative orbital angular momentum of the subsystem (cluster plus target or projectile) is smaller than the corresponding critical angular momentum for fusion. By this condition the transmission coefficients, parametrized in the form :

$$T_\ell(i) = \left\{1 + exp\,[\,(\ell - \ell_{lim}(i))\,]/\Delta\ell\right\}^{-1} \tag{2}$$

determine the localization in ℓ-space for different clusters. The limiting value ℓ_{lim} is related to the crititcal angular momentum for fusion(see ref. 10).

- invoking the unitarity condition (exhausting the total reaction cross section σ_R), the sum-rule [2] is formulated by :

$$N_\ell \left\{ \sum_{i=1}^{n} T_\ell(i)\,P(i) \right\} = K_\ell \tag{3}$$

with N_ℓ being the normalization factors as determined by the contribution of the particular angular momentum to σ_R.

Introducing the scattering amplitudes S_ℓ which can be deduced from elastic scattering the total reaction cross section is given by the well-known relation

$$\sigma_R = \pi/k^2 \sum_\ell (2\ell + 1)\,(1 - |S_\ell|^2) \tag{4a}$$

so that

$$K_\ell = (1 - |S_\ell|^2) \tag{4b}$$

Originally the sharp cutoff approximation

$$\sigma_R = \pi/k^2 \sum_\ell^{\ell max} (2\ell + 1) \rightarrow \pi R^2$$

$$K_\ell = \begin{matrix} 1 & for\ \ell \le \ell_{max} \\ 0 & for\ \ell > \ell_{max} \end{matrix} \tag{4c}$$

has been used. A realistic estimate of contributions around the grazing angular momentum, however, needs the smooth transition of S_ℓ from 0 to 1 as provided by optical model calculations, e.g.

With increasing projectile energy complete and incomplete fusion modes are less important, but nevertheless IMF emission gets more pronounced. The application of the OSM at higher incident energies is questionable due to following features :

(i) The OSM is a static model assuming an equilibrium condition of nuclear, Coulomb, and centrifugal forces to define the critical angular momenta ℓ_{cr} (i), which determine the transmission coefficients T_ℓ (i).

(ii) The derivation of the reaction cross-sections within the OSM ignores the energy dissipation. Only for explaining some features seen in the energy spectra and the Q_{opt}-values, it has been additionally assumed that an equal amount of energy is dissipated in the entrance channel, independently of the actual mass transfer.

The questions associated with IMF production at intermediate energies are :

- What are the sources of IMF emission ?
- By which mechanism are the fragments emitted ?

Some studies associate IMF emission to binary decays of a fully equilibrated compound nucleus [3, 4], formed in complete and incomplete fusion processes. Alternatively [5, 6] deep inelastic collisions have been shown to be an important source of complex fragment emission.

The energy dissipation in intermediate heavy ion collisions [7] and the type of interaction are dependent on the impact parameter :

- In more central collision (low impact parameters) IMF emission originates from incomplete fusion. Backward emitted particles are evaporated from the incompletely fused system, forward emitted particles are due to preequilibrium emission or are projectile-like fragments as remnants of incomplete fusion.
- In peripheral collisions (large impact parameters) deep inelastic collisions occur up to 50 MeV/u, and a "participant - spectator" mechanism (like projectile breakup) is evolving at higher energies.

There are uncertainties about the energy deposit [8] which may show a saturation effect, and about the onset of multifragmentation with more than two fragments in the exit channels [9] .

In the following an *extended sum-rule model* (ESM) is described which takes into account the dynamical evolution of the dinuclear system, via partially equilibrated states on the way to fusion. It suggests a new mechanism : *dissipative fragmentation*, covering very asymmetric fast fission, quasifission and deep inelastic reaction modes [10].

2. Dissipative phenomena viewed by ESM

The extension of the sum-rule model is based on the idea that in heavy ion collisions dissipative phenomena are crucial and cannot be ignored in modeling the reaction mechanism. Classical models are able to describe strong dissipative processes like deep inelastic collisions and fusion [11]. Using a simple description [12] of the formation of a dinuclear system when the ions collide, the time evolution of the system may be characterized by the evolution of three collective variables : r = the distance between the center-of-mass of the nuclei, Θ = the deflection angle and the mass asymmetry $x = (A_2 - A_1)/(A_1 + A_2)$.

In the actual calculations of the classical trajectories by solving the equation of motion a proximity potential has been used [13] :

$$U_N(r,x) = G(x)\, V_N(r,x) \tag{5a}$$

with

$$V_N(r,x) = \begin{Bmatrix} V_0 e^{-0.27 s^2}, & s \geq 0 \\ V_0 + 6.3 s^2, & s < 0 \end{Bmatrix} . \tag{5b}$$

G (x) is a geometric factor

$$G(x) = \left(\frac{A}{2}\right)^{1/3} \frac{(1-x^2)^{1/3}}{(1-x)^{1/3} + (1+x)^{1/3}} \tag{5c}$$

and

$$s = r - r_0\left(\frac{A}{2}\right)^{1/3}\left[(1-x)^{1/3} + (1+x)^{1/3}\right] \tag{5d}$$

with r_0, V_0 being the parameters of the nuclear potential.

