Isospin Dynamics and Dipolar degrees of freedom in Heavy Ion collisions

Massimo Papa[1,*], *Concettina* Maiolino[2], *Luis* Acosta[3], *Giuseppe* Cardella[1], *Enrico* De Filippo[1], *Elena* Geraci[4,1], *Brunilde* Gnoffo[1], *Chiara* Guazzoni[5], *Nunzia* Martorana[4,2], *Angelo* Pagano[1], *Emanuele Vincenzo* Pagano[2], *Sara* Pirrone[1], *Giuseppe* Politi[4,1], *Lucia* Quattrocchi[6], *Fabio* Risitano[6,2], *Francesca* Rizzo[4,2], *Paolo* Russotto[2], *Marina* Trimarchi[6,1], and *Cristina* Zagami[7,4,2]

[1]INFN, Sezione di Catania, Italy
[2]INFN, Laboratori Nazionali del Sud - Catania, Italy
[3]Instituto de Física. Universidad Nacional Autónoma de México, Mexico, Instituto de Estructura de la Materia, CSIC, Spain.
[4]Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Italy
[5]Dipartimento di Elettronica Informazione e Bioingegneria Politecnico Milano and INFN Sez. Milano, Milano, Italy
[6]Dipartimento di Scienze MIFT, Univ. di Messina, Messina, Italy
[7]CSFNSM-Centro Siciliano di Fisica Nucleare e Struttura della Materia, Catania, Italy

Abstract. In this contribution the connection between the Dipolar degree of freedom excited in Heavy Ion Collisions through pre-equilibrium dipolar modes and the Isospin-equilibration processes is discussed. The connection leads to the definition of a new observable the so called "dipolar signal", able to describe the equilibration process in the momentum space related to the final fragmentation produced by the HIC. Preliminary results on this observable measured on the system $^{48}Ca + ^{27}Al$ at 40 MeV/nucleon and corresponding to different degrees of dissipation/centrality are presented. The beam was accelerated through the Superconductor Cyclotron at the Laboratori Nazionali del Sud di Catania (Italy) and fragments were detected and identified with the 4π multi-detector CHIMERA.

1 Introduction

One of the main goals in studying Heavy Ion Collisions (HIC) is to obtain information about the nuclear matter equation of state (EoS) at densities different from the saturation one. The relevance of this information is also due to the fact that the symmetry energy plays a fundamental role in describing matter within neutron stars (NS) including NS mergers and core collapse supernovae [1]. The so-called isospin equilibration phenomenon that is triggered by means of HIC performed by impinging nuclei having different charge/mass asymmetry naturally depends on the symmetry energy. In particular, in the hydrodynamical limit [2, 3], the flux of neutrons with respect to that of protons is the sum of two main contributions associated with the density and concentration gradients i.e. the isospin drift and the diffusion term.

*e-mail: Massimo.Papa@ct.infn.it

The related strength coefficients explicitly depend on the symmetry energy and on its density gradient respectively [2]. Up to now the isospin equilibration process has been investigated by focusing mainly on the diffusion term. Similar systems but with projectiles (PR) and targets (TA) having different charge/mass asymmetry have been studied around the Fermi energy. Observables related to the isotopic yields have been compared using the so called Isospin Transport Ratio [4–6]. In [7] a new alternative method was proposed based on the measurement of the so called "dipolar signal". As it will be discussed in the next sections, the method is able in principle to integrate the information obtained from the Isospin Transport Ratios studies. In Sect. 3 are also shown preliminary results of an analysis on experimental data collected to investigate on the global dynamics of this equilibration process in the system $^{48}Ca +^{27} Al$ at 40 MeV/nucleon. The measurement was performed with the CHIMERA multi-detector at Laboratori Nazionali del Sud di Catania (Italy). Sect. 4 contains the final remarks.

2 Dipolar degrees of freedom and the Isospin equilibration processes

In this section a simple connection between the dipolar degrees of freedom in HIC and the isospin equilibration process will be established.

