Extended sum-rule model view of light and intermediate mass fragment emission in nuclear reactions at intermediate energies

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The original sum-rule model worked out by Wilczyński *et al.* and successfully used for a global description of complete and incomplete fusion reactions has been extended by a term accounting for dissipative processes of the dinuclear system on its way to fusion. When applying to light- and heavy-ion collisions with various targets at energies in the transitional region, the new term proves to be rather essential for reproducing the element distributions of the fragments emitted from rather asymmetric systems.

I. INTRODUCTION

At intermediate energies both equilibrium and nonequilibrium reaction mechanisms appear to coexist for complex-fragment emission in light- and heavy-ion reactions. Their relative importance depends as much on the mass asymmetry of the entrance channel as on the bombarding energy. In addition to fast quasifree and deep-inelastic processes which are responsible for the fragment production, in particular in the vicinity of the target and projectile masses, near-equilibrium emission of heavy clusters from fusionlike processes has been found to be a most important source[1–5] which is considered as an interesting phenomenon with signatures of the properties of excited nuclear matter. However, the origin and detailed mechanisms of intermediate mass fragment (IMF) emission are still a matter of debate. A most interesting aspect arises from the question to which extent IMF emission is associated with the decay of a fully equilibrated compound nucleus, or whether the system prefers to reseparate into fragments before equilibration by some kind of dissipative binary reaction modes.

Recently, the sum-rule model for complete and incomplete fusion reactions as worked out by Wilczyński *et al.*[6] has been generalized[7] in order to account for additional competing processes as sources of complex ejectiles from nuclear collisions. The extended sum-rule model (ESM) adopts the view that the near-equilibrated component may arise with the dynamical evolution of the dinuclear system via partially equilibrated states on the way to fusion and through some type of a rather asymmetric *fast* or *quasi-fission* process: "*dissipative fragmentation.*"

The present paper briefly describes the basis and the formalism of the extended sum-rule model and applies it to analyses of IMF emission in nuclear reactions, in particular of various asymmetric colliding systems like the case of collisions of 156 MeV ^{6}Li.[8,9] We show that the sum-rule model leads to a consistent description of the element distributions and of the localization of the reaction in the angular momentum space.

II. FORMALISM OF THE SUM-RULE MODEL

Certainly part of the observed cross section of light and intermediate fragment emission has to be attributed to incomplete fusion processes in the sense of massive transfers predominantly from the projectile to the target, signaled by fast projectile-like remnants of breakup fusion reactions in various partitions. Considering complete and incomplete fusion channels on equal footing the original sum-rule model has been worked out as a global description of the contributions of the different competing channels. Following the assumption of partial statistical equilibrium[10] of the strongly interacting dinuclear system, the different channel (i) reaction probabilities are governed by the available phase space, as determined by the ground-state Q values Q_{gg}, i.e., by the scaling factor

$$P(i) \propto \exp\{[Q_{gg}(i) - Q_c(i)]/T\} , \tag{2.1}$$

with T being the effective (apparent) temperature. $Q_c(i)$ is the change in the Coulomb interaction energy due to charge transfer [assumed to happen at a relative distance $R_c = r_{0c}(A_1^{1/3} + A_2^{1/3})$ where the system is supposed to separate]. Whether for a given partial wave a reaction channel is closed or open depends on the critical angular momentum $[l_{\rm crit}(i)]$ above which a particular fragment cannot be captured. The entrance channel angular momentum limitation $l_{\rm lim}(i)$ follows the concept of the generalized angular momentum.[11] With the plausible assumption that the entrance channel angular momentum is shared between the ejectile and the remainder in the ratio of their reduced masses the critical angular momentum value $l_{\rm crit}(i)$ is related to $l_{\rm lim}(i)$ by

$$l_{\rm lim}(i) = \frac{A_1}{a} l_{\rm crit}(i) \tag{2.2a}$$

if the target A_2 picks up the cluster a or

$$l_{\rm lim}(i) = \frac{A_2}{b} l_{\rm crit}(i) \tag{2.2b}$$

if the projectile A_1 picks up the cluster b. Actually, the limitation is expressed by a smooth transition of the channel transmission coefficients $T_l(i)$ parametrized as

$$T_l(i)=\left[1+\exp\left[\frac{l-l_{\lim}(i)}{\Delta l}\right]\right]^{-1} . \tag{2.3}$$

