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Isospin equilibration processes and dipolar signals: Coherent cluster production

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Summary. — The total dipolar signal related to multi-break-up processes induced on the system ^{48}Ca + ^{27}Al at 40 MeV/nucleon has been investigated with the CHIMERA multi-detector. Experimental data related to semi-peripheral collisions are shown and compared with CoMD-III calculations. The strong connection between the dipolar signal as obtained from the detected fragments and the dynamics of the isospin equilibration processes is also shortly discussed.

1. – Introduction

The experimental evidences on Heavy-Ion Collisions highlight, in different ways, processes which evolve on different time scales. At Fermi energies, semi-classical dynamical models cannot describe the system during its overall time evolution. As an example the average life time for neutron emission of a source at a temperature $T = 2\,\mathrm{MeV}$ can be estimated of the order of $\tau_n \simeq 2500\,\mathrm{fm/c}$. The observed data needs to be interpreted phenomenological through a fast pre-equilibrium stage described using dynamical models, and later-stage processes described by statistical decay models. Different densities and excitation energies are explored in these time intervals and therefore the measured observable associated to the yields of particles and fragments are always affected by both the mechanisms. Consequently the information concerning the interaction at densities different from the saturation one can be in general blurred through final stage effects. Some examples of these interplays have been discussed in [1-3]. They concern the studies of isospin effects on nuclear level densities, the iso-scaling parameter from isotopic distribution and the sideward flow around the balance energy. Taking full advantage (as much as possible) of the today's high-efficiency multi-detectors, the attempt to measure observable in principle closely linked to only one of the two regimes is therefore highly desirable.

2. – The dipolar signal

By using the charge an velocity of the different produced fragments a rather interesting observable evaluated for well reconstructed events, is the following quantity:

$$\langle \overrightarrow{D} \rangle = \langle \sum_{i=1}^{m} Z_i (\overrightarrow{V}_i - \overrightarrow{V}_{c.m.}) \rangle_{\mathcal{K}}. \qquad (1)$$

The brackets indicate the average value over the ensemble $\mathcal{K}$. 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 $\overrightarrow{V}_{c.m.}$ is the center of mass (c.m.) velocity. We note that in this expression the contribution of produced neutral particles is implicitly contained in $\overrightarrow{V}_{c.m.}$. The interest on this quantity was triggered by two main reasons:

a) As shown in ref. [4] 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). In particular, it can be expressed as an average value of the isotopic distribution weighted with the related average momentum [4, 5]. In fact, as an example, for binary systems, in the absence of dynamical neutron-proton collective motion we have $\langle \overrightarrow{D} \rangle \equiv \overrightarrow{D}_m = \frac{1}{2}\langle \mu \rangle (\langle \beta_2 \rangle - \langle \beta_1 \rangle)(\langle \overrightarrow{V}_1 - \overrightarrow{V}_2 \rangle)$. μ is the reduced mass number of the system, β_1, β_2 are the isospin asymmetries of the two partners 1 and 2 and finally $\overrightarrow{V}_1$ and $\overrightarrow{V}_2$ the related velocities. In the above expression we have supposed negligible the correlation of fluctuations between charge/mass ratios of the partners and their relative velocity. On the other limit, the same quantity is zero if evaluated for a system represented by an equilibrated source before or after the statistical decay. As shown from dynamical microscopic calculations in a collision process between two nuclei having different charge/mass asymmetries, $\mid \langle \overrightarrow{D} \rangle \mid$ changes during the time towards smaller values in the pre-equilibrium stage (spontaneous approach to the equilibrium) producing γ-ray emission through the excitation of a more or less damped dipolar dynamical mode [4, 5].

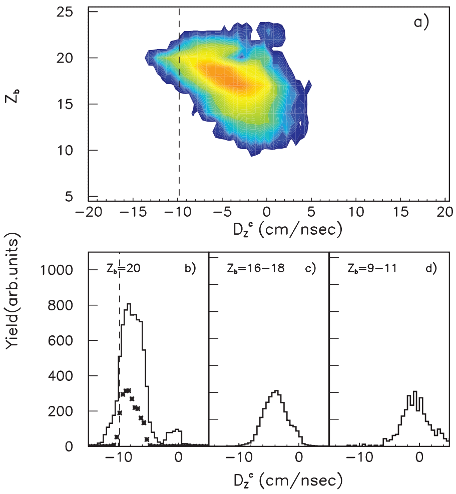

Fig. 1. – Panel (a): For the system ^{48}Ca + ^{27}Al at 40 MeV/nucleon the measured values of D_Z^c are plotted for different Z_b associated to the selected events (charged multiplicity $m \geq 2$). The dashed vertical line indicates the reference limiting values D_m (see the text). Panels (b), (c), (d): D_Z^c distributions obtained as projection of the above bi-dimensional plot for different Z_b intervals. In panel (b) the D_Z^c spectrum for $Z_b = 20$ and for quasi-elastic events TKEL < 70 MeV is plotted with star symbols.

