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A MULTISTEP EVAPORATION MODEL FOR INTERMEDIATE MASS FRAGMENT EMISSION

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Abstract
A multistep evaporation model for intermediate mass fragment emission in heavy ion reactions is described. It applies the canonical transition-state method for the determination of the probability for disintegration of a fused system. The energy and angular momentum relations at the saddle and scission points are calculated on the basis of the finite range liquid drop model. The derivation of the total kinetic energy release uses the concept of amplifying modes which is equivalent to that of shape fluctuations at the ridge point. The model reproduces fairly well the mass and angular distributions and the energy spectra of intermediate mass fragments yields from inclusive and coincidence experiments.

EIN MEHRSTUFEN - VERDAMPFUNGSMODELL FÜR DIE EMISSION VON NUKLEAREN FRAGMENTEN MITTLERER MASSE

Zusammenfassung
Es wird ein Mehrstufen-Verdampfungsmodell für die Emission von Fragmenten mittlerer Masse in Schwerionen-Reaktionen beschrieben. Zur Bestimmung der Zerfallswahrscheinlichkeit des fusionierten Systems wird die kanonische Methode der Übergangszustände angewandt. Energie und Drehimpuls-Relationen an Sattel- und Zerreißpunkt der Potentialenergie-Fläche werden auf der Grundlage des Tröpfchen-Modells unter Berücksichtigung von Kräften endlicher Reichweite berechnet. Bei der Bestimmung der kinetischen Energie der Fragmente werden "verstärkende " Zerfallsmoden auf Grund von Gestaltsfluktuationen explizit betrachtet. Das Modell reproduziert recht gut Massen- und Winkelverteilungen, sowie die Energiespektren der Fragmente mittlerer Masse, die in inklusiven und exklusiven Experimenten beobachtet werden.

1. INTRODUCTION

The emission of complex fragments of intermediate mass (IMF's) in light and heavy ion reactions appears to be of considerable current interest since studies of this phenomenon are expected to provide new insight into the way how hot nuclei are formed and what limits the momentum transfer and energy deposits. However, the origin and the mechanism of the production of the cluster - like fragments are still subject of various uncertainties, which, in turn, has induced numerous theoretical speculations, in some cases envisaging rather fancy processes[1,2]. For relatively low bombarding energies, there is convincing evidence that IMF emission originates from completely equilibrated nuclei[3] while at intermediate and high energies the cluster particles may be emitted prior to the attainment of a full statistical equilibrium, thus associating the IMF production to more complex phenomena such as emission from locally equilibrated nuclear subsystems. There seems to be a broad consent[4] that both direct binary reactions modes and modes with thermal equilibration contribute in the transitional energy domain above 20 MeV / amu. In fact, a main issue is the aspect to which extent the dinuclear system manages to fuse or whether it prefers to reseparate into fragments of deep - inelastic interactions before equilibration.

The parametrization of the kinetic energy spectra of the IMF's in terms of emission from moving sources[5] has been found to be not very conclusive. On the other side, scrutinizing carefully compound nucleus emission has led to the conclusion that compound nuclei are able to eject the full range of complex fragments from α - particles to fission products[6], with increasing probability when the excitation energy increases. In fact, there is a set of results [7-10], mostly analysed in terms of the asymmetric fission model of Moretto[6], which favour the statistical evaporation from a completely fused system to be the prevailing mechanism of IMF emission, thus prompting the question[9] : "Compound Nuclei Forever ? "

The present work follows the idea of IMF emission from equilibrated systems. The large excitation energies, however, suggest that the particles are evaporated in a decay - chain rather than in one - step process (as assumed in ref. 11). This paper describes the general layout and the ingredients of a *multistep evaporation* model which successfully reproduces the dominant components of IMF emission in light and heavy ion reactions of various projectile - target combinations, which have been so far considered in our current studies. Our model assumes that after a violent stage of the reaction at least *partial thermal equilibrium* is reached by the nuclear system or subsystem, respectively, which subsequently evaporates light

or intermediate mass particles. Thus, the model includes explicitely, in addition to complete fusion, incomplete fusion entrance channels, too.