Introducing energy dissipation by friction forces [14], the friction tensor γ has been taken diagonal with components corresponding to radial and tangential motion and to mass transfer :

$$\begin{aligned} \gamma_{rr} &= C_r \,|\, \partial V_N / \partial r \,|^2 \\ \gamma_{\Theta\Theta} &= C_\Theta\, r^2 \,|\, \partial V_N / \partial r \,|^2 \\ \gamma_{xx} &= \gamma_x \,|\, \partial V_N / \partial r \,| \end{aligned} \tag{6}$$

The idea is to define a *dynamical critical angular momentum*, corresponding to the case that the friction forces are sufficient to fuse the dinuclear system.

Using the proximity potential shown in fig. 1, the classical trajectories for collisions of 156 MeV ^{6}Li with ^{nat}Ag have been calculated [15] (fig. 2). Obviously for angular range 50-65 $\hbar$ deep inelastic collisions occur.

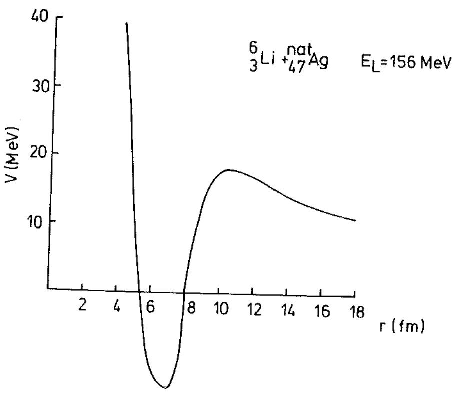

Fig. 1 : The interaction potential for ^{6}Li + ^{nat}Ag system (ℓ = 0) : Coulomb and proximity nuclear potential.

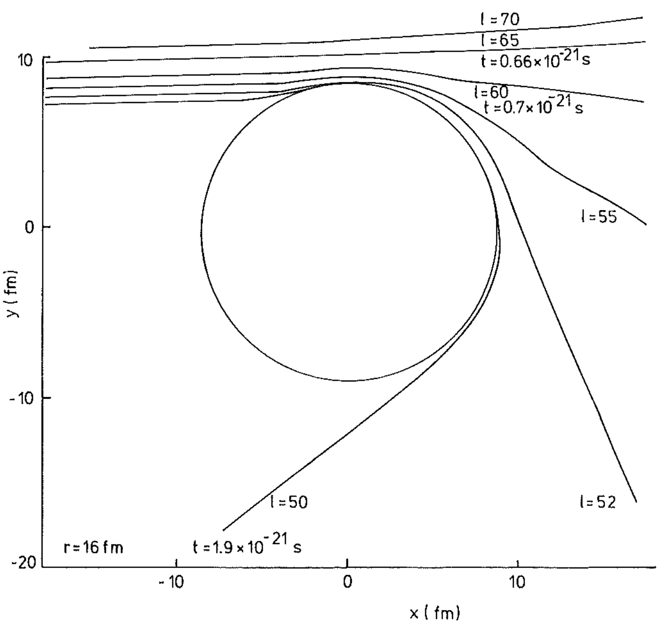

Fig. 2 : Classical trajectories for 156 MeV ^{6}Li + ^{nat}Ag collisions.

Tab. 1 shows that for increasing interaction times at lower ℓ-values the energy dissipation is increasing,too. For damped collisions, ℓ = 50 - 55 $\hbar$, the energy is dissipated mainly through the radial component, leading to large internal excitations. For higher ℓ-values, 65-70 $\hbar$, the radial dissipation appears to be reduced, and (smaller) dissipation is due to the nucleon transfer.

Fig. 3 displays the time evolution of the reaction in a channel of an angular momentum close to ℓ_{cr}^{dyn} = 51 $\hbar$. Strong energy dissipation of the radial

Tab. 1 : Dynamical parameters of collisions of 156 MeV ^{6}Li ions with ^{nat}Ag resulting from classical trajectory calculations with friction forces. The interaction time while energy dissipation occurs is defined as the time till the system has reseparated, reaching a distance of r = 11 fm (r = 30 fm, respectively, for the values given in Fig. 1).

ℓ ($\hbar$)	t (10^{-21} s)	ΔE_r (MeV)	ΔE_{tg} (MeV)	ΔE_x (MeV)	E* (%)
49	fusion				
50	1.2	– 72.8	– 1.36	– 39.5	49
52	1.0	– 59.5	– 0.82	– 34.6	40
55	0.7	– 37.2	– 0.46	– 29.1	25
60	0.6	– 9.4	– 0.12	– 19.5	6
65	0.56	– 0.8	– 0.01	– 7.2	
70	0.54	– 0.3	– 0.007	– 1.8	