The original sum-rule model explicitly assumes that the total reaction cross section is fully exhausted by complete $(i=1)$ and incomplete $(i>1)$ fusion channels for entrance channel angular momenta up to a particular value $l_{\max}$. Thus, using the unitarity condition

$$N_l \sum_i^n T_l(i)P(i)=1 , \tag{2.4}$$

the angle integrated cross section for the channel i is given by

$$\sigma(i)=\pi\lambda\!\!\!^{-2} \sum_{l=0}^{l_{\max}} (2l+1)\frac{T_l(i)P(i)}{\sum_j T_l(j)P(j)} . \tag{2.5}$$

The l value which corresponds to the partial wave with its classical turning at the critical distance is adopted for $l_{\max}$. Though the expression Eq. (2.5) resembles strikingly the Hauser-Feschbach formula, it should be noted that the $T_l(i)$ are entrance channel transmission coefficients applying to the captured fragment rather than to the ejectile in the exit channel. Specifying the ingredients of the model, in particular the apparent temperature T and the critical angular momenta $l_{\text{crit}}(i)$ through an estimate based on the liquid-drop model, the model has been remarkably successful in predicting absolute cross sections as well as their localization in the l space for reaction of 140 MeV ^{14}N with ^{159}Tb.[6]

With increasing projectile energies when complete and incomplete fusion modes appear to be reduced, IMF emission gets generally more pronounced. For such a situation Fig. 1 displays the result of an application of the original sum-rule model to collisions of 156 MeV ^{6}Li ions with $^{\text{nat}}$Ag. Typically (see also Ref. 7) the best fit to the measured data leads to an unreasonable value of the apparent temperature; it fails also to reproduce the observed Z distribution, in particular by underestimating the emission of heavier products.

As is obvious in Fig. 1, already the original sum rule predicts at higher energies the onset of a reverse mass flow as the phase-space factors $P(i)$ do not make any distinction between the mass flow in one or the other direction. However, in contrast to deep-inelastic processes with dissipation of kinetic energy and orbital angular momentum, this reverse mass flow has signatures of quasielastic processes for which the sum-rule model predicts only minor contributions due to the large Q values of "multinucleon-pickup" reactions. Nevertheless, the localization around the grazing angular momentum does no more tolerate the simplification of a sharp cutoff at $l=l_{\max}$ in Eq. (2.5).

The unitarity condition for the partial reaction cross section given by Eq. (2.4) has to be modified to

$$N_l \sum_i T_l(i)P(i)=1-|S_l|^2=K_l , \tag{2.6}$$

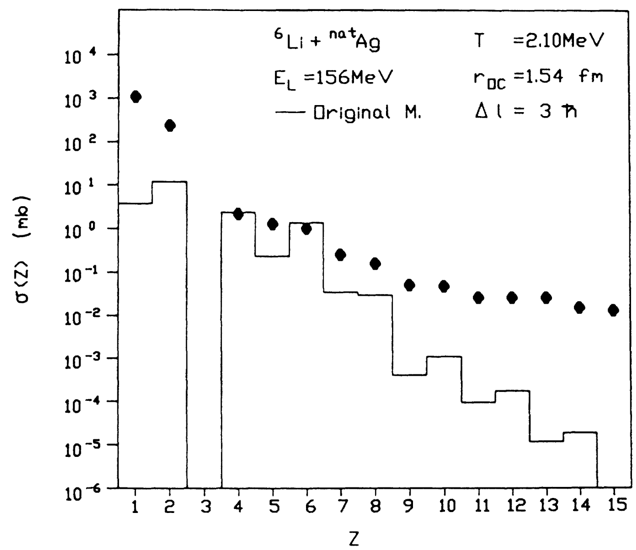

FIG. 1. Element distribution of light and intermediate mass fragment emission from collisions of 156 MeV ^{6}Li ions with $^{\text{nat}}$Ag (Refs. 9 and 12) as compared with results of the analysis based on the original sum-rule model (Ref. 16).

