Production Mechanism of Hot Nuclei in Fermi Energy Domain: from Peripheral to Central Collisions

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A detailed knowledge of the production mechanism of hot nuclei is desirable for the understanding of multifragmentation. In this article, a framework based on simple phenomenological assumptions is presented. A more detailed description can be found in [1].

Pre-equilibrium emission is a process where fast particles are emitted during the initial approach of the projectile and target. In the present work, we use a phenomenological description [2] based on similar assumptions as the exciton model. The probability of preequilibrium emission is evaluated using the formula

$$P_{pre}(n/n_{eq}) = 1 - e^{-\frac{(n/n_{eq-1})^2}{2\sigma^2}} \qquad (1)$$

for $n < n_{eq}$ and is assumed to be zero for $n < n_{eq}$, where n is the number of excitons at given stage and n_{eq} is the number of excitons in the equilibrium configuration for given excitation energy. The σ is a free parameter. An initial exciton number is equal to the mass number of the beam. The equilibrium number of excitons is calculated according to [3]. The emission of neutron, proton and ∀-particle is considered and the Weisskopf-Ewing emission widths are used. The Maxwellian spectrum of kinetic energy with the apparent temperature [4]

$$T_{app} = \left[\frac{2.5}{A_P} (E_P - V_C) \right]^{1/2} \qquad (2)$$

is assumed, where A_P is the projectile mass number, E_P is the projectile energy and V_C is the Coulomb barrier. The emission angle is determined according to [5]. After emission, the exciton number is increased by a value obtained using the formula

$$\Delta n = A_{pre} \frac{\kappa}{\beta_{rad}}$$

where A_{pre} is the mass of emitted particle, $∃_{rad}$ is the radial velocity in the contact configuration at a given angular momentum and 6 is a free parameter. If no pre-equilibrium emission occurs at a given emission stage, the pre-equilibrium stage is finished.

In our description, different scenarios are employed in the post-pre-equilibrium stage depending on the angular momentum. At large angular momenta, the model of deep inelastic transfer is used. In the more central collisions, where a stationary di-nuclear configuration cannot be created, the framework of a geometric overlap is used. In the new-central collisions a model of Wilczynski [6] is employed.

For every event the Monte Carlo DIT code of Tassan-Got [7] is used. In the case where di-nuclear configuration is created, deep inelastic transfer takes place and excited quasi-projectile and quasi-target are created. In the cases, where overlap of nuclei is too deep, the more violent scenario is considered. The geometric overlap formula of the abrasion-ablation model [8] is used in a refined way where a minimum distance between projectile and target on the classical Coulomb trajectory is used instead of the asymptotic value of impact parameter. Such a choice is compliant to the conservation of angular momentum.

The charges of the spectators are determined according to the combinatorial formula [9, 10]

where i==P(T) for the projectile (target), $A_{P(T)}$, $Z_{P(T)}$, $N_{P(T)}$ are the mass number, charge and neutron number of the projectile (target) and $A_{P(T)S}$, $Z_{P(T)S}$, $N_{P(T)S}$ are mass, charge and the neutron number of the projectile (target) spectator.

In the Fermi energy domain one can assume that the participant zone can be captured by either projectile or target spectator zone. In order to decide between these two, the volume occupied by the neighboring nucleons

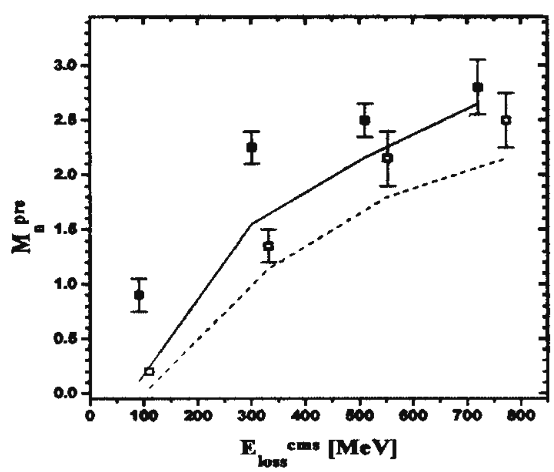

Figure 1: Experimental [12] (symbols) and calculated (lines) mean multiplicities of pre-equilibrium neutrons as a function of kinetic energy loss of the projectile-like fragment. Solid squares - experimental multiplicities measured in reaction of 35 MeV/nucleon ^{48}Ca beam with ^{112}Sn target, open squares - ditto for 35 MeV/nucleon ^{40}Ca beam, solid line - calculated multiplicities in reaction of 35 MeV/nucleon ^{48}Ca beam with ^{112}Sn target, dashed line - ditto for 35 MeV/nucleon ^{40}Ca beam.

