NON EQUILIBRIUM PARTICLE EMISSION IN NUCLEAR REACTIONS*

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When two nuclei collide, a large fraction of the excitation energy is dissipated through the emission of particles before reaching a state of statistical equilibrium. A theory of these processes based on the Boltzmann master equation approach is discussed. It is shown that it allows a comprehensive description of all the processes that may occur at incident energies of some ten MeV/nucleon.

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A large number of experimental data indicate the existence of a reaction mechanism intermediate in character between the direct processes which involve few nucleons and require short interaction times and the compound nucleus reactions in which the projectile energy is divided among a large number of nucleons in a completely statistical way and any further concentration of energy on one particle, which may be evaporated, requires very long times. All these intermediate processes are called *pre-compound* or *pre-equilibrium* reactions [1]. Perhaps the best illustration of the existence of this reaction mechanism is afforded by the spectra of particles emitted in a process initiated by an energetic projectile which show three distinct contributions: at low energies the Maxwellian peak corresponding to the particles evaporated from the compound nucleus, at the high energy end the monoenergetic peaks of direct transitions to discrete low-energy levels of the residual nucleus, and at intermediate energies the structureless contribution of pre-equilibrium emissions that displays a weak energy dependence and,

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for a particular projectile, does not notably depend on the target mass. The angular distributions of these particles are strongly forward-peaked, but lack any distinctive feature of the structure of the nuclei involved in the process that are present in the case of direct processes.

The guiding idea that influences all the attempts to describe these pre-equilibrium reactions is the hypothesis that the interaction of the projectile with the target can, at first, excite only states with a *simple* configuration, the *doorway* states. States of a somewhat more complex configuration, the *hallway* states, can then be excited from the doorway states by additional nucleon-nucleon interactions and, pursuing this chain of interactions, that henceforth we will call the *thermalization phase* of the reaction, one may finally reach a state of statistical equilibrium. The nature of the doorway states is not specified. They may be, for instance, particle-hole states or vibrational and rotational excitations. The former case raised the greatest interest and had an enormous influence on the development of pre-equilibrium theories. The nature of the doorway state affects in a peculiar way all the processes which occur during the thermalization phase.

Let us consider for simplicity the case of a reaction induced by a high energy nucleon. Initially, all the energy is concentrated on the incident nucleon and the target nucleus may be depicted as a Fermi gas in its ground state. Two-body nucleon-nucleon interactions lead to a spreading of the projectile energy among an increasing number of nucleons of ever decreasing energy. A nucleon emitted in a later stage of the thermalization cascade has, on the average, less energy than a nucleon emitted in a previous stage. The very asymmetric heavy ion interactions display an analogous feature: the spectrum of the nucleons emitted in a given time interval becomes softer and softer with increasing emission time.

Let us consider Fig. 1a where the angle integrated spectrum of neutrons emitted in the central collision of 25 MeV/Amu ^{12}C ions with ^{165}Ho is shown. Let us assume that both nuclei may be described as Fermi gases with Fermi energy of about 40 MeV. They move one against the other in the CM system of the composite nucleus with different energy. The average translational energy of the ^{12}C nucleons is about 22 MeV. Coupling the translational momentum with the internal momentum one gets a maximum initial nucleon kinetic energy of about 121 MeV inside the composite nucleus corresponding to a continuum energy of about 73 MeV which is quite near to the maximum energy of the observed spectrum. So, the hardest observed neutrons are emitted at the beginning of the thermalization phase. A completely different situation occurs when one considers a symmetric heavy ion interaction as shown in Fig. 1b. In this case the incident ^{40}Ar ion energy is 20 MeV/Amu and, repeating the previous calculation, one finds a maximum initial kinetic energy in the continuum of about 20 MeV, much