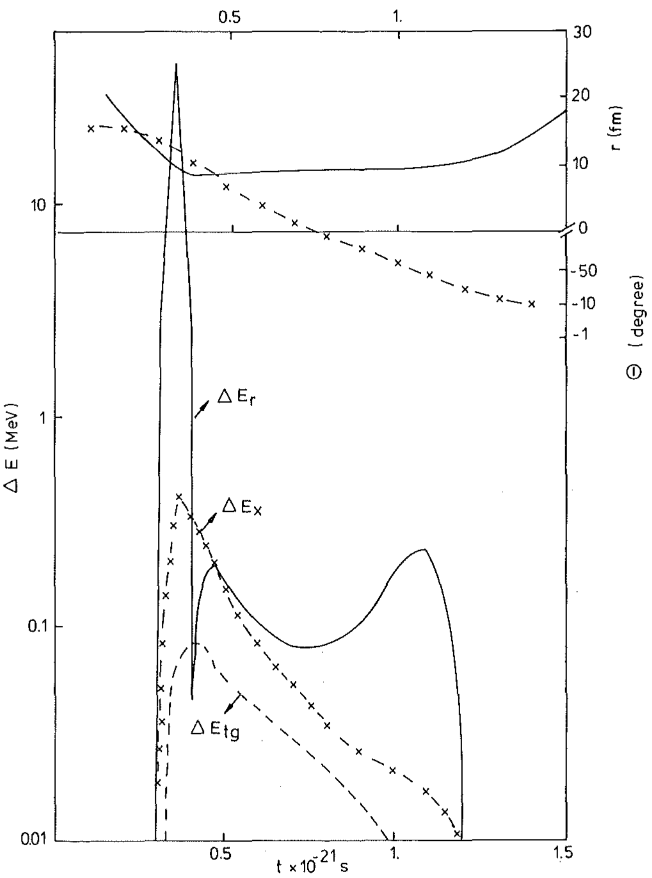

Fig. 3 : Time evolution of the collective coordinates : center-of-mass distance r, deflection angle Θ and of energy dissipation (ΔE) for the ℓ = 52 $\hbar$ trajectory in collisions of 156 MeV ^{6}Li ions with ^{nat}Ag.

component accompanies the formation of the dinuclear system at about $0.4 \cdot 10^{-21}$s. Subsequently transfer of nucleons occurs and the system starts rotating, as indicated by the energy dissipation of the tangential component and by the mass transfer. The time dependence of the distance between the center-of-mass of the two colliding nuclei and of the deflection angle is additionally shown.

The basic assumption of the ESM is that fragments of intermediate mass are produced *during* the dynamical evolution of the dinuclear system before the complete fusion takes place. Associated with dissipative processes, the corresponding transmission coefficients are considered to depend on the *dynamical critical angular momentum* for fusion ℓ_{cr}^{dyn}.

Thus, assuming that all processes simultaneously compete, an extension of the sum-rule is proposed [10] , namely :

$$N_\ell \left\{ \sum_{i=1}^{n} T_\ell(i) P(i) + \sum_{i=2}^{n} T'_\ell P(i) \right\} = K_\ell \qquad (7)$$

where again N_ℓ are normalization factors accounting additionally for the fragmentation of the dinuclear system.

The extension with the transmission coefficients T'_ℓ depending on ℓ_{cr}^{dyn} is parametrized to be identical for all exit channels :

$$T'_\ell = \left\{ 1 + exp \left[(\ell - \ell_{cr}^{dyn}) / \Delta\ell \right] \right\}^{-1} \qquad (8)$$

Consequently, the cross section for each channel (i) is given by a sum of two contributions :

$$\sigma^{tot}(i) = \sigma(i) + \sigma'(i) \qquad (9)$$

where

$$\sigma(i) = \pi\lambda^2 \sum_{l=0}^{\ell max} (2\ell + 1) N_\ell T_\ell(i) P(i) \qquad (10)$$

accounts for the complete (i=1) and incomplete (i=2, ... n) fusion contributions, while

$$\sigma'(i) = \pi\lambda^2 \sum_{\ell=0}^{\ell max} (2\ell + 1) N_e T'_\ell P(i) \qquad (11)$$

represents the light and intermediate mass fragment emission by dissipative fragmentation of the dinuclear system in the exit channels : i=2, ... n. In this case, for $\ell < \ell_{cr}^{dyn}$, dissipative fragmentation can be associated to phenomena similar to very asymmetric fast fission or quasifission phenomena, while for $\ell > \ell_{cr}^{dyn}$ contributions from deep inelastic collisions are expected.

3. Extended sum-rule analysis of IMF emission from ^{6}Li and ^{4}He induced reactions at 26 MeV/amu

Measurements of IMF emission have been performed for rather asymmetric systems of ^{6}Li reactions with ^{46}Ti, ^{nat}Cu and ^{nat}Ag at incident energies of 26 MeV/amu [16]. Fig. 4 displays the comparison of experimental element distribution with the results from OSM and ESM (parameter values for ESM given in Fig. 4). From the improvement by the ESM it may be deduced that with increasing asymmetry in the entrance channel, dissipative effects get more pronounced. The discrepancies are largely removed by the second term of eq. 9.