where S_l are the scattering amplitudes which may be independently deduced from elastic-scattering analysis. The general behavior of S_l in cases of strong absorption guarantees a smooth transition of the transmission factor K_l from unity to zero (see also the formulation given in Ref. 13). Thus, Eq. (2.5) is rewritten

$$\sigma(i)=\pi\lambda\!\!\!^{-2} \sum_{l=0}^{\infty} (2l+1)K_l\frac{T_l(i)P(i)}{\sum_j T_l(j)P(j)} . \tag{2.7}$$

While incomplete fusion apparently contributes to "nonequilibrium" components, the *extended* sum-rule model[7,14] regards the near-equilibrated IMF component to originate from cluster emission during the dissipative evolution of the dinuclear system before the partners have completely given up their individualities and collapse to a mononucleus without memory. Without further specification we associate IMF emission predominantly to deep-inelastic reactions or to a reaction mode intermediate between deep-inelastic reactions and compound-nucleus formation, say, to rather asymmetric fast or quasi-fission modes proceeding through partially equilibrated states: "*dissipative fragmentation.*" Introducing corresponding transmission coefficients T_l' alters the normalization [Eq. (2.4)] to

$$N_l \left[\sum_{i=1}^n T_l(i)P(i)+\sum_{i=2}^n T_l'P(i)\right]=K_l . \tag{2.8}$$

For the dissipative processes under consideration it appears quite natural to assume that the corresponding transmission coefficients T_l' are limited by a critical l value $l_{\text{cr}}^{\text{dyn}}$ which includes the angular momentum dissipation[15] during the dynamical evolution of the system:

$$T_l'=\{1+\exp[(l-l_{\text{cr}}^{\text{dyn}})/\Delta l]\}^{-1} . \tag{2.9}$$

Thus, the cross section is expressed by a sum of two contributions

$$\sigma^{\rm tot}(i)=\sigma(i)+\sigma'(i)\ , \tag{2.10}$$

where

$$\sigma(i)=\pi\lambda\!\!\!^{-2}\sum_{l=0}^{\infty}(2l+1)K_l\frac{T_l(i)P(i)}{\sum_{j=1}^{n}T_l(j)P(j)+\sum_{j=2}^{n}T_l'P(j)} \tag{2.11}$$

gives the complete fusion and the incomplete fusion ($i=2,\ldots,n$) contributions while

$$\sigma'(i)=\pi\lambda\!\!\!^{-2}\sum_{l=0}^{\infty}(2l+1)K_l\frac{T_l'P(i)}{\sum_{j=1}^{n}T_l(j)P(j)+\sum_{j=2}^{n}T_l'P(j)} \tag{2.12}$$

represents the intermediate fragments emission by dissipative fragmentation of the dinuclear system feeding the exit channels $i=2,\ldots,n$. For angular momenta less than $l_{\rm cr}^{\rm dyn}$ dissipative fragmentation can be associated to phenomena similar to fast fission or quasi-fission processes, while for $l>l_{\rm cr}^{\rm dyn}$ contributions from deep-inelastic collisions are expected to show up.

The present approach of the extended sum rule [specified by the condition of Eq. (2.8)] assumes that incomplete fusion processes contribute to heavy cluster emission only with the "fast" remnants when part of one collision partner, say, of the projectile, fuses with the other partner. In principle, however, like with the evolution of the full dinuclear system, intermediate mass fragments may be additionally emitted with the dissipative evolution of the partially fusing system.[30–32] A corresponding extension of the sum-rule model (based on a somehow alternative normalization condition assuming sequential processes) is in progress.[33]

III. APPLICATION TO THE ANALYSES OF Z DISTRIBUTIONS

The phenomenological application of the model prescriptions implies the adjustment of three parameters: the apparent temperature T, the effective relative distance $R_c=r_{0c}(A_1^{1/3}+A_2^{1/3})$ where the charge transfer takes place and which determines $Q_c(i)=(Z_1^fZ_2^f-Z_1^iZ_2^i)e^2/R_c$, and the "diffuseness" Δl in the angular momentum space of the contributions around $l_{\rm lim}(i)$. In addition, the critical angular momenta $l_{\rm crit}(i)$ and $l_{\rm cr}^{\rm dyn}$, as well as the entrance transmission factor K_l or $l_{\rm max}$, respectively, have to be specified on the basis of independent considerations.

