Dipolar degrees of freedom in Heavy Ion Collisions and the CoMD model

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- A short review of the model and some applications
- Cluster formation in CoMD and the EoS (T=0)
- Dipolar degrees of freedom and Isospin equilibration processes in Heavy Ions Collision

Main feature of the CoMD approaches

- CoMD model is a QMD like model. The Nucleonic wave functions are wave packets in phase-space. The N-body wave function is the direct product of N wave functions.

- The microscopic interaction is a Skyrme interaction + Coulomb+surface terms.

- <u>A numerical algorithm based on nucleon-nucleon multi-scattering processes constraints the phase-space distribution to satisfy the Pauli principle.</u>

- Contrary to others Molecular Dynamics approaches the kinetic contribution is associated to a real motion of the wave packets. (in other models the kinetic Fermi motion is given by "frozen" term $3N\frac{\sigma_P^2}{2m}$) .

- Good ground state properties of nuclei (stability up to ~ 1000 of fm/c) are obtained with a dedicated cooling-warming procedure coupled with the constraint associated to the Pauli principle (this is a delicate and time consuming stage which ask for a dedicated algorithm).

CoMD-II

-<u>In high collisional regimes (collisions as due to hard-core repulsive interaction are simulated through Monte Carlo technique) the total angular momentum is not conserved. Through appropriated transformations in phase-space we restore this fundamental conservation law at each time step.</u>

M. Papa, T. Maruyama and A. Bonasera, Phys. Rev. C 64 024612(2001).
M.Papa, G.Giuliani A.Bonasera; Jou. of Comp. Physics 208,403(2005).

Dynamical multi-breakup processes in the ^{124}Sn+^{64}Ni system at 35 MeV/nucleon (LNS)

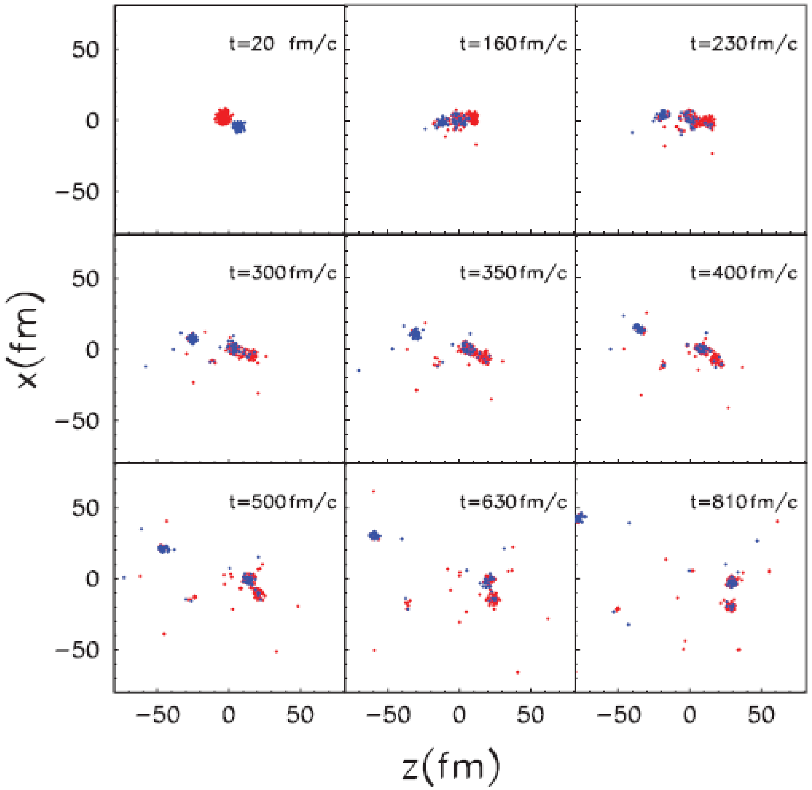


FIG. 4. (Color online) Configurational map, at different time steps, of one event related to the ^{124}Sn+^{64}Ni system at 35 MeV/nucleon leading to the fission of the heavy partner.

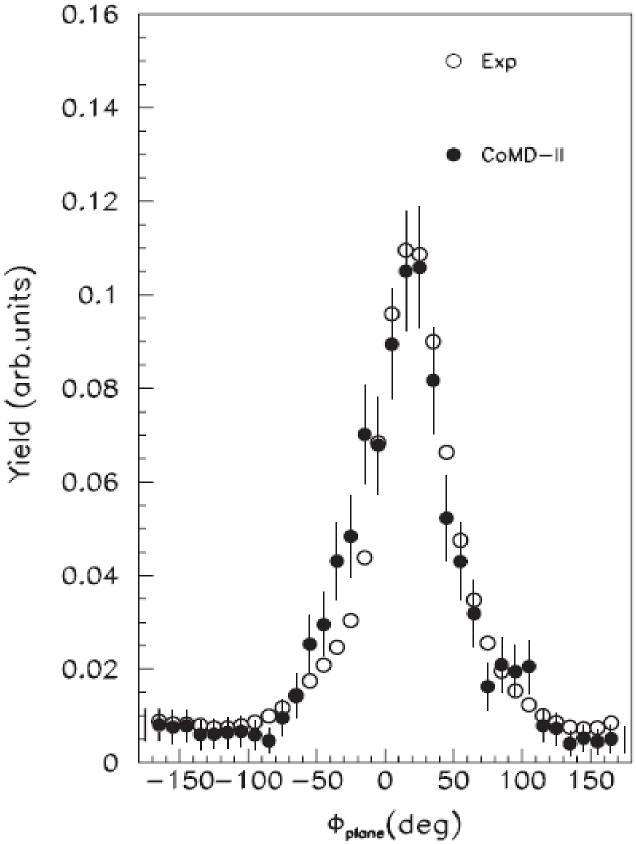


FIG. 10. Experimental and calculated Φ_{plane} distribution for ternary events with $A_{\text{HL}} < 5$ and $V_{\text{thr}} = 3$ cm/ns. The bars indicate the errors related to the statistics of simulations. For the experimental data the errors are smaller than the size of the symbol.