As it is well known, the excitation of dipolar degree of freedom in nuclei is associated with one of the most investigated collective motion in nuclei, i.e. the Giant Dipolar Resonances (GDR) [8]. As for other electromagnetic excitations, it can be built-in on every excited state. The possibility of its survival (finite damping) even at high temperatures has been a long-lasting field of investigation [9]. According to the liquid drop model, this mode can be described from a macroscopic point of view as harmonic oscillations of the neutron sphere with respect the proton one (GT mode) and out of phase density oscillations of neutrons and protons inside a fixed spherical surface (JS mode) [10]. For a nucleus with mass A radius R, with N neutrons and Z protons, the excitation is associated with a dipole moment (in the following the dipolar degree of freedom are expressed in units of the elementary charge):

$$\mathbf{D}_j = \alpha_j \frac{NZ}{A}\mathbf{R} \tag{1}$$

the α_j coefficients determine the strength of the two possible modes.

The possibility of exciting exotic GDR modes during the formation of intermediate systems produced by the collision between nuclei having different charge/mass asymmetry ratios $\beta = \dfrac{N-Z}{A}$ was investigated until the early 2000s. An extra-yield with respect the one predicted according to the statistical model in the gamma-ray spectra around 10 MeV has been highlighted in different systems at incident energy ranging from about 9 up to 25 MeV/A [11, 12]. Different investigations have shown that these evidences can be associated with pre-equilibrium dynamical dipolar emissions. For systems consisting of partners with different β values and for a touching configuration, the associated dipolar degrees of freedom can be introduced according to the following expressions evaluated in the center of mass system(c.m.s.):

$$\mathbf{D} = \frac{1}{2}\mu(\beta_t - \beta_p)\mathbf{R}; \quad \mathbf{V} = \frac{1}{2}\mu(\beta_t - \beta_p)(\mathbf{V}_p - \mathbf{V}_t) \tag{2}$$

μ is the reduced mass number associated with the binary system formed by PR and TA, $\mathbf{R}$ is the relative distance between the two nuclei in the touching configuration and $\mathbf{V}_p$, $\mathbf{V}_t$ are the PR and TA velocities. In particular, $\mathbf{D}$ represents the dipole associated with the relative displacement of the neutron center of mass (c.m.) with respect to the proton one, while **V** represents a "kinetic" contribution associated with the corresponding relative velocity. Assuming that at the very beginning of the interaction the change in time of the μ and β quantities is negligible, the time derivative of **D** is well approximated by **V**. In particular, it is possible to estimate the δE energy associated to these degrees of freedom in the following way: from the total energy due to the strong interaction of the binary system (for simplicity here the difference in the Coulomb interaction is not taken into account), the contributions related to the relative motion of the neutron c.m. with respect to the proton one (let to think to a GT mode) are easily isolated. By neglecting possible small differences of the surface effects [10] one obtain:

$$\delta E = A_p E_{sym}\beta_p^2 + A_t E_{sym}\beta_t^2 + \frac{1}{2}\mu_{NZ}v_{rel}^2 - AE_{sym}\beta^2 \tag{3}$$

β_p, β_t and β represent the PR, TA and total system charge/mass asymmetries respectively. E_{sym} is the symmetry energy per nucleon, μ_{NZ} is the reduced mass associated with the total number of neutrons N_T and proton Z_T and v_{rel} is relative velocity between neutrons and protons c.m. $\mathbf{v}_{rel} = (\frac{N_p}{N} - \frac{Z_p}{Z})\mathbf{V}_b$ can be directly controlled through the beam velocity $\mathbf{V}_b$. In other words, δE represents the total energy due to the strong interaction and to the kinetic contribution referred to an analogues system (with same total mass and charge)in the binary configuration in which the TA and PR nuclei, at rest, have the same charge/mass asymmetry as the one related to the total system.

As an example, according to eq. 3, in the case of a ^{48}Ca+^{27}Al at 40 MeV/A the contribution related to the symmetry energy is about 8.7 MeV (considering E_{sym} =30 MeV) while the kinetic contribution associated with the beam energy is about 4.6 MeV.

Despite the approximation used to obtain the expression in the eq.(3), its structure can reveal also in this case the main factors determining the time evolution of the dipolar degrees of freedom. The main forces establishing the changes of δE (an therefore the changes of the dipolar coordinates) at the beginning of the interaction are the ones that develop from the density gradient of the symmetry energy i.e. the drift contribution and the explicitly (spontaneous and temperature dependent) change in time of the unbalance of charge/mass asymmetries due to the isospin diffusion mechanism. Dealing with open systems the above mentioned effects give rise also to outwards contributions.