2. GENERAL DESCRIPTION

The model is devised with the basic assumption that the projectile and target form initially a fused system, which can be sufficiently characterised by following parameters : the *mass* of the system A, the *excitation energy* E*, the thermodynamical *temperature* T, the Cartesian components of the *linear momentum* p_x, p_y, p_z and the Cartesian components of the internal *angular momentum* L_x, L_y, L_z. Due to the large excitation energy and high spin values, the compound system undergoes as sequence of binary decays schematically indicated in Fig. 1. All channels with binary splitting events contribute to the cascade according to the corresponding partition probability.

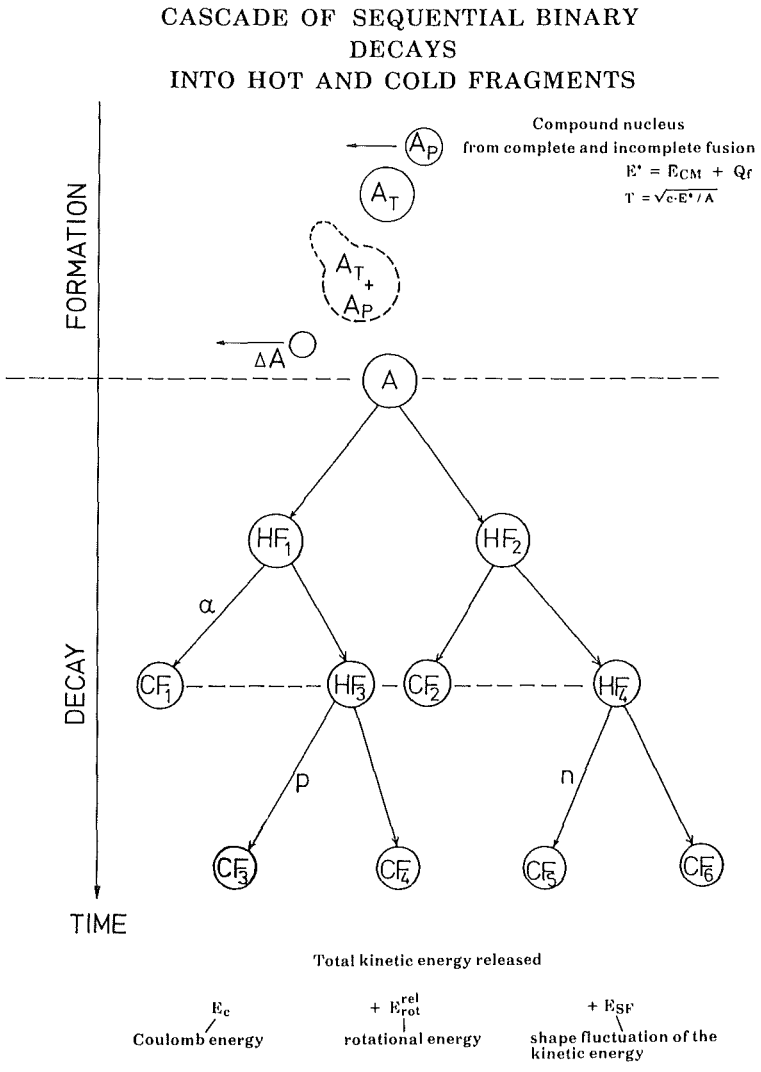

Fig. 1 Schematic diagram of the multistep evaporation model proceeding via a cascade of sequential binary decays.