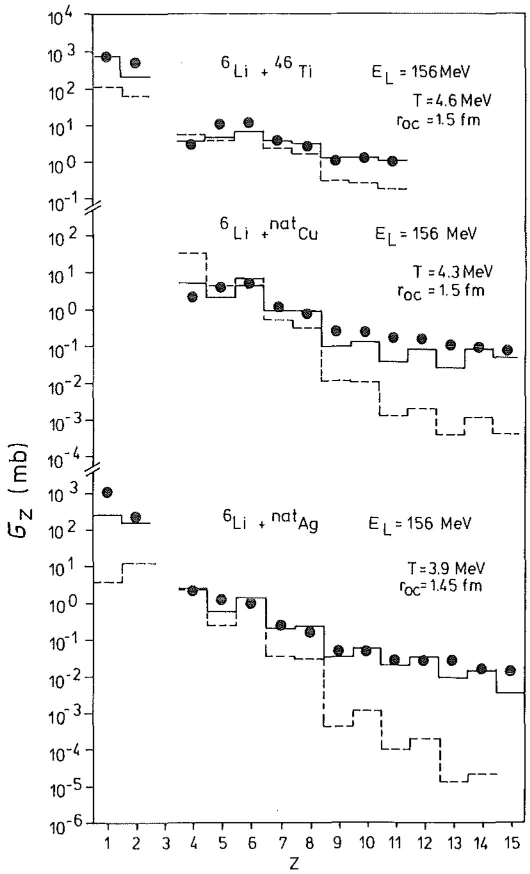

Fig. 4 :
The experimental element distributions from reactions of 156 MeV ^{6}Li with ^{46}Ti, ^{nat}Cu and ^{nat}Ag as compared with the results of the ESM (full line) and OSM (dashed line).

Both sum-rule models imply three parameters to be adjusted : T, - the effective temperature, R_c - the distance where the charge transfer occurs and $\Delta\ell$ - the half-width in the ℓ-space. The calculations prove to be rather insensitive to $\Delta\ell$, which has been fixed to 3 $\hbar$ in all the cases. There is a strong correlation between T and R_c since the probability P (i) is essentially determined by the product $R_c \cdot T$.

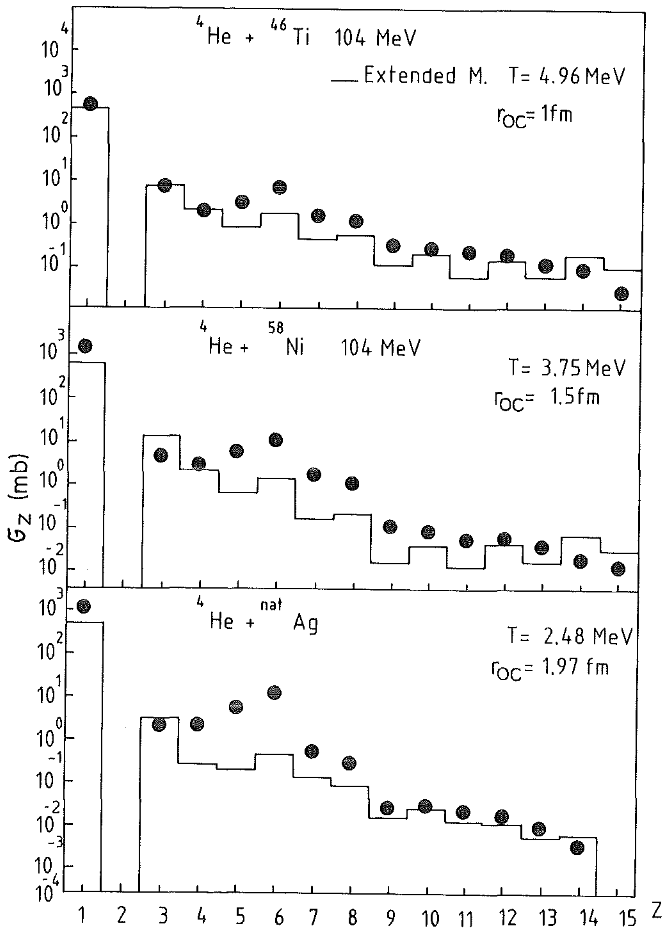

Fig. 5 :
The experimental element distributions from reactions of 104 MeV α-particles with ^{46}Ti, ^{58}Ni and ^{nat}Ag as compared with the results of the ESM analysis.

The resulting values of the temperature T are in good agrement with the usual estimate from statistical considerations [17] : $T = \sqrt{E^*c/A}$ where E^* is the excitation energy and $c = 8$.

The reaction cross sections values are computed in the frame of OSM and ESM by using the computer code LIMES [18] including a programm [19], which calculates the values of the dynamical critical angular momenta by solving the equation of motion with friction forces. The K_ℓ values or the $|S_\ell|$, respectively, are taken from results of elastic scattering analyses.

Fig. 5 compares ESM predictions for reactions of 104 MeV α-particles with ^{46}Ti, ^{58}Ni and ^{nat}Ag [20] to experimental data. The agreement is particularly good for clusters with $Z > 9$. The excess in the experimental distributions around C and O might be explained by small C and O impurities in the targets.

The validity of ESM at larger incident energies has been tested by applying to further cases of asymmetric systems [21, 22]. Fig. 6 presents the experimental element distributions measured in the collisions of various projectiles at different energies : ^{40}Ar (30 MeV/amu), ^{12}C (48 MeV/amu), ^{20}Ne (48 MeV/amu) and ^3He (66 MeV/amu) colliding with ^{nat}Ag targets, and compared to calculated values by ESM.