(a) A reasonable estimate of the apparent temperature is provided by the well known relation

$$T=\sqrt{E^*c/A}\ , \tag{3.1}$$

where E^* is the excitation energy and $8\le c\le 13$ (see Ref. 16). As far as experimental Z distributions are available, the phenomenological sum-rule analysis infers T from the parameter adjustments, but it is expected that the result does not significantly differ from the estimate of Eq. (3.1).

(b) Through the exponential factors [Eq. (2.1)] the results can be considerably influenced by the particular choice of Q_c or R_c, respectively, and there appears also for the best-fit results a correlation between R_c and T (see Ref. 7). Within some limits smaller values of R_c can be compensated by larger values of T, which is obvious from the structure of $P(i)$. It is also possible that R_c, the distance where charge transfer takes place, is different for different types of processes. The cluster emission during the evolution of the dinuclear system may happen from rather deformed intermediate shapes. Some attempts following the suggestion[17] to use

$$R_c=1.225(A_1^{1/3}+A_2^{1/3})+d\ ,$$

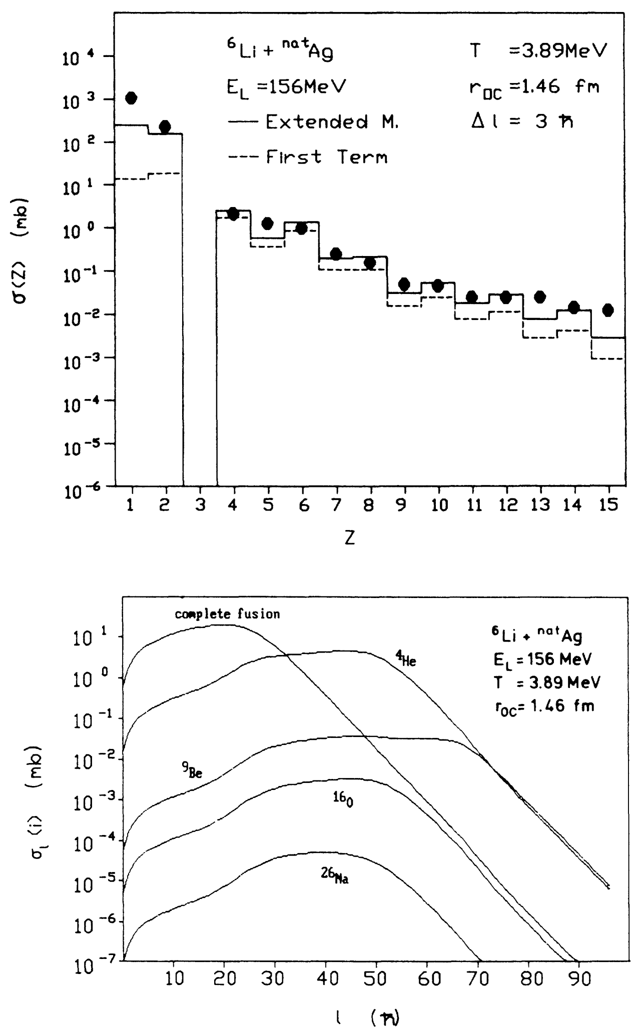

FIG. 2. (a) Extended sum-rule analysis of IMF emission from the ^{6}Li+$^{\rm nat}$Ag reaction at 156 MeV (Ref. 9). The dashed curve represents the contribution of the first term [Eq. (2.10)]. (b) The partial cross sections σ_l for the ^{6}Li+$^{\rm nat}$Ag reaction at 156 MeV ($l_{\rm cr}^{\rm dyn}=51\hbar$).

with d roughly simulating deformation effects and treated as a free parameter, did not lead to distinct differences from the choice

$$R_c = r_{0c}(A_1^{1/3} + A_2^{1/3}) .$$

(c) The values of the critical angular momenta $l_{crit}(i)$ limiting the formation of a compound nucleus in complete and incomplete fusion channels are calculated with a statical condition assuming that a given fragment can be captured only if it penetrates the region of attraction of the total nucleus-fragment potential.[18] The cluster emission from the dinuclear system on its way to fusion is supposed to depend on the critical angular momentum value l_{cr}^{dyn}, for fusion, which takes into account the angular momentum dissipation. The specification of l_{cr}^{dyn} is based on a dynamical model of fusion and follows the procedure of Ngô *et al.*[15,19] The computer routines necessary for sum-rule analyses are compiled by the program LIMES.[20]

(d) The entrance transmission coefficient $K_l = 1 - |S_l|^2$ may be derived by optical model or parametrized phase-shift analyses of elastic-scattering data, or more simply by introducing a smooth cutoff factor around $l_{max} \simeq l_{grazing}$ with a reasonable estimate of the transition width ΔL.