The hot fragments (HF) decay sequentially until they become "cold" (CF). A daughter nucleus is considered to be "cold" when its mass is equal or less than 4, e.g. being n, p, ^{4}He etc., when the excitation energy is less than any particle separation energy, or when the partition probability forbids a particle decay, i.e. when E* approaches the Yrast line. The parent nuclei at the top of the cascade are formed by complete and incomplete fusion reactions resulting in mass values A : $A_{target} < A < A_{target} + A_{projectile}$. The angular momentum population of the parent nucleus follows the usual ($2 L_{max}^{(i)} + 1$) distribution with a smooth Gaussian cut off (quantified by a width ΔL). The limiting values $L_{max}^{(i)}$ correspond to the maximum angular momentum of all contributing complete and incomplete channels (labelled by the superscript i). All cold fragments from any stage of the cascade are accumulated as the particle yield. The numerical evaluation of the model by means of a package of Fortran computer programs and operated with an IBM PC - AT (DEFINICON board with Motorola processor) e.g., utilizes Monte Carlo techniques.

In the following, we consider the procedures how mass distributions, angular distributions and energy spectra of the emitted IMF's are calculated in the frame of the model.

3. MASS DISTRIBUTION

The mass distribution of the IMF's is dominantly determined by the partition probability $P(A=A_1+A_2) \equiv P(A_1, A_2)$ determined[12] by the microcanonical ensemble $\rho(E^*)\Delta E^*$, $\rho(E^*)$ being the level density of the system A with the excitation energy E*. Following Świątecki[12] we adopt

$$P(A_1, A_2) \propto \frac{1}{\rho(E^*)} \int_0^U \rho(x)\, dx \qquad (1)$$

where U is the saddle point energy of the (A_1, A_2) ridge point configuration. There are two alternative expressions in use for $\rho(E^*)$:

(i)
$$\rho(E^*) \propto \frac{1}{E^2} exp\left\{2(a E^*)^{1/2}\right\} \qquad (2a)$$

leading to

$$P(A_1, A_2) \propto \frac{exp\left\{2(a U)^{1/2}\right\}}{exp\left\{2(a E^*)^{1/2}\right\}} \qquad (2b)$$

or

(ii)
$$\rho(E^*) \propto exp\left\{2(a E^*)^{1/2}\right\} \qquad (3a)$$

and correspondingly

$$P(A_1, A_2) \propto \frac{T_S \exp\left\{2(a\,U)^{1/2}\right\}}{\exp\left\{2(a\,E^*)^{1/2}\right\}} \tag{3b}$$

with

$$a = A/c \qquad (c = 8.5\,MeV) \tag{4a}$$

and the saddle point temperature

$$T_S = \sqrt{U/a} \quad . \tag{4b}$$

The potential energy at the saddle point can be expressed as

$$U = E^* - \left[(E_c - E_c^\circ) + (E_s - E_s^\circ) \right] - E_{Rot}^{RLDM} \tag{5}$$

with E_c and E_s the Coulomb and surface energies of the deformed system, and E_c° and E_s° denote the same for spherical shapes. The quantity E_{Rot}^{RLDM} is the rotational energy at the saddle point.

The quantities determining U in eq. 5 are derived from the rotating liquid drop model (RLMD)[13]. Following the approach of Blocki and Świątecki[13] three dimensionless (distance, neck and asymmetry) variables

$$\rho = \frac{r}{R_1 + R_2} \quad , \quad \lambda = \frac{d_1 + d_2}{R_1 + R_2} \;\; and \;\; \Delta = \frac{R_1 - R_2}{R_1 + R_2} \tag{6}$$