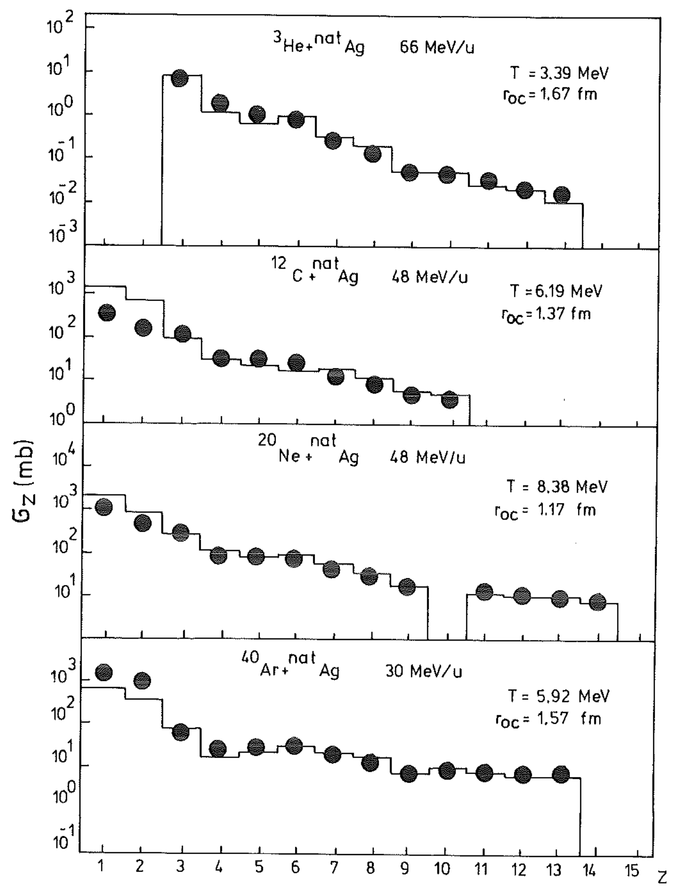

Fig. 6 :
Comparison of ESM results with experimental Z-distributions from various colliding systems.

Tab. 2 : Values of the apparent temperature T obtained from ESM analysis, T ' from statistical estimate and T " from analysis of the slope of energy spectra.

Reaction	E_{inc}	T	T '	T "
^{6}Li + ^{46}Ti	26 MeV/amu	4.63	4.93	4.9
^{nat}Cu		4.3	4.29	4.2
^{nat}Ag		3.89	3.48	3.4
^{4}He + ^{46}Ti	26 MeV/amu	4.96	4.18	
^{58}Ni		3.75	3.75	
^{nat}Ag		1.97	2.77	
^{40}Ar + ^{nat}Ag	30 MeV/amu	5.92	7.3	5.5
^{12}C + ^{nat}Ag	48 MeV/amu	6.19	6.32	6.0
^{20}Ne + ^{nat}Ag	48 MeV/amu	8.38	7.65	6.0
^{3}He + ^{nat}Ag	66 MeV/amu	3.43	4.0	3.9

Tab. 2 presents the temperature values T resulting from the analysis showing increased apparent temperatures for higher incident energies. They are in good agreement with the values T' estimated by statistical considerations [17] and with the values T" found in the analysis of the experimental energy spectra of the fragments.

4. Alternative formulation and refinement of the ESM

Arguments and results presented up to this point are based on the assumption that all contributing processes are simultaneously proceeding and competing. Alternatively [3, 4] IMF emission has been also associated to the decay of a completely equilibrated system after fusion. Following this view a variant of the ESM can be alternatively formulated including a refinement accounting for particle emission from the evolution of the incomplete fusion channels [23].

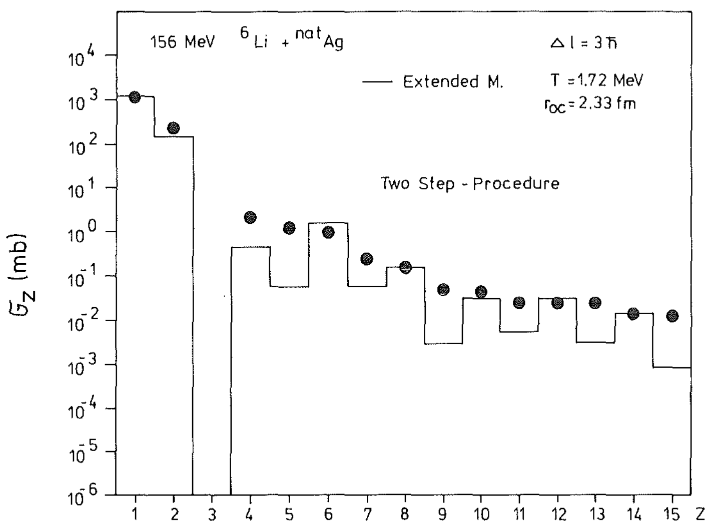

Fig. 7 : Application of a simplified two-step procedure to experimental data for 156 MeV ^{6}Li collisions with ^{nat}Ag.

We still consider the formation of equilibrated nuclei and the dissipative fragmentation as competing processes during dynamical evolutions of the dinuclear systems, following an initial reaction step which has two modes, called in a rather general sense, *complete* and *incomplete fusion entries*, respectively, accounting for the cases when the total system starts a further dissipative evolution or only a particular participant part of it.

Like in OSM the first step is governed by a normalization condition

$$N_\ell \sum_{i=1}^{n} T_\ell(i) P_{1i} = K_\ell \tag{12}$$

assuming that complete (i = 1) and incomplete (i > 1) entry reaction paths exhaust the total reaction cross section.