b) Because of the symmetries of the statistical decay mode, $\langle \overrightarrow{D} \rangle$ is not affected by the statistical emission of all the produced sources in later stages. This essentially happens because, due to the vectorial kinematical character of this quantity, for well reconstructed events statistical effects by definition are self-averaged to zero. Therefore $\langle \overrightarrow{D} \rangle$ is a rather well suited global variable to selectively evidence dynamical effects related to the isospin equilibration process. All these feature allows to unambiguously relate $\langle \overrightarrow{D} \rangle$ to the dynamics of the isospin equilibration processes.

3. – Experimental results and comparison with model calculations

Recently, the experimental investigation on this subject [6] was realized for the first time on the ^{48}Ca+^{27}Al system at 40 MeV/A with the multi-detector CHIMERA [7-9] at the LNS laboratories. In this first stage of investigation we have measured the effective partial dipolar signal $\langle D_Z^c \rangle$ 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. As an example in fig. 1 (panel (a)), for the main system, we show the correlation plot Z_b *vs.* D_Z^c for the selected events. Z_b represents the atomic number of the biggest fragment. The ridge in the plot highlights an increasing trend of $\langle D_Z^c \rangle$ going from negative values to almost zero for decreasing values of Z_b respect to Z_{PLF}.

We note that according to the expression given for D_m, in the initial configuration the system should exhibit a limiting value of $\langle D_Z^c \rangle$ (grazing collisions) close to about -9.8 cm/ns.

The increasing average values of $\langle D_Z^c \rangle$ for Z_b different from projectile atomic number (less peripheral collision), represents a clear signature of the evolution through

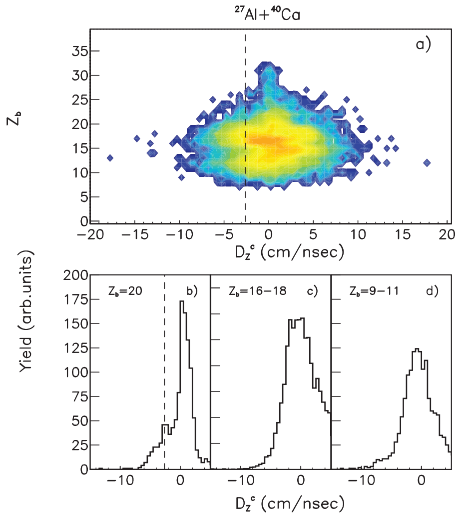

Fig. 2. – Same as fig. 1 but for the reference system $^{27}\mathrm{Al} + {}^{40}\mathrm{Ca}$.

charge/mass equilibration values (see next section). The limiting value corresponding to almost "grazing" collisions (along the beam axis), is evidenced in fig. 1 by dashed vertical lines. Panels (b), (c) and (d) show the projections of the bi-dimensional plot for different intervals of Z_b and we can clearly see the trend of $\langle D_Z^c \rangle$. In particular, in panel (b) the spectrum with star symbols is obtained by imposing a value of TKEL < 70 MeV typical for quasi-elastic processes. The large fluctuations of D_Z^c around the average value are due to physical reasons (the particular "history" of each event) and to the measurement procedure. In fig. 2 we show analogous plots for the reference isospin quasi-symmetric system $^{27}\mathrm{Al} + {}^{40}\mathrm{Ca}$ at 40 MeV/nucleon. In this case the limiting value for "grazing" collision, D_m is about -2.6 cm/ns and, how can be clearly seen, the experimental plots show values close to zero and an enhancement near the D_m value (fig. 1(b)). The check on this system as compared to the main one ensures a good level of confidence in the determination of $\langle D_Z^c \rangle$. Global results are given in fig. 3 where we show with red points $\langle D_Z^c \rangle$ as a function of 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 [6, 10] calculations.