are introduced in order

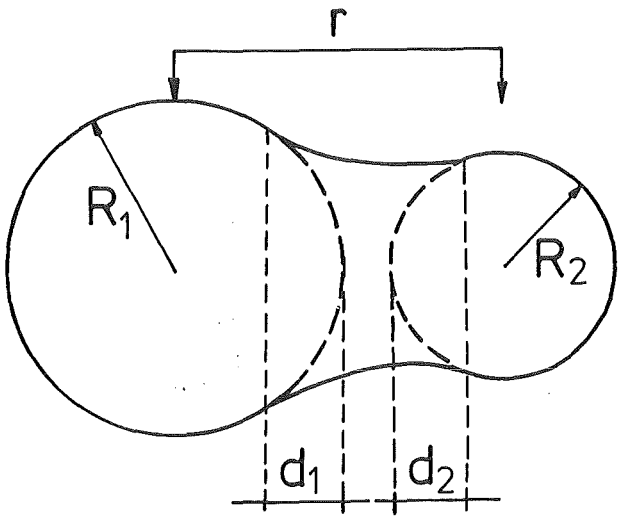

Fig. 2 Parametrization of the nuclear shape

to parametrize the nuclear shapes of the coalescing and reseparating nuclei along the dynamical trajectory. An explanation of the geometrical parameters r, R_1, R_2, d_1, d_2 is given in Fig. 2.

In contrast to the liquid drop model with a sharp surface the calculations use a refinement by folding the shapes with a finite range nuclear interaction given by Krappe, Nix and Sierk[14]. Thus, an attractive force of finite range works between nascent fragments at the saddle point.

The rotational energy

$$E_{Rot}^{RDLM} = \left(I_1 + I_2 + \mu r^2 \right) \frac{\omega^2}{2} \tag{7}$$

is expressed in terms of the moments of inertia (I_1, I_2) of the two separating fragments, the angular velocity ω of the system at the sticking condition and by the reduced mass μ.

The probability for binary splitting is in all cases (for fission as well as for evaporation) deduced by applying the canonical version of the transition-state method[12] (i.e. using eqs. 2 - 5). However, the decomposition of the total energy and its moments of inertia are somewhat in question when the rotating liquid drop model is invoked for the emission of n, p, α etc. For these cases the shape at the saddle point may be optionally approximated by two touching spheres so that eq. 5 reads as

$$U = E^* - \left(E_{Sep}^{\infty} + E_{TKE}^{\infty} + E_{Rot}^{\infty} \right) \tag{8}$$

with E^{∞}_{Sep}, E^{∞}_{TKE}, E^{∞}_{Rot} beeing the separation energy, the total kinetic energy release and the rotational energy of two sphares, respectively. The separation energy can be calculated by a modified Weizsäcker formula

$$E_{Sep}^{\infty} = E(A) - E(A_1) - E(A_2) \quad , \tag{9}$$

$$E(A) = 15.56\,A - 17.23\,A^{2/3}\,\beta\,(T, T_{cr}) - 0.7\,\frac{A^2}{4\,A^{1/3}} \quad , \tag{10}$$

$$\beta\,(T, T_{cr}) = \left[\frac{T_{cr}^2 - T^2}{T_{cr}^2 + T^2} \right] \quad . \tag{11}$$

The critical temperature T_{cr} is defined here by the term which reduces the magnitude of the surface tension of the nuclear liquid when the temperature approaches the critical value T_{cr}.

How to get E^{∞}_{TKE} is explained below (sect.5). The rotational energy E^{∞}_{Rot} is defined by the

$$E_{Rot}^{\infty} = \left(\frac{2}{5}\,A_1\,R_1^2 + \frac{2}{5}\,A_2\,R_2^2 + \mu r^2 \right) \frac{\omega^2}{2} \tag{12}$$

The simplification introduced by eq. 9 and used in previous multistep evaporation model analyses[15,16] is equivalent to ignoring the difference between saddle point and scission configuration.

4. ANGULAR DISTRIBUTION

The model assumes either an isotropic or a $1 / \sin \theta_c$ angular distribution where θ_c corresponds to emission angle in the rest system of the decaying products of the corresponding evaporation step. It is believed that the isotropic decay prevails for central interactions in the entrance channel while the $1 / \sin \theta_c$ distribution emerges for large channel angular momenta. The model applies a smooth transition between the two modes.

As compared with Hauser - Feshbach calculations the model adopts the simplification that the binary decay products are emitted in the plane only *perpendicular* to the initial angular momentum as spin fluctuations are ignored (see also ref. 26). The initial angular momentum is in turn uniformly oriented perpendicular to the beam axis. Recoil effects are taken into account without any approximation.