Obviously a more realistic description of the time evolution of these processes will require a many-body approach. In Figure 1 as an example results of calculations performed with the Constrained Molecular Dynamical Model CoMD [13] on the ^{48}Ca+^{27}Al system at 40 MeV/A and for an impact parameter $b = 3$ fm are shown. In the first two upper panels, the average values of the dipolar signal $< \mathbf{V} >$ along the X impact parameter direction and along the Z beam direction are shown as a function of time. The averages are computed over several realizations or events and are indicated through the curly brackets. **V** in this case is evaluated event by event starting from the microscopic configuration as: $\mathbf{V} = \sum_{i=1}^{Z_T} \mathbf{v}_i$ where $\mathbf{v}_i$ are the proton velocities evaluated in the c.m.s.. The bottom panel of Figure 1 shows instead the average density ρ_{cm} computed in the c.m.s.: from the figure are clearly seen the fast changes in time of $< \mathbf{V} >$ able to produce a pre-equilibrium gamma-ray emission. This is consistent with the experimental evidences collected at low incident energy [11, 12]. The largest changes are obtained for the beam axis component whose initial value is established through the beam energy. As can be seen in this example, these fast changes are strictly correlated in time with the fast changes in the density around the c.m. in the first 100-150 fm/c. There the changes cover a relative wide range of value around the saturation value ρ_0, from sub-saturation up to about $1.6\rho_0$ and there the largest forces are produced.

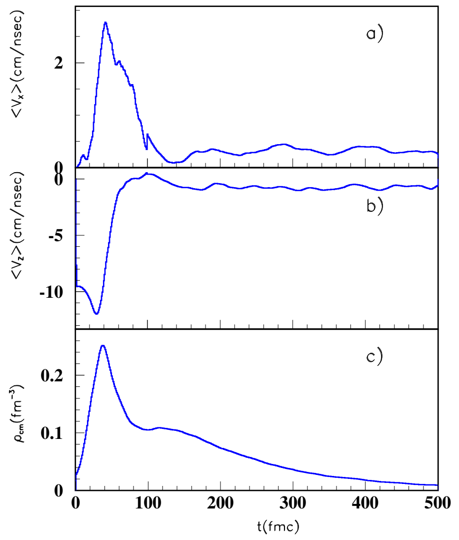

Figure 1. CoMD calculations for the $^{48}Ca + ^{27}Al$ system at 40 MeV/A and $b = 3$ fm: in panels a) and b) the average dipolar signal along the impact parameter direction and the beam axis are plotted respectively as function of time. Panel c): the corresponding average density in the c.m.s. is shown.

The other rather remarkable aspect is the fact that, within the uncertainty (small oscillations at time larger than about 150 fm/c) due to the statistics of the simulated events, after the pre-equilibrium stage $< \mathbf{V} >$ remains steady. This means, on one hand, that the steady value is "decided" from the high non-equilibrium dynamics of the first moment of the interaction and on the other one that this value can be in principle determined by measuring the velocity, charge and mass of all the fragments produced by the collision process ($< \mathbf{V} >$ is in fact a cluster-invariant quantity). More generally, in the Appendix B of Ref [12] it was shown that the final statistical de-excitations of the hot fragments, representing the later cooling stage of the process, is not able to change the average value of the dipolar signal after the pre-equilibrium stage just because of the usual conservation laws and of the average symmetry properties of the statistical decay processes. In Figure 2, as an example, density maps at different times corresponding to the calculations shown in Figure 1 are plotted. The maps are obtained by considering only 10 events. From the figure it is seen clearly a kind of multi-fragmentation of the light target. A fraction of the target is also transferred to project like fragment (PLF) leading globally to a kind of incomplete fusion process. The calculations produce also de-excitation decays of the hot sources after the main dipolar pre-equilibrium stage in the fist 100 fm/c.