The comparison allows to establish a good agreement with experimental data for an iso-vectorial stiffness parameter $\gamma \simeq 1$. At this level of investigation, due to the lack of direct information about possible systematic error on the velocity measurements, we have discussed the behavior of $\overline{D_Z^c}$ which shows a good sensitivity to the parameters of the effective interaction. To recover information on the global degree of isospin equilibration we can evaluate $\overline{D_Z}$ through calculations by using the same set of parameters which "best fit" the experimental value of $\overline{D_Z^c}$. In fig. 4, we compare the calculated values of $\overline{D_Z}$ for $\gamma = 1$ with CoMD-II+GEMINI (including the efficiency effect) with the experimental values $\overline{D_Z^c}$. The connection between the two quantities can be approximated by the following simple relation: $\overline{D_Z} \cong \overline{D_Z^c} + Z_{tot}^d(\overline{V_{c.m.,c}^Z} - V_{c.m.})$ where $\overline{V_{c.m.,c}^Z}$ is the c.m. velocity for the subsystem of the charged particles. Therefore the difference between $\overline{D_Z}$ and $\overline{D_Z^c}$ (red and black points in fig. 4) gives us an estimation of the effect associated

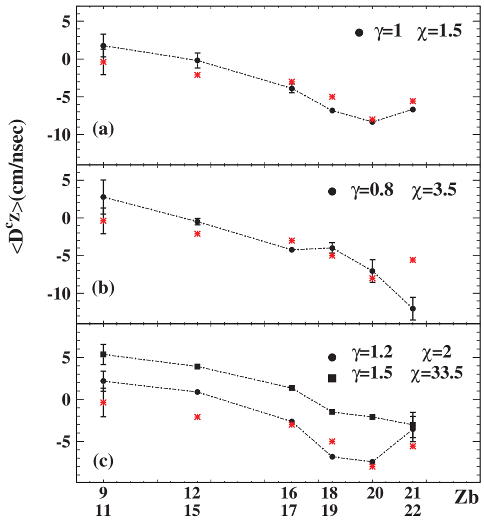

Fig. 3. – Experimental values of the effective dipolar signal for the ^{48}Ca + ^{27}Al at 40 MeV compare with CoMD-III calculations for different stiffness values of the symmetry energy.

to the undetected free neutrons which clearly participate in to determining the global degree of isospin equilibration. More experimental investigation should involve different systems and different reaction mechanisms. In particular, a next step forward in this kind of measurements would require a more detailed investigation including a reliable valuation and/or minimizations of possible systematic errors on the velocity of the produced charged particles. This would permit a reliable experimental estimation of $\langle D_Z \rangle$ allowing also for a corresponding experimental valuation of the global effect associated to the dynamically emitted neutrons. For this purpose long measurements involving targets and projectiles having the same charge/mass asymmetry (vanishing values of $\langle D_Z \rangle$

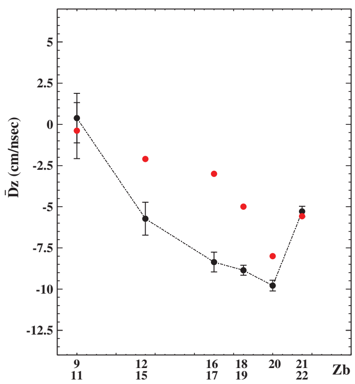

Fig. 4. – The calculated values of $\overline{D_Z}$ for $\gamma = 1$ are compared to the experimental values for $\overline{D_Z^c}$. The error bars represent statistical uncertainties due to the simulations. The estimated uncertainties related to the experimental values $\overline{D_Z^c}$ are in many cases smaller than the plotted symbols.

independently from the reaction mechanism) are could be very useful. A more detailed analysis could also allow to estimate the specific contribution to the equilibration process produced by the prompt and mid-rapidity emission as compared to the transfer of charge/mass between the main partners.

REFERENCES

[1] BRONDI M. *et al.*, *EPJ Web of Conferences*, **2** (2010) 04002.
[2] ZHOU P., TIAN W. D., MA Y. G., CAI X. Z., FANG D. Q. and WANG H. W., *Phys. Rev. C*, **84** (2011) 036705.
[3] CUSSOL D. *et al.*, *Phys. Rev. C*, **65** (2002) 044604.
[4] PAPA M. *et al.*, *Phys. Rev. C*, **72** (2005) 064608.
[5] GIULIANI G. and PAPA M., *Phys. Rev. C*, **73** (2006) 031601R.
[6] PAPA M. *et al.*, *Phys. Rev. C*, **91** (2015) 041601R.
[7] PAGANO A., *Nucl. Phys. News*, **22** (2012) 25.
[8] LOMBARDO I. *et al.*, *Nucl. Phys. A*, **834** (2010) 458c.
[9] CARDELLA G. *et al.*, *Phys. Rev. C*, **85** (2012) 064609.
[10] PAPA M., MARUYAMA T. and BONASERA A., *Phys. Rev. C*, **64** (2001) 024612.