within the reach of nuclear interaction (1 fm) is determined in both spectators. The volume is approximated by a 1 fm thick slice of the sphere. The number of neighboring nucleons (A_{NS}) is then determined using a normal distribution centered at the value exactly corresponding to the volume with the standard deviation equal to . The numbers of neighboring nucleons are compared and the participant zone is captured by the spectator with more neighboring nucleons. Such a procedure reflects the saturation of the nuclear force. The capturing spectator and the captured participant zone form a hot fragment. The other spectator is much colder. In this case, the excitation energy is determined using the formula

Where and are the kinetic energy and the mass number of the effective projectile after pre-equilibrium emission, , is the Coulomb barrier, < s > is the mean effective path of the nucleon along the spectator trajectory within the slice, (is the mean free path between the nucleon-nucleon collisions in the nucleus (a value 6 fm is chosen) and x is a random number between zero and one. The energy and the angle of the spectator is determined using the formula of Matsuoka et al. [11] based on the Serber approximation.

In order to describe reactions in the inverse kinematics, namely when the projectile is heavier than the target, the system is transformed into the inverse frame where the projectile becomes a target and vice versa. Then the calculation proceeds as described above and the final kinematic properties of the reaction products are obtained after a re-transformation into the lab frame.

The model of pre-equilibrium emission was compared to the results of work [12] where a multiplicity of the pre-equilibrium particles

4

Figure 2: Calculated correlation between the primary mass and the excitation energy of a projectile-like fragment in the reaction ^{93}Nb with ^{116}Sn at 25 MeV/nucleon. Four different bins of are defined. Black squares - PI+DIT events, grey squares - PE+RGF events.

was determined in coincidence with projectile-like fragments (PLFs) in the reactions of Ca beams with ^{112}Sn target at 35 MeV/nucleon. In Fig. I are given the values of pre-equilibrium neutron multiplicity in reaction ^{40,48}Ca+^{112}Sn for several bins of kinetic energy loss of the projectile-like fragment. The solid (open) squares represent the results of work [12] and the lines represent the results of the calculation. The agreement is quite good. The parameters Φ=0.25 and 6=0.3 were used in the calculation. The some values of Φ, and 6 were tested in other reactions and lead to results which track well with the results of experimental works where multiplicities of pre-equilibrium particles were determined in coincidence with heavy residues or fission fragments [13, 2] or in coincidence with the quasi-projectile [14].

In the recent experimental work [15] a linear correlation between the primary mass of the projectile-like fragment and the net mass loss due to the de-excitation was reported in the nearly symmetric reactions of ^{93}Nb with ^{116}Sn at 25 MeV/nucleon in both normal and inverse kinematics for different dissipation bins. The net mass loss increases with the primary mass of the projectile-like fragment. With increasing dissipation this trend occurs in the still broader range of primary masses. Since the net mass loss is possibly correlated to the excitation energy of the hot primary projectile-like nucleus, one may expect similar trends for excitation energy. Such a trend is a possible signal of the breakdown of the concept of deep inelastic transfer. In Fig. 2 is given a calculated correlation between the excitation energy and the mass of the hot projectile-like nucleus for different bins of kinetic energy. One can see that the calculation follows the experimental trend. At masses close to the beam the deep inelastic transfer takes place but the range of