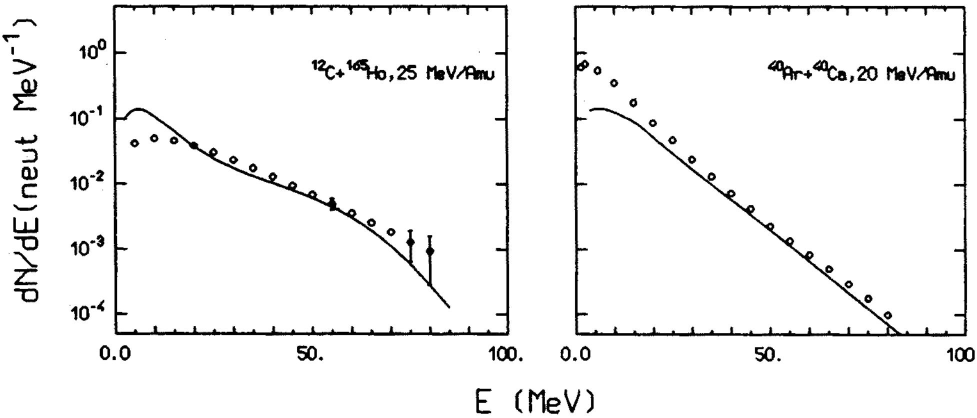

Fig. 1. Experimental [2,3] (open circles) and theoretical (solid lines) spectra of neutrons emitted in an asymmetric and a symmetric heavy ion interaction. In both cases the comparison between experiment and theory is meaningful only for emission energies exceeding approximately 20 MeV. In fact, the experimental spectrum of neutrons from $^{12}C+^{165}Ho$ includes only the contribution of pre-equilibrium neutrons, while the theoretical spectrum, which includes all the neutrons emitted up to $5 \cdot 10^{-22}$ s, presumably includes also neutrons emitted at the beginning of the evaporation chain. On the contrary, the experimental spectrum of neutrons from $^{40}Ca+^{40}Ar$ includes also the contribution of evaporated neutrons while the theoretical spectrum, which also includes all the neutrons emitted up to $5 \cdot 10^{-22}$ s, does not account for most of evaporated neutrons.

smaller than the observed one. This means that during the thermalization cascade the nucleons gain energy. The different behaviour is related to the different doorway states in these two heavy ion reactions. In the first case the initial excitation energy of the composite nucleus is essentially concentrated on the projectile nucleons which interact with the target nucleons with energy mainly below the Fermi energy, and thus may only lose energy. In the second case the energy of the excited composite nucleus is initially shared also among a considerable number of deep holes. They may have energy more than 20 MeV smaller than the Fermi energy and are progressively filled in the course of the thermalization cascade since when one reaches the statistical equilibrium the average energy of the particles and the holes is about 5 MeV (this estimate is made considering that about one half of the excitation energy is dissipated during the thermalization phase as it will be shown later). Each time a nucleon fills a deep hole after a two nucleon interaction, the interaction partner gains energy and may be emitted into the continuum with increased energy. It may seem strange to speak of a doorway state to describe the initial state of the composite nucleus when two nuclei collide. However, this initial state has still a much simpler configuration than the equilibrated nuclei. In this initial state the motion of the excited nucleons is highly correlated and only during the thermalization phase randomizes. Part of the excitation energy is dissipated by the emitted pre-equilibrium particles, part transforms into thermal energy left to an equilibrated residue.

The previous discussion shows the need for a microscopic description of the thermalization phase. To do that in a first order approximation one may describe the two interacting nuclei as two Fermi gases with equal Fermi energy. In the Thomas-Fermi approximation, for incompressible nuclear matter and volume conserving deformations, the density of states of the nucleons bound in a potential well does not change appreciably for different contour shapes of the mean field. The time evolution of the di-nuclear system (the composite nucleus) which forms when the two ions overlap may be described evaluating, by means of a set of coupled Boltzmann master equations, the time variation of the nucleon energy distribution [4–6]. To do that, in an Eulerian description, one introduces a set of equispaced energy bins. The number N_i of nucleons within each of these bins is given by the product of an occupation number $0 \leq n_i \leq 1$, times the total number g_i of the states of the bin. The occupation numbers vary with time as a consequence of the rearrangement of nucleon energies which follows the nucleon-nucleon interactions and of the emission into the continuum of unbound nucleons and clusters of nucleons. This variation is evaluated by solving the set of master equations that, in the case of the protons occupation numbers, are