5. ENERGY SPECTRA

Fig. 3 shows schematically a dynamical trajectory of the system in the ρ - λ - space. The mass partition of the excited system is defined by the density of internal states at the saddle point as formulated by eqs. 2 - 5. From the saddle point the system moves to the scission line. The actual trajectory depends on the initial conditions. Calculations in the frame of the RLDM - finite range approach show that the approximation that the scission line is reached on the shortest way from the saddle point is rather good.

At the scission point the two fragments reseparate definitively , and the gain of the kinetic energy E^{∞}_{TKE} in that instant is considered to be the total kinetic energy release. This value would be the experimentally observed energy in the case of a one-step binary decay:

$$E^{\infty}_{TKE}(A_1 + A_2) = E^{SC}_{C} + E^{SC}_{Rel} + E_{SF} \qquad (13)$$

where E_C^{SC} is the hight of the Coulomb barrier at the scission point, and E_{Rel}^{SC} is the relative rotational energy:

$$E^{SC}_{Rel} = E^{SC}_{Rot} - \left(\frac{I_1 \omega^2}{2} + \frac{I_2 \omega^2}{2} \right) \qquad (14)$$

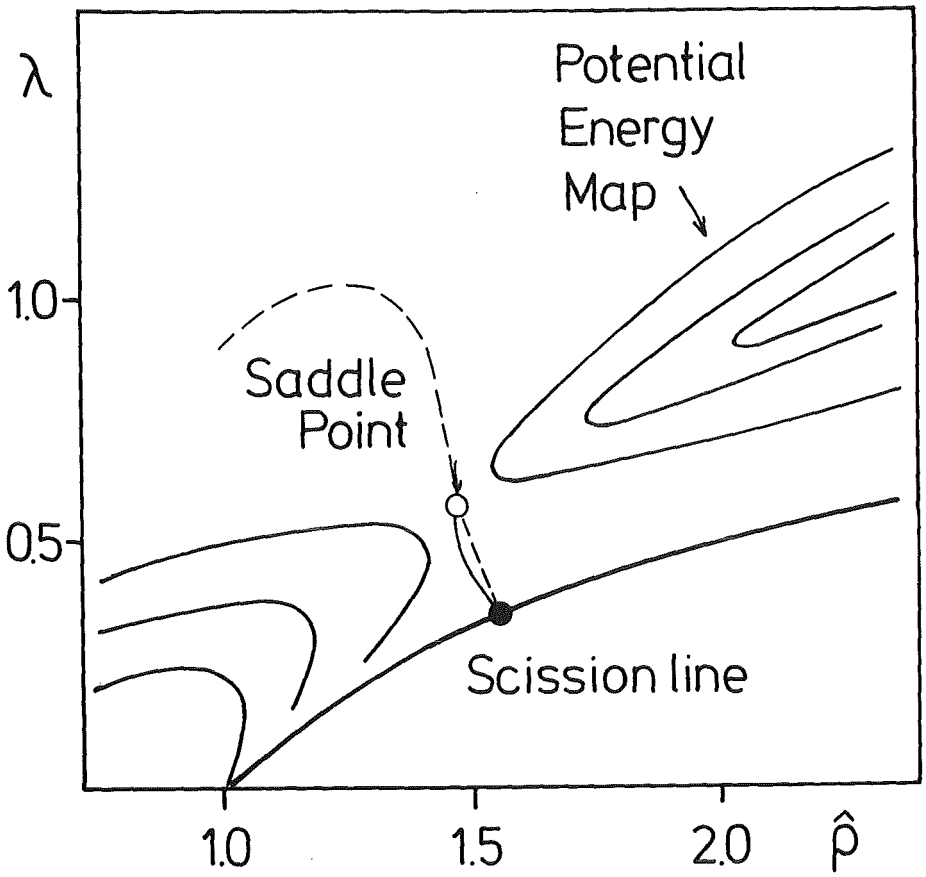

Fig. 3 Schematic dynamical trajectory in the $\hat{\rho} - \lambda$ – space.