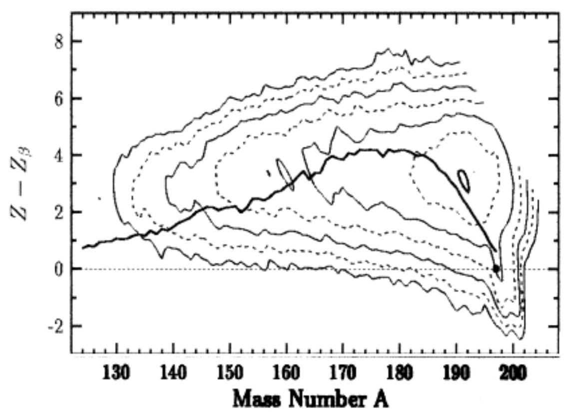

Figure 3: Measured yields [16] of heavy residues at the forward angles in the reaction ^{197}Au(20 MeV/nucleon)+^{nat}Ti as a function of A and Z. Z is expressed relative to the line of ∃-stability. Solid line - calculated centroids of the fragment charge for given residue mass (the code GEMINI [17] was used for de-excitation).

primary masses is quite narrow. To achieve larger mass change a more violent collision should occur. When the target strips a part of the projectile, the projectile-like fragment remains relatively cold. Hot projectile-like fragments are produced if a part of the target is picked-up by the projectile.

The production of heavy residues in inverse kinematics was measured recently by Souliotis et al. [16] in the reaction ^{197}Au+^{nat}Ti at projectile energy 20 MeV/nucleon. Fig. 3 shows the measured yields of heavy residues at the forward angles as a function of A and Z. The solid line represents the calculated centroids of Z for a given residue mass. The code GEMINI (17] was used for the de-excitation stage. One can see that the calculation follows the experimental trend quite well. In this case the participant zone sticks almost exclusively to the heavy projectile and the incomplete fusion leads to the production of neutron-deficient residues with masses close to the beam. The comparison to the broad range of experimental observables measured in various reactions in the Fermi energy domain appears to imply that the present approach describes correctly the processes leading to the production of excited projectile-like and target-like nuclei in the range between 20 and 50 MeV/nucleon. With increasing projectile energy, the production of three-body events and the compression phenomena start to play an important role. Primary candidates for three-body events can be considered hot fragments where the relative motion of the participant zone leads to values of intrinsic angular momenta above the critical angular momentum for fusion. The compression phenomena can primarily take place in events where the fragment with a mass close to the compound nucleus is produced with low intrinsic angular momentum.

In conclusion, the approach presented in the present work appears to be a suitable tool to describe the production of hot nuclei which later undergo multifragmentation. Furthermore, production of rare beams in the Fermi energy domain can be addressed using this approach.

References

[1] M. Veselsky: nucl-th/0010069.

[2] M. Veselsky *et al.*: Z Phys. A **356,** 403 (1997).

[3] M. Böhning: Nucl. Phys. **A152,** 529 (1970).

[4] H. Fuchs and K. Möhring: Rep. Prog. Phys. **57,** 231 (1994).

[5] D. J. Parker *et al.*: Phys. Rev. C **44,** 1528 (1991).

[6] J. Widozynski: Nucl. Phys. **A216,** 386 (1973).

[7] L. Tassan-Got and C. Stéfan, Nucl. Phys **A524,** 121 (1991).

[8] J. Gosset *et al.*: Phys. Rev. C **16,** 629 (1977).

[9] W. A. Friedman: Phys. Rev. C **27,** 569 (1983).

[10] J. -J. Gaimard and K. -H. Schmidt: Nucl. Phys. **A531,** 709 (1991).

[11] N. Matsuoka *et al.*: Nucl. Phys. **A311,** 173 (1978).

[12] D. K. Agnihotri *et al.:* Adv. Nucl. Dyn., **3,** 67, (1997).

[13] E. Holub *et al.:* Phys. Rev. C **28,** 252 (1983).

[14] M. Veselsky *et al.*: Phys. Rev. C **62,** 64613 (2000).

[15] G. Casini *et al.:* **nucl-ex/0010001.**

[16] G. A. Souliotis *et al.*: in preparation, see also G. A. Souliotis *et al.:* Phys. Rev. C **57,** 3129 (1998).

[17] R. J. Charity *et al.*: Nucl. Phys. **A483,** 371 (1988).