$$\begin{aligned}\frac{d(n_i g_i)^\pi}{dt} &= \sum_{jlm}[\omega^{\pi\pi}_{lm\to ij} g^\pi_l n^\pi_l g^\pi_m n^\pi_m (1-n^\pi_i)(1-n^\pi_j) \\ &\quad - \omega^{\pi\pi}_{ij\to lm} g^\pi_i n^\pi_i g^\pi_j n^\pi_j (1-n^\pi_l)(1-n^\pi_m)] \\ &\quad + \sum_{jlm}[\omega^{\pi\nu}_{lm\to ij} g^\pi_l n^\pi_l g^\nu_m n^\nu_m (1-n^\pi_i)(1-n^\nu_j) \\ &\quad - \omega^{\pi\nu}_{ij\to lm} g^\pi_i n^\pi_i g^\nu_j n^\nu_j (1-n^\pi_l)(1-n^\nu_m)] - \frac{dN^\pi(\epsilon_i)}{dt} - \frac{dD^\pi(\epsilon_i)}{dt},\end{aligned} \tag{1}$$

where π and ν stand for the proton and the neutron, respectively.

The decay rates $\omega_{ij\to lm}$ describe the scattering of nucleons in bins i and j to bins l and m, $dN^\pi(\epsilon_i)/dt$ is the decay rate for emission of protons into the continuum and $dD^\pi(\epsilon_i)/dt$ is the depletion rate which takes into account the emission of protons bound in clusters. How to evaluate these quantities is discussed in Refs [5, 6]. The set of equations corresponding to neutron occupation numbers is easily written with obvious substitutions.

As discussed above, the time evolution of the occupation numbers critically depends on the initial energy distribution of the nucleons of the composite nucleus. A simple and reasonably accurate way of evaluating this distribution is the coupling of the translational and internal momenta of the nucleons of the two interacting ions. The result one obtains is in good agreement with that obtained by solving the Boltzmann–Nordheim–Vlasov equation up to the time corresponding to the overlapping of the interacting ions.

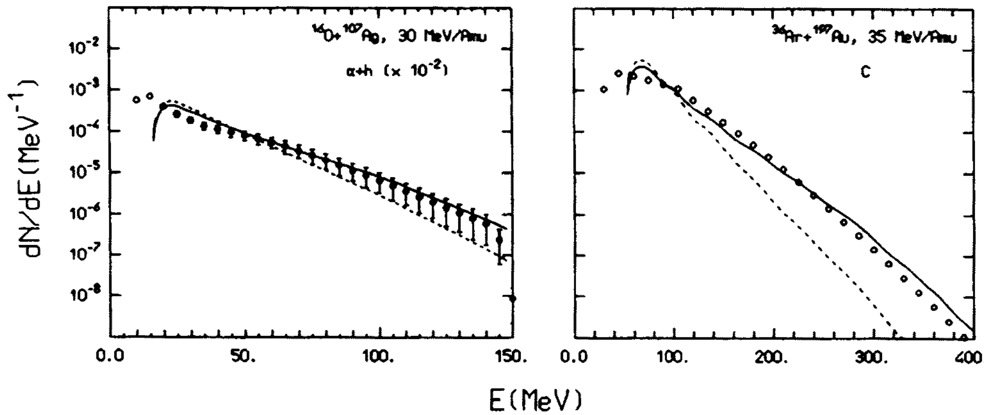

Fig. 2. Experimental [7,8] and theoretical spectra of helions and C fragments emitted in central collisions of the heavy ions given in the figure. The full lines show the results of the calculation for anisotropic initial momentum distributions corresponding to the coupling of the translational and internal momenta of the projectile and target nucleons. The dashed lines show the results corresponding to isotropic momentum distributions from the beginning of the thermalization cascade.