The quantity E_{SF} is the shape fluctuation component[6]. It is randomized after each partition according to the formulas given by Moretto[6,17] in order to simulate the CM energy distribution of the reseparating fragments. A one-decay, one amplifying, and one non-amplifying mode were taken into account. The distribution of the kinetic energy fluctuation at infinity is given by

$$P(E_{SF})\,dE_{SF} \sim \left| (2E_{SF} - p)\,exp\left(\frac{E_{SF}}{T}\right) erfc\left(\frac{p - 2E_{SF}}{2\sqrt{pT}}\right) + 2\sqrt{\frac{pT}{\pi}}\,exp\left(-\frac{p^2 + 4E_{SF}}{4pT}\right)\right| dE_{SF} \tag{15}$$

where T denotes the apparent temperature and erfc is the conjugate error function. The amplification factor p maps the fluctuations of various collective degrees of freedom onto the Coulombic part of the potential energy[6]. By extensive RLDM calculations a semiempirical parametrization of the amplification factor has been found

$$p = p_{sym} - (p_{sym} - 1)\left(\frac{A - 2A_1}{A - 8}\right), \qquad A > 8$$

$$p_{sym} = 7.289 \cdot 10^{-5} \cdot X^2 + 0.019 \cdot X + 0.233 \cdot L + 1.4$$

$$X = Z^2 / A^{1/3} \quad , \tag{16}$$

where p_{sym} stand for the amplification factor of a symmetric splitting: $A_1 = A_2 = A/2$ and L denotes the angular momentum of the system.

In the randomization process the energy is conserved in the average. The parametrization (eq. 16) p differs from the procedure of previous analyses [15,16] using the approximation of Maxwellian distributions of p.

6. CONCLUDING REMARKS

The numerical evaluation of the described multistep evaporation model is feasible by means of Monte Carlo techniques. A statistically sufficiently large set of complete or incomplete fusion events has to be processed along all possible chains. In principle, there are no free parameters to be fitted since the values of the empirical ingredients (the value of c, e.g., see eq. 4a, etc.) are adopted from independent sources. The entrance channel decomposition into complete and incomplete fusion processes and the corresponding angular momentum limitations may be taken either from experimental information or from independent theoretical considerations, for example sum rule descriptions of the considered reaction modes [18,19], can provide quite useful information of this kind.

In the model the avaiable thermal energy is shared between the binary reaction products in the ratio of their masses ("equal temperature"). The concept of a partial statistical equilibrium may be optionally introduced into the early steps of the decay chains by introducing *different* temperatures of the fragments, dependent on the mass asymmetry.

Up to know the model has been successfully applied for the analyses of a wide variety of experimental data of intermediate mass fragment emission in light and heavy ion reactions at intermediate energies, such as for the cases ^{3}He + ^{nat}Ag (198 MeV) [20], ^{6}Li + ^{46}Ti [15], ^{nat}Cu, ^{nat}Ag [21], (E_{Li} = 156 MeV), ^{14}N + ^{nat}Cu, ^{nat}Ag, ^{159}Tb (308 MeV) [22] and to more exclusive results of ^{14}N + ^{232}Th collisions (35 MeV / amu) [23]. Details of the analyses will be reported elsewhere [21, 24]. Though in general, the experimental data prove to be fairly well described, there evolves also convincing evidence of the presence of an additional multinucleon transfer component. In fact, a linear momentum transfer analysis [25] of the ^{6}Li + ^{46}Ti (156 MeV) results has indicated a change in the reaction mechanism with increasing mass of the emitted fragments and for larger emission angles. More recently, Borderie et al. [26] have shown the importance of the deep - inelastic contribution in the ^{40}Ar + ^{nat}Ag reaction at 27 MeV / amu. With these aspects

the IMF emission originating simultaneously from equilibrated and partially equilibrated systems requires adequate modifications and extensions of the present sum rule model descriptions [19].

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