Figure 2(a) shows the result of the analysis of the experimental Z distribution of the fragments emitted in collisions of 156 MeV ^{6}Li ions with ^{nat}Ag.[9,12] In contrast to the result shown in Fig. 1, the calculations reproduce fairly well the experimental data, and the apparent temperature is consistent with the value estimated on the basis of Eq. (3.1), as used for a multistep-evaporation analysis of the same data.[9] The corresponding partial cross sections $\sigma_l(i)$ calculated by a smooth cutoff entrance transmission factor K_l deduced from elastic scattering are given in Fig. 2(b). The contribution at large-l values is due to the second term $\sigma'(i)$ of Eq. (2.10), which obviously explains the experimentally observed enhancement in the production of light fragments in the

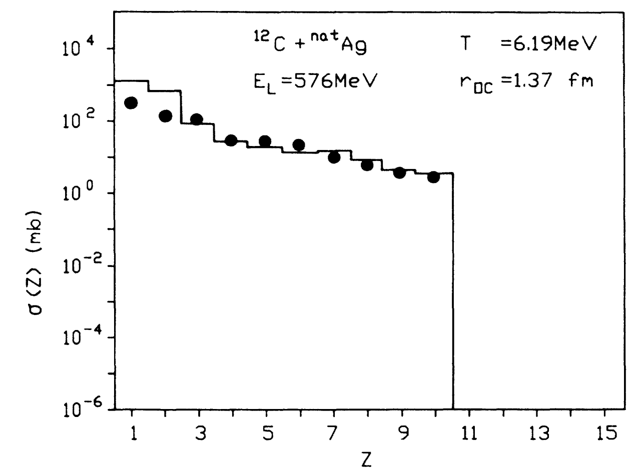

FIG. 4. Extended sum-rule analysis of IMF emission for the reaction $^{12}C + ^{nat}Ag$ at $E/A = 48$ MeV (Ref. 22).

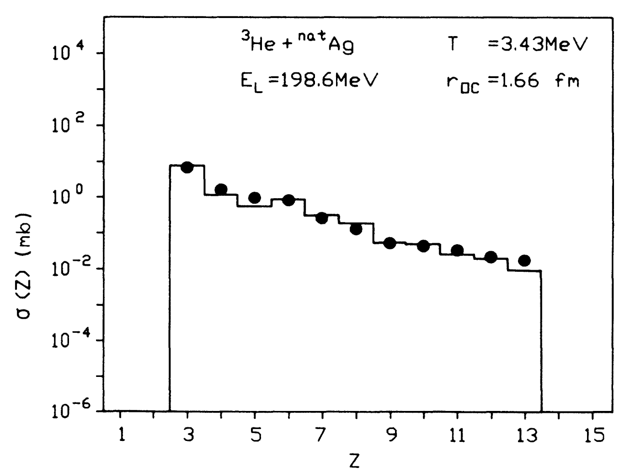

FIG. 3. Extended sum-rule analysis of IMF emission for collisions of 198.6 MeV ^{3}He with ^{nat}Ag (Ref. 21).