In the final configuration the average dipolar signal reconstructed from the final fragments and particles can be re-written in the following form in the c.m.s.:

$$< \mathbf{V} >= \frac{1}{m_0} \sum_{Z,A,k=1}^{N} \frac{Z}{A} \frac{m^k_{Z,A} \overline{\mathbf{P}}^k_{Z,A}}{N} = \frac{1}{m_0} \sum_{Z,A} \frac{Z}{A} < m_{Z,A} >< \overline{\mathbf{P}}_{Z,A} > C_{Z,A} \quad (4)$$

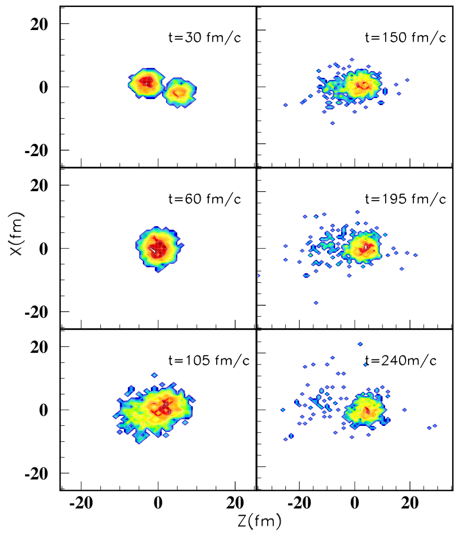

Figure 2. Density maps at different times for 10 events corresponding to the CoMD calculations shown in Figure 1.

In the above expressions for each event k $\overline{\mathbf{P}}^{k}_{Z,A}$ represents the average momentum of the produced fragments with charge Z and mass number A with multiplicity $m^{k}_{Z,A}$. The average on the total number of event N is expressed through the correlation functions between the multiplicity and average c.m. momenta of the different produced fragments i.e. $C_{Z,A} = \dfrac{< m_{Z,A}\overline{\mathbf{P}}_{Z,A} >}{< m_{Z,A} >< \overline{\mathbf{P}}_{Z,A} >}$. From eq.(4) it is evident that the average dipolar signal is strictly related to a final average charge/mass of the produced charged fragments. This average being obtained through a particular weighed mean with a distribution defined in the momentum space of the final fragmentation through the correlation between multiplicities and momenta.

3 The measurement

All the above illustrated peculiarities of the observable $< \mathbf{V} >$ make it able to give a new alternative and complementary way to look at the isospin-equilibration process in momentum space. Therefore the study of this observable continued with the experimental investigation using the multi-detector CHIMERA at Laboratori Nazionali del Sud. The rather unbalanced charge/mass system $^{48}Ca + ^{27}Al$ at 40 MeV/A was chosen. The use of the light target makes the identification of the slow target like fragments (TLF) easier. The multi-detector CHIMERA covers about 94% of the solid angle [14, 15] . Fast fragments emitted in the forward direction can be identified through the $\Delta E - E$ technique applied to the signals produced by the $Si - CsI$ telescopes. Time-of-flight measurements can be used to determine the fragments velocity. In particular, the time signals allow to identify slow fragments stopping in the silicon detectors. Fast light particles are identified by using the Fast-Slow correlations of the signals produced in the CsI. In this section preliminary results of the data analysis are presented. In Figure 3 bi-dimensional plots displaying the charge of the detected fragments as a function of the parallel velocity V_{par} along the beam axis in different bins of total kinetic energy evaluated in the so called reduced center of mass system r.c.m.s. (TKE^{CM}) are shown. r.c.m.s. is defined through the reduced c.m. velocity $\mathbf{V}_{c,CM}$ obtained event by event from the velocity, charge and mass of the identified charged fragments.

The plots are filled with events for which the total detected charge and momentum reconstruction fractions are better than 90% and 80% of the nominal values. The bumps in the 2 upper panels are associated with the projectile like (PLF) and target like TLF fragments. According to the different degrees of dissipation, displacements of the PLF and TLF velocity centroids are observed. The bottom panel collects the more dissipative events. In this plot the disappearance of the TLF bump is observed. This last selection of events recall the typology of events shown in Figure 2 obtained through CoMD calculations for central events as shortly discussed in the previous section. From the identified fragments with velocity $\mathbf{V}_i$

