Cluster production and nuclear dynamics

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Abstract. In this contribution we will briefly illustrate some general aspects related to the cluster production in heavy ion collisions. They concern the necessary interplay between effective interaction and the description of the cluster formation processes in Molecular dynamics approaches and the time scales separation in Isospin equilibration processes.

1. Introduction
Clustering in nuclei, at the ground state and relatively low excitation energy, is a phenomenon which characterizes the structure of several light nuclei and highlights the role played by the many body correlations and symmetries in nuclear systems [1, 2, 3]. But, clusters and the related formation processes, play a central role also in heavy ion collisions and in astrophysical phenomena in which densities and excitation energies can reach rather high values. In this contribution we want to focus on two aspects in which the mechanism of the reaggregation of nucleons in to cluster, after a violent heavy ion collision, can give information on the behavior of the effective interactions describing and modeling the dynamics in a wide range of densities and excitation energies. In the following section we will try to describe the way in which the necessary correlations introduced in the model, able to produce clusters, affect the parameter values characterizing one of the more widely used effective interaction, the Skyrme one. For this purpose we use the Constrained Molecular Dynamical Model (CoMD)[4, 5]. In section 3 we will show that by looking at the cluster production from an heavy ion collision in a global and "coherent way" it is possible to access in an exclusive way to the early stages of the dynamics of the collision processes. Also in this case other information can be still obtained concerning the effective interaction.

2. Wave-Packets dynamics and Effective interaction.
In heavy ion collision at the Fermi Energy and beyond, the production of light clusters is the most intense cooling mechanism. Every theoretical approach aiming to describe the dynamics of the reactions in a reasonable way has necessarily to describe in some way the nucleon aggregation processes. Moreover, if the description, how desirable, needs to be related directly with the nucleon-nucleon effective interaction it has to be necessarily time dependent on one hand and, on the other, the used approach has to go beyond the mean-field approximation (MFA) just to describe the cluster formation processes. Such approaches due to the extreme complexity of the problem will be necessarily semi-classical. A rather wide class of them is represented by the so called Molecular Dynamics models. All these approaches, which are different from each other for the way in which quantal effects are eventually introduced, are characterized by...
the usage of well localized wave-packets to represent the single particles wave functions. It is just this assumption which allows the spontaneous formation of clusters in this kind of models. Concerning the microscopic interaction usually these models use however an effective interaction, like the Skyrme, Gogny, whose strength factors are determined through calculations based on the MFA. Recently [6] this aspect has been investigated in some detail by means of the CoMD model in which Pauli principle is fulfilled at each time step by constraining the N-body equation of motion through a well established numerical algorithm. We start this investigation by studying a relatively simply case: we have studied the Equation of State of the asymmetric Nuclear Matter (NM) around the saturation density by means of the dynamical model, starting from a typical Skyrme interaction containing two and three body interaction plus the iso-vectorial one described by different density functionals. Through an iterative procedure the total energy functional obtained by the model has been determined in such a way to obtain commonly accepted saturation properties $\rho_0 = 0.16 fm^{-3}$, $K_0 \simeq 220 MeV$. From this condition, a new set of parameters depending on the degree of stiffness of the iso-vectorial interaction has been found ($T_0 \simeq -159 MeV$ and $T_3 \simeq 57 MeV$ for $\gamma = 1$). The values of these parameters are rather different from the ones corresponding to the mean-field limit $T_0 \simeq -263 MeV$ and $T_3 \simeq 208 MeV$ and independent on $\gamma$. In figure 1 in panel a) we show the total energy $E$ for symmetric NM as a function of the density computed by the model by using an effective Skyrme interaction with standard parameters values as obtained from the semiclassical MFA approach. Different kind of lines refers to different option concerning the iso-vectorial interaction. It is evident that the nuclear matter properties at the saturation in these cases are not reproduced. In the panel b) we plot the so called $E_{bias}$. This terms arises just from the iso-vectorial interaction coupled in a self-consistent way with the Pauli principle for which, on average, neutron-proton tend to stay closer with respect to neutron-neutron and proton-proton (deuteron effect). In figure 2 instead we report the obtained results concerning the total energy after the convergency of the iterative procedure which fixes the new set of parameters. A shown in [6] the reasons of this strong differences acting already at density near the saturation one, are related to the spacial correlation introduced by the usage of the Gaussian wave packets. Therefore such results acquire a more general meaning being strictly linked to the cluster formation process and should be investigated also at different densities and in the framework of others approaches.