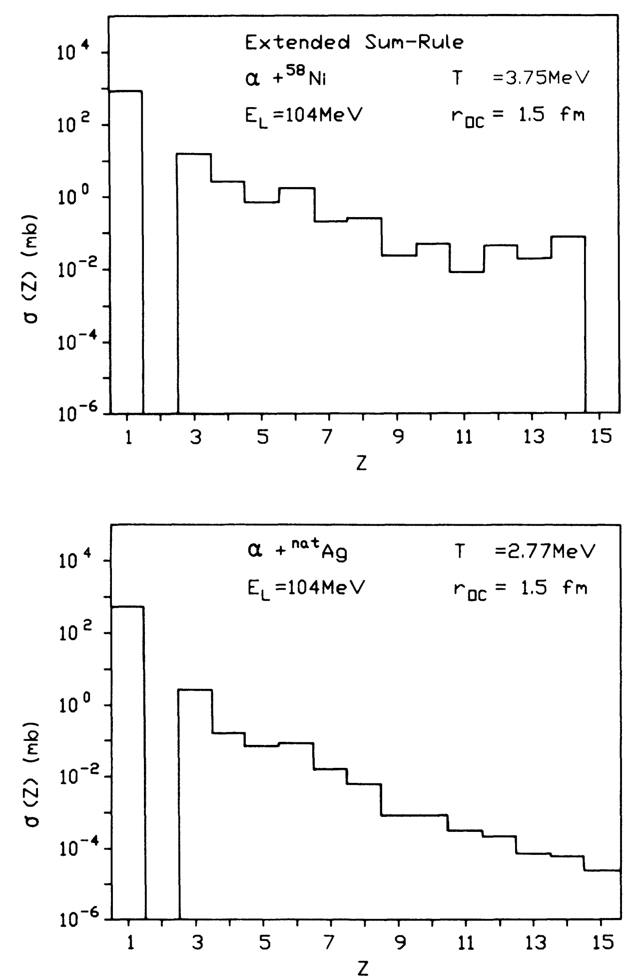

FIG. 5. Sum-rule predictions of the element distributions of IMF emission for α-particle-induced reactions at $E_\alpha = 104$ MeV.

forward direction and small energy dissipation (see also Fig. 7).

Figure 3 displays the result for the data[21] of another very asymmetric case: 198.6 MeV ^{3}He+^{nat}Ag. The value of the apparent temperature is in reasonable agreement with that found by a multistep-evaporation model analysis.[9] The analysis of the element distribution observed[22] for ^{12}C collisions with ^{nat}Ag at $E/A = 48$ MeV reproduces the increased apparent temperature expected for this incident energy (Fig. 4).

Figure 5 shows, additionally, predictions of the Z distributions from reactions of 104 MeV α particles with ^{nat}Ag and ^{58}Ni. A value $r_{0c} = 1.5$ fm and T corresponding to Eq. (3.1) ($c = 10$) have been adopted for the calculations.

IV. ENTRANCE CHANNEL ANGULAR MOMENTUM WINDOWS

With the calculation of the element distribution $\sigma(Z)$ the model predicts the partial cross sections $\sigma_l(i)$, i.e., the angular momentum localization of the various reaction channels [Fig. 2(b)]. When applying the ESM to IMF ($3 \leq Z \leq 9$) emission to data measured[23] for the emission in the backward hemisphere in the 336 MeV ^{40}Ar+^{nat}Ag reactions (see Fig. 6), we may compare with independent information about the angular momentum windows, available from recent coincidence studies[24] of the same nuclear system at the same incident energy.

The results shown in Figs. 7(a) and 7(b) demonstrate that the major part of IMF emission (in the backward angular region) has to be attributed to the second term of Eq. (2.10). Obviously the fast fragments originating from incomplete fusion are fairly well concentrated in the angular momentum range with $(60-100)\hbar$ while dissipative fragmentation is found at larger $l \approx (90-140)\hbar$, i.e., in the region around $l_{cr}^{dyn} = 113\hbar$. This finding is in reasonable agreement with the results of Ref. 24 attributing the quasi-fission channel to, e.g., $l = (103-133)\hbar$. The example may demonstrate the predictive power of the ESM

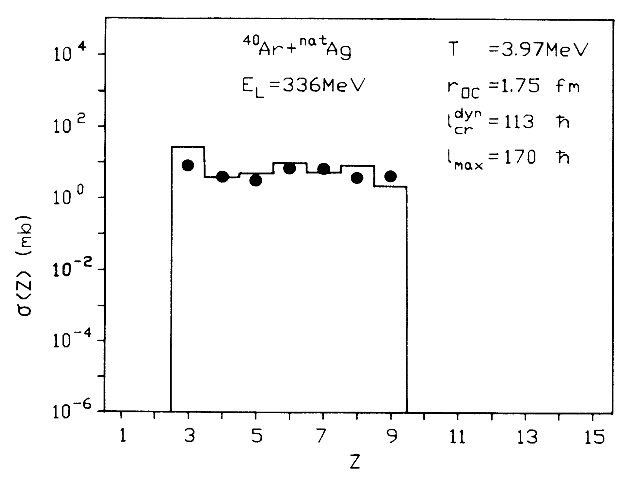

FIG. 6. Extended sum-rule description of $\sigma(Z)$ of IMF emission from collision of 336 MeV ^{40}Ar ions with ^{nat}Ag (Ref. 23).