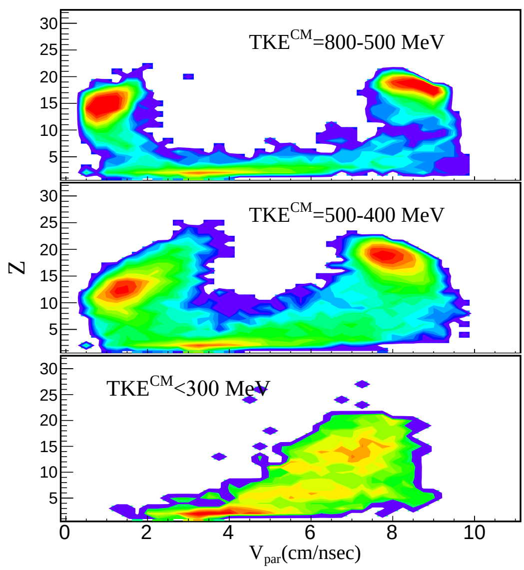

Figure 3. Z-V_{par} plot for the ^{48}Ca+^{27}Al system at 40 MeV/A for different degrees of dissipation as deduced from the displayed different bins of TKE^{CM} (see the text).

in well reconstructed events belonging to the selected class of events (the selection can be performed according to some other order observable) the reduced average dipolar signal can be evaluated according to the following relations:

$$< \mathbf{V}_c > = < \sum_{i=1}^{m} Z_i(\mathbf{V}_i - \mathbf{V}_{c,CM}) > \tag{5}$$

$< \mathbf{V}_c >$ is therefore a reduced value in the sense that does not take into account the effect related to the production of free neutrons which instead is taken into account when using the c.m. velocity of the total system (see also the following). However, $< \mathbf{V}_c >$ has the advantage that uncertainties on the event reconstruction of the sub-system formed by all the produced charged fragments are event by event partially eliminated.
From this preliminary analysis, in Figure 4 and 5 the beam axis components of the average dipolar signal obtained from the reconstructed events as a function of the charged fragment

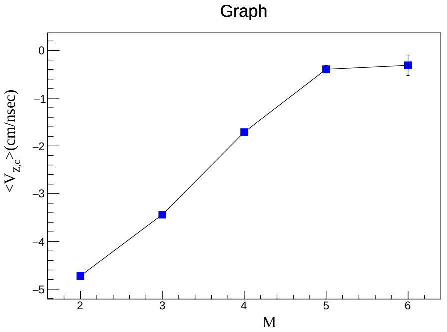

Figure 4. Beam axis component of the reduced dipolar signal for different multiplicities M of the identified charged fragments. Errors associated with the statistics of the collected events are represented by vertical bars or are within the symbols size.

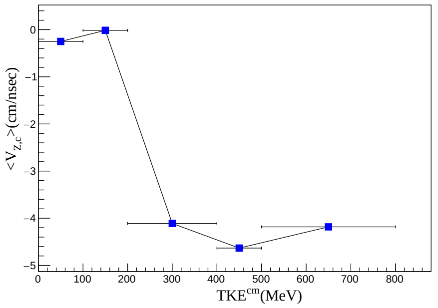

Figure 5. Beam axis component of the reduced dipolar signal for different windows (horizontal bars) of the total kinetic energy (TKE) in the r.c.m.s.. Errors associated with the statistics of the collected events are within the symbols size.

multiplicity M and of the TKE^{CM} are shown. The other components are currently being analysed. As can be observed, the increasing of the dissipation and of the fragment multiplicity of the detected fragments, which is consistent with the selection of increasing degrees of centrality, produce a decreasing of the absolute value of the reduced dipolar signals through more isospin equilibrated configurations (on average). However, a definitive answer on the global degree of isospin equilibration as obtainable from the total average dipolar signal can be obtained after a comparison with model calculations including the effects of the experimental filter. To conclude, in Figure 6, the reduced values of the c.m. velocity $V_{c,CM}$ obtained for different events ordered according to the TKE^{CM} are shown. As can be seen, for moderate dissipation the values $V_{c,CM}$ are on average lower than theoretical value. By assuming, at this level of analysis, that this deviation is essentially due to the contribution of the undetected free neutrons then the related average contribution has to be positive, i.e. the free-neutrons are emitted on average on the PR side. The opposite happens for more dissipative events probably due to the contribution of the target multi-fragmentation.
Finally, it should be also mentioned that in previous works [7, 16] by means of a comparison of collected data on the same system for events with a low degree of dissipation a connection was established between the measured average dipolar signal and the parameter associated with the EoS symmetry energy .
However, the subject still needs more investigations especially taking into account the improved versions of the molecular dynamical model[13] and of the identification procedure in the data analysis [17].