The first step leads to a partial cross section for emission of fragments i

$$\sigma_\ell(i) = \pi/k^2 (2\ell + 1) \frac{T_\ell(i) P_{1i}}{\sum_{j=1}^{n} T_\ell(j) P_{1j}} \tag{13}$$

In the equilibration phase (second step) compound nucleus formation and dissipative processes compete in all channels, and, in general, dissipative fragmentation of incomplete fusion channels k may additionally feed all exit channels (i > 1). This implies the relations

$$N_\ell^{(1)} \left[T_\ell(1) P_{1i} + \sum_{i=2}^{n} T'_\ell(1) P_{1i} \right] = N_\ell T_\ell(1) P_{1i} \tag{14a}$$

in the complete fusion channel and

$$N_\ell^{(k)} \left[T_\ell(k) P_{kk} + \sum_{i=2}^{n} T'_\ell(k) P_{ki} \right] = N_\ell(k) P_{1k} \tag{14b}$$

for incomplete fusion channels (k > 1) with

$$N_\ell^{(k)} = \frac{K_\ell}{\sum_j T_\ell(j) P_{1j}} \, \frac{T_\ell(k) P_{1k}}{T_\ell(k) P_{kk} + \sum_{j=2}^{n} T'_\ell(k) P_{kj}} \tag{15}$$

We note that the T_ℓ (k) and the probabilities P_{kj} (k denoting the entry mode) depend on the particular channel through different values of $\ell_{crit}{}^{dyn}$.

Simplifying the further procedure we neglect for the moment dissipative fragmentation in the incomplete fusion channels and write

$$\sigma'_\ell(i) = \pi/k^2 (2\ell + 1) N_\ell^{(1)} T_\ell(1) P_{1i} \tag{16}$$

which corresponds to the dissipative fragmentation term of the ESM, but *renormalized for a sequential process* (through $N_\ell{}^{(1)}$).

Some exploratory calculations have been performed applying the two-step procedure to the Z-distributions from 156 MeV ^{6}Li collisions with ^{nat}Ag. The data can be described only with unreasonable values of the apparent temperature and the Coulomb radius (Fig. 7). We conclude from this finding that, at least in the considered case, IMF emission is not dominated by a simple two-step mechanism.

5. Angular momentum localization by the reaction dynamics

The two terms in the sum-rule expression lead to different localizations in the angular momentum space. This is demonstrated for reaction of 336 MeV ^{40}Ar with ^{nat}Ag, measured at large angles [24]. Fig. 8 shows Z-distribution and fig. 9 displays the corresponding partial cross-sections with contribution of the first term, and of the sum given by eqs. 10 and 11. It is obvious that the emission of fragments measured in the backward region has to be mainly attributed to the second term of eq. 9, i. e. to dissipative processes. These results are in good agreement with experimental findings about angular momenta windows, deduced from coincidence measurements of light particles emission [25]. Incomplete fusion channels have been attributed to angular momenta less than 100 $\hbar$, whereas the quasifission appears with larger values momentum, $\ell = (103 - 133)\,\hbar$.

The situation is different in the case of α-particle and ^{6}Li reactions at 26 MeV/amu where the reaction is strongly localized around the grazing ℓ-value : $\ell_{graz} \sim \ell_{max}$. This feature would no more tolerate the previously used approximation $K_\ell = 1$ (see eq. 4).

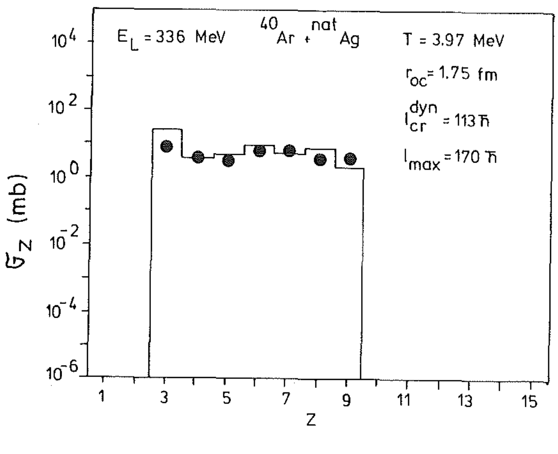

Fig. 8 :
Elemental distribution of IMF emission in reactions of 336 MeV Ar ions with ^{nat}Ag : experimental data [24] compared with ESM result.

This is indicated in fig. 10 showing the partial cross sections of collisions of 156 MeV ^{6}Li with ^{nat}Ag.

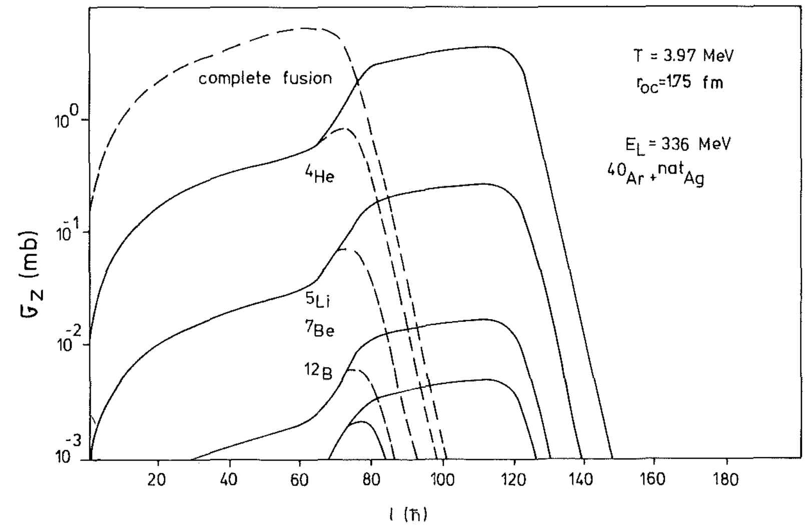

Fig. 9 : Partial cross sections for different channel of IMF emission in 336 MeV Ar collisions with ^{nat}Ag : the full line refers to the ESM result, while the dashed line shows the prediction of the OSM term (eq. 10).