A novelty of our calculations is the consideration of the possible decay of the composite nucleus by emission of clusters. This occurs because A_c nucleons, with correlated momenta, and a Fermi distribution around the momentum per nucleon of the cluster centre of mass, may be at a given time near the nuclear surface and thus may be emitted at a rate which depends on the cluster translational energy and the height of the Coulomb barrier. In [6] it is shown how the probability of finding A_c nucleons with correlated momenta and of the right type to form a given cluster depends on the nucleon occupation numbers and how the depletion of nucleon bins which results from the emission of clusters into the continuum may be evaluated. It may be shown that the probability of finding A_c nucleons with correlated momenta depends on the nucleon momentum space density distribution. Fig. 2 shows the comparison of the experimental spectra of α-particles and C fragments emitted in heavy ion interactions [7, 8] with those calculated for an isotropic nucleon momentum distribution from the beginning of the thermalization phase (dashed lines), and for the anisotropic initial distribu-

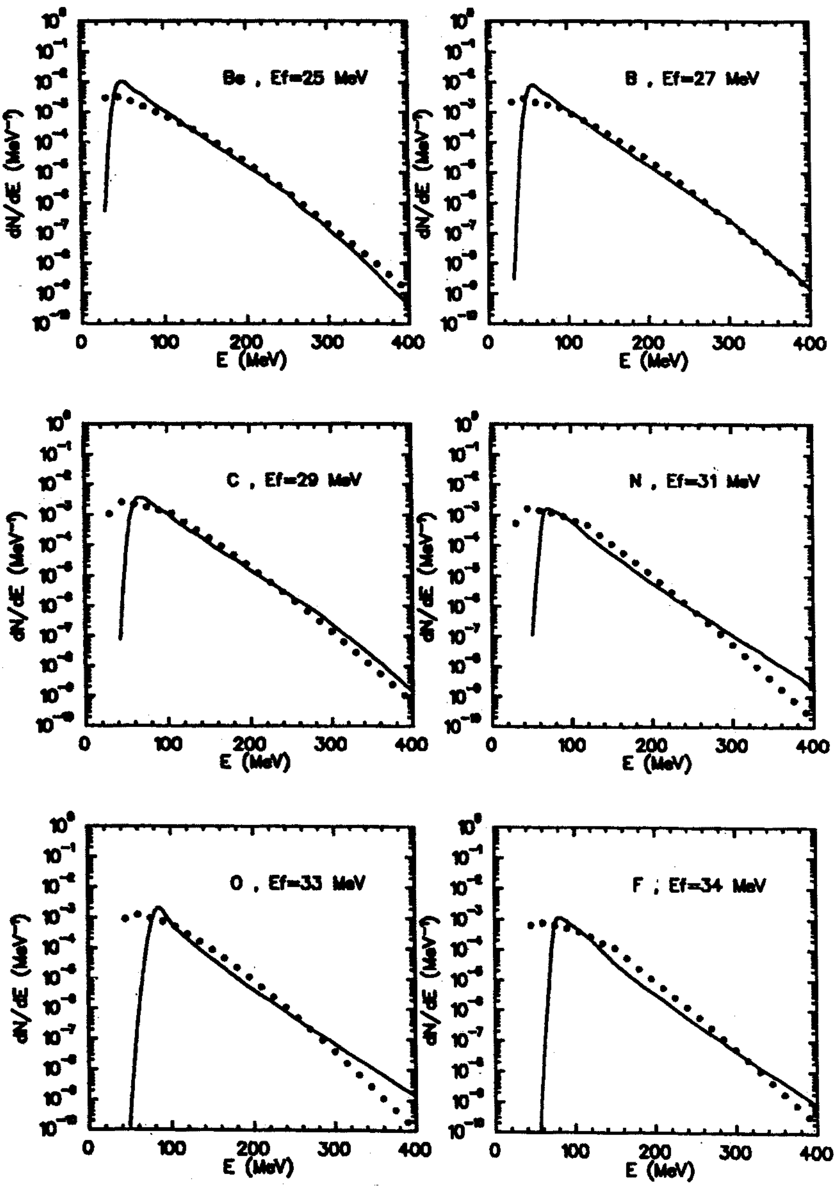

Fig. 3. Angle integrated centre of mass multiplicity spectra of IMF emitted in central collisions of ^{36}Ar with ^{197}Au at 35 MeV/Amu incident energy. The experimental values [8] are given by solid dots, the theoretical spectra by the full lines. The Fermi energies of the IMF are given in the figure.

tion with forward peaked momenta which occurs when the two ions overlap (solid lines). As one may see, the initial anisotropic distribution hardens substantially the cluster spectra the more as the cluster mass increases.

This result shows the influence of the initial doorway state on the time evolution of the composite system and, since after a few steps of the thermalization cascade the calculated spectra become independent of the angular distribution of the nucleon momenta, suggests that emission of energetic clusters occurs in a short time after the overlapping of the two ions, in agreement with the findings of correlation experiments [9, 10]. We feel that the pre-equilibrium heavy clusters (intermediate mass fragments) are emitted in their ground state or with a little excitation since they are emitted in a short time, when the composite nucleus is still far from equilibration and the momenta of the nucleons of the cluster are still highly correlated, mainly contributing to the cluster translational kinetic energy.