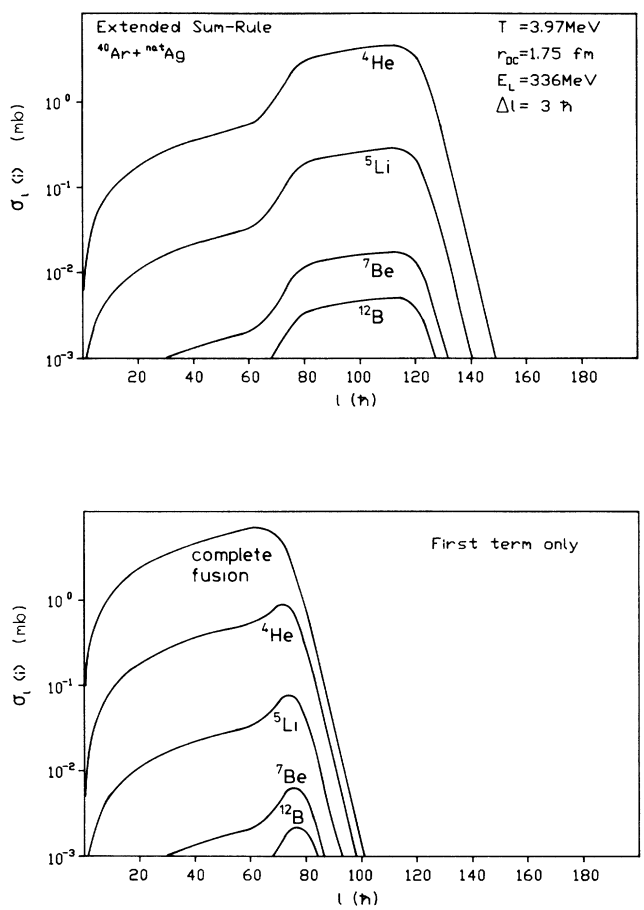

FIG. 7. Partial cross section σ_l for the emission of various complex fragments in 336 MeV ^{40}Ar+^{nat}Ag collisions: Prediction of the extended sum-rule model.

though, of course, such a global model cannot be invoked for predictions of further details of the reaction mechanism. Nevertheless, the result suggests that the emission of IMF may be understood as arising during the dynamical evolution of the dinuclear system via partially equilibrated states, in a mode which is similar to a rather asymmetric fast or quasi-fission process.

V. CONCLUDING REMARKS

Light and intermediate mass fragment emission is a quite general phenomenon in nuclear reactions. Though the details may depend in a rather complicated way on the specific properties of the particular system under consideration, the general features and overall tendencies, evident in results of inclusive experiments, are conspicuously similar and point to a common basic process and origin which should be accessible to a simple phenomenological description of the most prominent global observations. Generalizing the original sum-rule model[6] for complete and incomplete fusion processes, the extended sum-rule model, illustrated in the present paper, adopts the view that IMF emission preferentially originates from cluster emission during the dissipative evolution of the dinuclear system *before* complete equilibration. The

ESM describes the nearly equilibrated component of IMF emission with entrance channel transmission coefficients limited by the critical value of the angular momentum for fusion with angular momentum dissipation taken into account. This view seems to be supported by a successful description of the element distributions (including light particle emission) and of the angular momentum localization, though the model in its present form does not intend to specify explicitly energy spectra and angular distributions. The sum-rule model is based on the very general assumption of partial statistical equilibrium and does not further specify the dynamics of the underlying process. Nevertheless, we may envisage one of the variants of various dissipative processes,[25–28] say, some type of rather asymmetric fast fission or (complete or incomplete[27]) deep-inelastic processes.[28] A recent extension[29] of the random-walk model for mass-exchange reactions is guided by similar ideas.

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