4 Conclusive remarks

In this contribution the connections between the excitation of pre-equilibrium dipolar mode in heavy ions collision, the isospin equilibration processes and the EoS symmetry energy at density different from the saturation one have been discussed. In particular, it has been shown as the study of the average asymptotic "dipolar signal" produced in heavy collisions, in an independent way from statistical mechanisms, can offer the possibility to investigate the average properties of the isospin equilibration processes in the momentum space of the

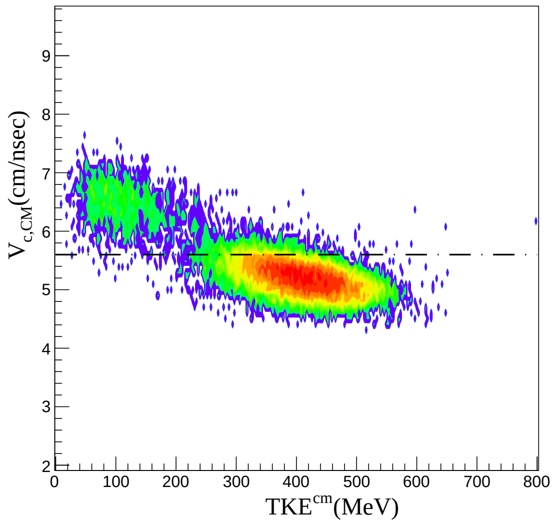

Figure 6. bi-dimensional plot showing for the reconstructed collected events the reduced value of the c.m. velocity $V_{c,CM}$ versus the related total kinetic energy TKE^{CM} evaluated in the r.c.m.s.. The dashed horizontal line represents the V_{CM} theoretical value.

final fragmentation. Preliminary results of an analysis on the $^{48}Ca +^{27} Al$ at 40 MeV/A in reaction mechanisms characterized by different degrees of dissipation and/or centrality have been presented. A procedure based on the determination of the dipolar signal along the transversal directions it is also developing for a better estimation of the uncertainty on the discussed $< \mathbf{V}_c >$ observable.

References

[1] WG. Lynch, M.B. Tzang, Phys. Lett. B **830**, 137098 (2022) and reference there in.
[2] R. Balian, *From Microphysics to Macrophysiscs* (Springer Verlag, Berlin, 1992) Vol. II.
[3] V. Baran, M. Colonna, M. Di Toro, M. Zielinska-Pfabe, and H. Wolter, Phys Rev. C **72**, 064620 (2005).
[4] F.Rami et al, Phys. Rev. Lett. B **84** 6 (2000).
[5] M. B. Tsang, Y. Zhang, P. Danielewicz, M. Famiano, Z. Li, W. G. Lynch, and A. W. Steiner, Phys. Rev. Lett. **102**, 122701 (2009).
[6] Q.Fable, Phys. Rev. C **107**, 014604 (2023) and reference there in.
[7] M.Papa et al, Phys. Rev. C **91**, 041601(R) (2015).
[8] K. A. Snover, Annu. Rev. Nucl. Part. Sci. **36**, 545 (1986).
[9] D. Santonocito et al, Phys. Lett. B **782**, 427 (2018).
[10] W. D. Myers, W. J. Swiatecki, T. Kodama, L. J. El-Jaick E. R. Hilf, Phys. Rev. C **16** NUMBER 6 (1977).
[11] F. Amorini et al., Phys. Rev. C **69**, 014608 (2004).
[12] M.Papa et al; Phys. Rev. C **72**, 064608 (2005) and reference there in.
[13] M.Papa, Nucl. Phys. A **1041** 122780 (2024).

[14] A. Pagano et al, Nucl. Phys. A **734**, 504 (2004).
[15] G.Cardella et al, Nucl.Instr.and Meth.inPhys.Res.Sect.**A799**, 64 (2015).
[16] C.Agodi et al, Eur. Phys. J. Plus, 138:1038 (2023).
[17] P.Russotto et al nim A **1056** 168593 (2023).