3. Cluster production and pre-equilibrium effects.
It is well known that that the time related to the heavy ion dynamics extend in a rather wide range of times typically, at the Fermi energy, from $10^{-23} sec$ to $10^{-15} sec$. On the other hand only in the first stages of the reaction the total system experiences the extreme conditions of density and excitation energies. In our scopes the selection of information strictly linked with the first moment of the interaction is therefore of fundamental importance. Usually the complex scenario involving the time evolution is managed by interpreting the obtained results through a weighted sum of quantities obtained from pre-equilibrium models and statistical ones. This last one in general tends to blurry more or less the dynamical effects on the yields of cluster distributions and their correlations. As examples of this unwanted interplay we can quote [7, 8].

In this regard we note that the global and coherent cluster productions can be investigated by looking at the behavior of the following quantity:

$$\langle \vec{D} \rangle = \langle \sum_{i=1}^{m} Z_i (\vec{V}_i - \vec{V}_{c.m.}) \rangle_K. \quad (1)$$

The brackets indicate the average value over the ensemble $K$. $Z_i$, $V_i$, $m$ are the charges, laboratory velocities, charged particle multiplicity respectively of the produced particles in the selected class of events, respectively. Finally $\vec{V}_{c.m.}$ is the center of mass (c.m.)velocity. The interest on this quantity is triggered by two main reasons:
Figure 1. panel a: Total energy per nucleon E for symmetric NM as a function of the reduced density. The solid line represents the results obtained through the semiclassical-MFA. With discontinuous lines we plot the results for CoMD-II calculations corresponding to the first step of the iterative procedure (see the text). panel b: for the same parameter values the values of $E_{bias}$ (see the text) are plotted as a function of the reduced density.

Figure 2. Total energy as a function of the reduced density after the iterative procedure applied to CoMD-II calculations.

-a) because of the symmetries of the statistical decay mode, $\langle \vec{D} \rangle$ is not affected by the statistical emission of all the produced sources in later stages, as it is shown in Ref. [9]. This essentially happens because, due to the vectorial kinematical character of this quantity, for well reconstructed events statistical effects are self-averaged to zero. Therefore $\langle \vec{D} \rangle$ is a rather well suited global variable to selectively evidence dynamical effects related to the Isospin equilibration process;

-b) as shown in Refs [9, 10] this quantity is closely linked with charge/mass equilibration process because it represents the average time derivative of the total dipolar signal in the asymptotic stage (expressed in unit of $e$).

Recently the experimental investigation on this subject was realized for the first time on
the $^{48}$Ca + $^{27}$Al system at 40 MeV/A with the multi-detector CHIMERA [11] at the LNS laboratories [12]. In this first stage of investigation we have measured the effective partial signal dipolar signal $\langle D_2^Z \rangle$ along the beam axis. In this quantity, to eliminate the indetermination associated to systematic errors on the velocities, the true center of mass velocity has been substituted with the ones associated to the subsystem formed by all the charged particles. In

![Graph](image-url)

**Figure 3.** Experimental values of the effective dipolar signal for the $^{48}$Ca + $^{27}$Al at 40 MeV compare with CoMD-III calculations for different stiffness values of the symmetry energy.

In figure 3 we show with red points $\langle D_2^Z \rangle$ as a function of the charge of the biggest fragment $Z_b$ for a total kinetic energy loss less than 350 MeV. In the different panels we show with black points the calculated value according to CoMD-III [12] calculations. The comparison allows to establish a good agreement with experimental data for an iso-vectorial stiffness parameter $\gamma \simeq 1$. Some efforts will be necessary in the next future to evaluate systematic errors on the velocity measurements by studying symmetrical systems, this will allow to reconstruct the total signal including the effect related to the neutrons. We conclude by noting that taking advantage of the today large efficiency multi-detectors, further investigation on this subject performed for more central events and higher energy aimed will contribute to a clear identification of the isospin dynamical effects and a more accurate study of the related effective interaction.

**References**

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