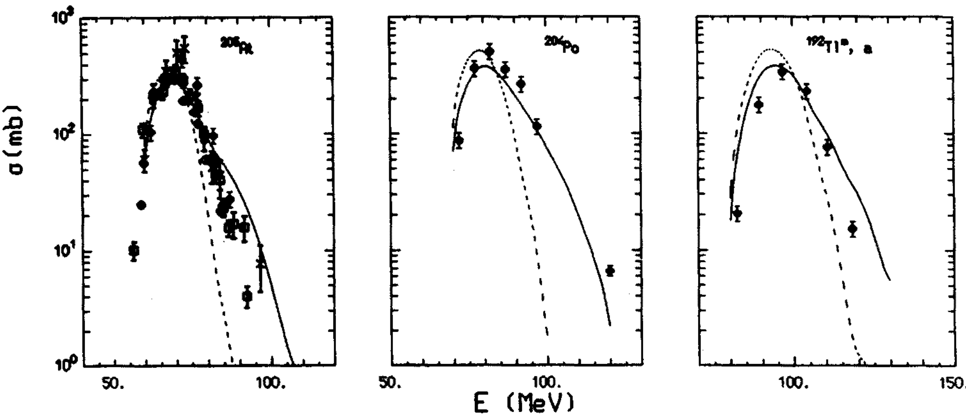

Fig. 4. Experimental [13-16] and theoretical excitation functions for production of (a) ^{205}At and ^{204}Po in the interaction of ^{12}C ions with ^{197}Au and (b) ^{192}Tl^m in the interaction of ^{16}O ions with ^{181}Ta. The solid lines show the result of the calculation made including the emission of pre-equilibrium nucleons as predicted by (1), the dashed lines show the results of calculations neglecting the emission of pre-equilibrium nucleons.

The model we have briefly described allows a unified description of a large number of processes, ranging from nucleon-induced reactions up to symmetric heavy ion interactions, in a large interval of incident energies using essentially as free parameters only the Fermi energies of the different clusters. Moreover, these values are not arbitrary, but vary with the cluster mass A_c as expected from surface corrections to the Fermi gas model. Other quantities which enter as parameters in the calculations, as the binding energies or the Coulomb barriers, are either the experimental values or values commonly reported in literature. The *survival factors* $\mathcal{R}_c$ which multiply the formation probability of the clusters and are introduced to limit the presence of the clusters at the nuclear surface, are approximately equal to the ratio between the volume of the surface layer and the total nuclear volume. The neutron spectra shown in Fig. 1 and the α and C fragment spectra shown in Fig. 2 are typical results one gets with these calculations. Experimental and calculated spectra of intermediate mass fragments emitted in the interaction of 35 MeV/Amu ^{36}Ar ions with ^{197}Au are compared in Fig. 3. All these are spectra of particles emitted in central heavy ion interactions, however, the same theory has been used, with a suitable initial condition, to describe the spectra of neutrons emitted in peripheral incomplete fusion processes with satisfactory results [11].