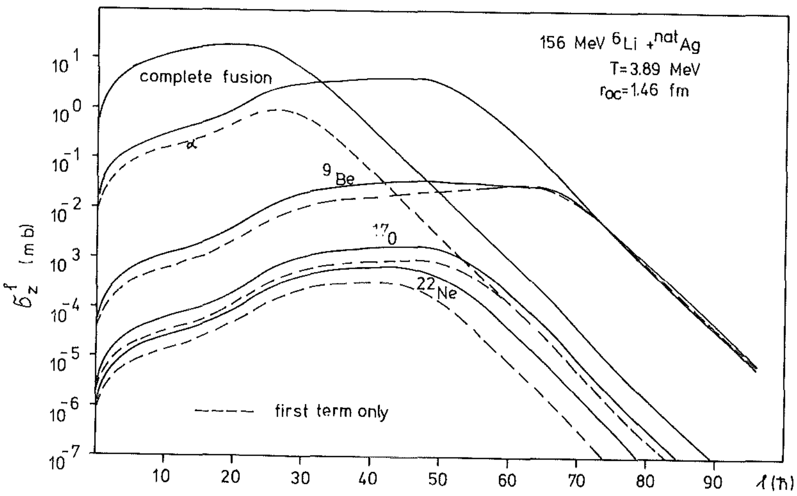

Fig. 10 : Partial cross sections of IMF emission of collisions of 156 MeV ^{6}Li ions with ^{nat}Ag, calculated with the extended sum-rule model.

The suggestions of the ESM are supported by the impact parameter description in classical trajectory calculations (see sect. 2). The study of the dynamics of the reaction ^{40}Ar + ^{nat}Ag at 27 MeV/amu by analysing the correlation between heavy residues and IMF [6], shows experimentally that the dominant mechanism is of binary type. The IMF angular distributions, strongly forward peaked, ressemble to incomplete deep inelastic collisions at low energy.

Using Landau-Vlasov equation approach, the dissipative mechanism has been detailed for the transfer of energy into intrinsic excitation energy. It gives evidence for various impact parameter ranges governed by different reaction mechanisms with different interaction times, ca. 0.5 – 1. · 10^{-21} s for deep inelastic collisions, thus supporting our analysis.

6. The role of dissipation in different approaches

The original sum-rule model implies that fusion takes place only if the bombarding energy is larger than the fusion barrier at the impact parameter under consideration (static fusion barrier). The influence of friction in fusing a dinuclear system has been considered by Ngô [11], introducing the dynamical "surplus" energy and by Swiatecki [26] as extrapush energy. Both models are successful in describing various features of dissipative processes, but the physical role of the dynamical surplus energy differs from that associated with the extra-push energy. In the dynamical surplus energy hypothesis the extra energy is supplied to overcome the friction forces.

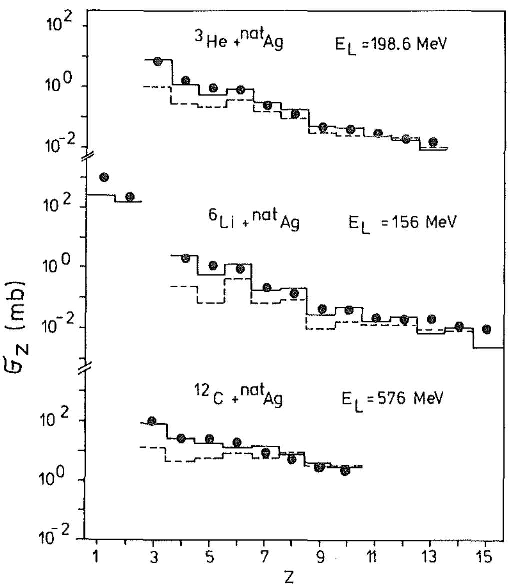

Fig. 11 :
IMF emission experimentally observed for various colliding systems :
comparison of results of the extended sum-rule model (full line) with those of the approach of Bhattacharya et al. [27].

The ESM is related to the dynamical surplus energy consideration since the transmission coefficients T'_ℓ are depending on the dynamical critical angular momentum ℓ_{cr}^{dyn} for fusion. We emphasize that on this way friction forces play an important role in the *entrance* channel, as the main part of the energy is dissipated in forming a dinuclear system.

In contrast, IMF emission has been also analysed [27] with a model based on the view that the collision of two nuclei forms a compound nucleus with excitation energies and angular momenta sufficient to undergo dynamical deformation [26]. Such a mechanism is assumed to appear in the exit channel towards a neck-development of the system. The cross-sections for the fragment production are calculated by means of decay widths, depending on the barrier height, the compound nucleus excitation energy and the temperature at the saddle point. These are also the ingredients of multistep evaporation models used in IMF emission analyses [28]. As seen in fig. 11, which compares the ESM results with results of ref. 27, IMF emission in 198 MeV ^{3}He, 156 MeV ^{6}Li and 576 MeV ^{12}C colliding with ^{nat}Ag target is well predicted for larger Z-values, but the underestimation for low Z-values indicates the existence of additional sources, not accounted by the decay of the fully equilibrated system.