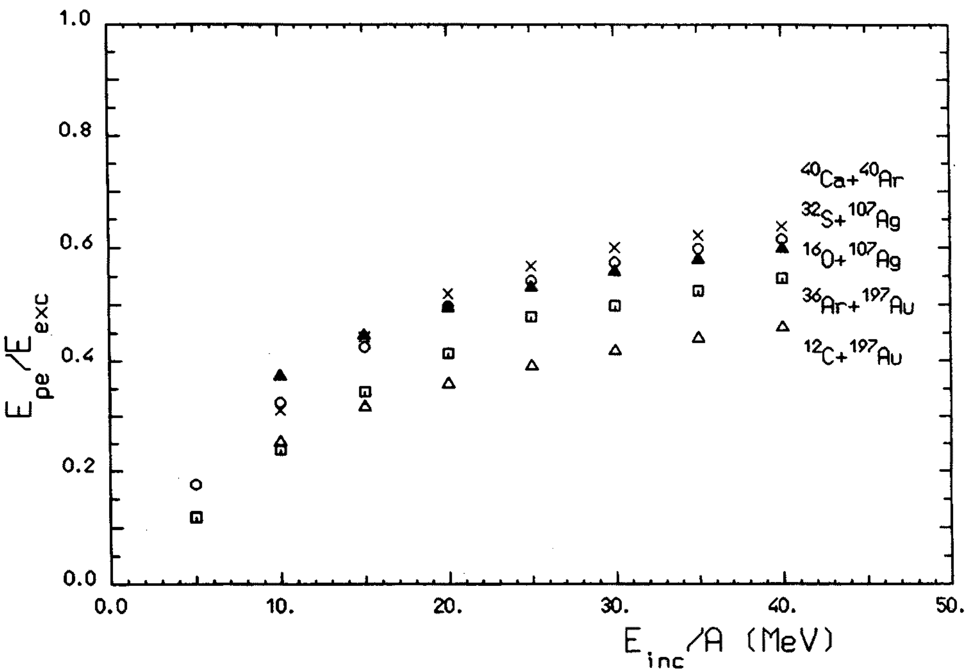

Fig. 5. Predicted fraction of the excitation energy dissipated by emission of pre-equilibrium particles in the central collision of the heavy ions given in the figure. The pre-equilibrium particles are emitted in a time smaller than 3 10^{-22} s.

One may ask at what energies the emission of pre-equilibrium particles starts to be relevant, what is the emission time of pre-equilibrium particles and how much these emissions contribute to the dissipation of the composite nucleus excitation energy. The excitation functions of several heavy ion reactions at bombarding energies of less than 10 MeV/Amu are broader than expected in the case of a purely evaporative contribution and may be satisfactorily reproduced only if the emission of pre-equilibrium nucleons is taken into account [12]. Typical examples are shown in Fig. 4.

The hardest part of the calculated pre-equilibrium particle spectra saturates in a quite short time which may be defined as the pre-equilibrium emission time. For heavy ion interactions, at incident energies up to some ten MeV/Amu, this time is typically of the order of $3\ 10^{-22}$ s. With increasing bombarding energy an ever increasing fraction of the excitation energy is predicted to be carried out by the pre-equilibrium particles, as shown in Fig. 5, greatly reducing the probability of forming very excited equilibrated systems. This is perhaps the most obvious proof of the paramount importance of pre-equilibrium emissions and of the need of an accurate prediction of these phenomena.

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