A recent approach [29] introduced dissipative effects through two different probabilities P (i) with two different Q-values : Q_{IF} (i,ℓ) representing the radial kinetic energy dissipation for incomplete fusion processes and Q_{DIC} (i,ℓ) calculated for each ℓ in the sticking limit for deep inelastic collisions. By such a modification of the OSM, introducing an explicit dependence of the reaction cross sections on the dissipated energy, the limitations of OSM are considerably alleviated. The approach has been successfully applied to reactions of 120 MeV ^{19}F with ^{64}Ni [29].

We emphasize that these analyses of dissipative mechanisms have been made in the same spirit as in our previous paper [30], analysing 156 MeV ^{6}Li + ^{46}Ti, ^{nat}Cu and ^{nat}Ag reactions and treating deep inelastic collisions on the same footing as incomplete fusion. In fact, with increasing incident energy, a major part of IMF emission is expected to emerge from deep inelastic collisions, as experimentally revealed in ^{40}Ar induced reactions with ^{nat}Ag at 27 MeV/amu [5].

To explain the energy spectra measured for different emergent particles in ^{14}N + ^{159}Tb reactions at higher incident energy 22 MeV/amu [31], the random walk model [32] has been extended to include random momentum transfer due to internal motion of the nucleons. The calculated spectra contain two contributions, a quasielastic component occuring at an optimum Q-value and a second component associated with additional exchange of nucleons leading to more inelastic collisions. Similary, results based on a diffusion model [33] reveal two possible mass-relaxation modes in asymmetric heavy ions collisions leading to a system Z = 108 : "fast fusion" and "quasifission". Differences found in the experimental mass distributions for 192 MeV ^{32}S + ^{238}U and 220 MeV ^{40}Ar + ^{232}Th reactions might be explained in this way.

There is a growing role of preequilibrium emission with increasing energy, a feature well reproduced by Laundau-Vlasov simulations of the collisions. The results for ^{40}Ar + Ag collisions at 27 MeV/amu indicate that a larger amount of excitation energy is carried by the fragments of (binary) deep inelastic processes within an impact parameter range of 5-8 fm, smaller values leading to fusion and to increased preequilibrium emission when increasing energy. This may be understood in applying the basic idea of an existence of a participant zone. For collisions at intermediate energies (20-200 MeV/amu) a dissipative process has been suggested [34] as proceeding through a two-step mechanism : the two partners first sticking together with an overlap (i.e. neck) defined by the impact parameter and with dissipation (converting radial kinetic energy into intrinsic energy of the fragments and orbital rotational energy into fragment spins). This is followed by some kind of abrasion, thus pointing to reconciling with the spectator-participant picture with three types of ejectiles at higher energies : projectile-like, target-like fragments and a "fire ball" (participant).

7. Conclusions

The analysis of light and intermediate mass fragment emission by the ESM follows the basic assumption that all competing processes proceed through partial statistical equilibria. The fragments originate from the evolution of a dinuclear system, and the emission probability is proportional to an exponential factor depending on Q_{gg} and on the apparent temperature T, which can be considered to be a measure of the excitation energy transferred to the intrinsic degrees of freedom by the friction forces.

The way, how the dinuclear system timely evolves, depends on the angular momenta involved, leading to different reaction paths. For low angular momenta complete and incomplete fusion dominate while for larger impact parameters a *dissipative fragmentation* of the dinuclear system shows up *before* complete equilibration. Consequently, two different types of transmission coefficients appear in the formulation of the ESM. The first (T_ℓ) is responsible for complete and incomplete fusion, being limited to specific regions in the angular momentum space, the second (T'_ℓ) associates IMF emission to *dissipative fragmentation* accounting for a class of processes with energy dissipation in different angular momentum regimes :

(i) for angular momenta less than ℓ_{cr}^{dyn}, dissipative fragmentation induces IMF emission through phenomena similar to asymmetric fast fission or quasifission processes,

(ii) for angular momenta larger than ℓ_{cr}^{dyn} deep inelastic collisions are a source.

The coherent view stems from the common origin of the dinuclear system with a time evolution driven by the same forces : conservative (nuclear, Coulomb and centrifugal) forces and dissipative forces of the nuclear friction. This view includes also the concept of centrifugal fragmentation discussed by Volkov [35].

We emphasize that ESM describes the fragment emission by dissipative effects in the *entrance channel* [11]. Comparing our results with that obtained following the Moretto - Swiatecki view [3, 26] the experimetal data obviously favor the ESM. Nevertheless the sum-rule model does not specify in detail the dissipative mechanisms which enter only through a simple quantity : ℓ_{cr}^{dyn}.

The model leads to a good prediction of the element production for a large range of incident energies and for asymmetric systems, and it reveals reliably the localization of different dissipative mechanisms in the angular momentum space. In addition, as the sum-rule model is easily to handle, it provides a convenient tool to analyse and to characterize quickly experimental data of IMF emission.

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