E. De Filippo *et al.*, Phys. Rev. C 71, 064604 (2005).

P.Russotto et al., Phys. Rev. C. 81, 064605 (2010).

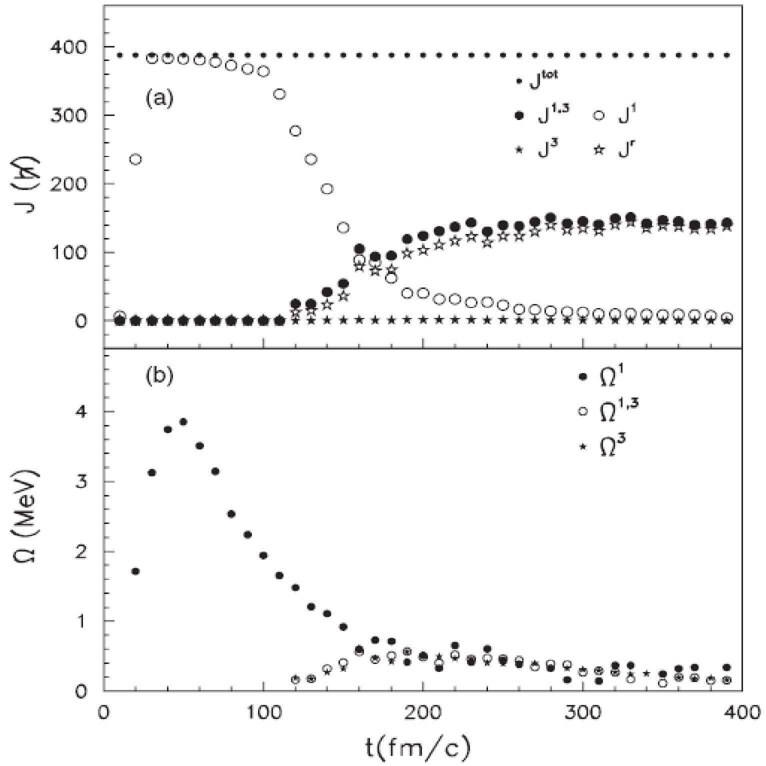


FIG. 11. (a) Calculated intrinsic angular momentum of different parts of the system as a function of time. The small circles represent the total angular momentum. The labels 1 and 3 indicate the biggest and third-biggest fragments. $J^{1,3}$ indicates the total spin of the binary system formed by fragments 1 and 3, whereas J^{r} is the part associated with relative motion. (b) Related average angular velocities evaluated according to Eq. (1).

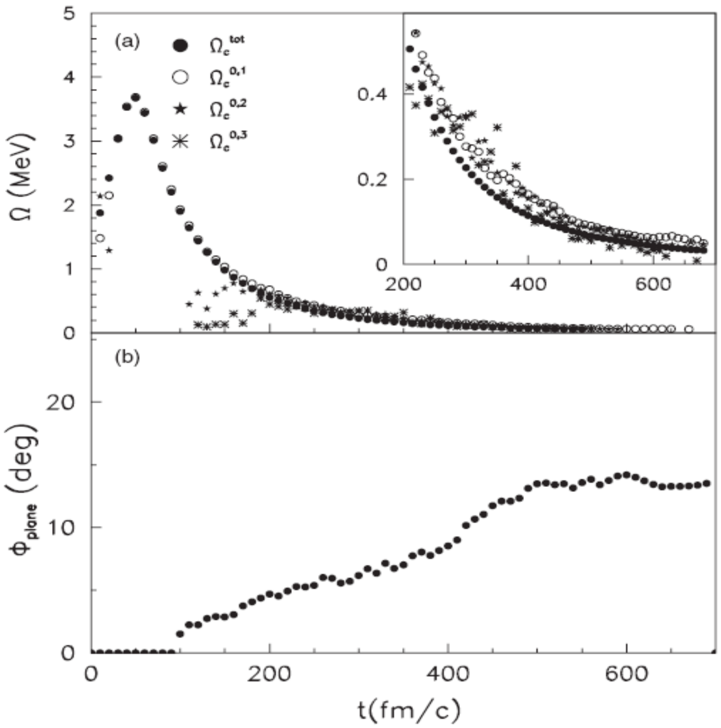


FIG. 12. (a) Average value of the angular velocities calculated for the total system (Ω^{tot}) and its different parts evaluated through Eq. (2). The inset represents an enlargement of the plot in the time interval 200–700 fm/c. (b) $\overline{\Phi_{\rm plane}}$ as a function of time calculated for $A_{\rm HL} < 5$.

Time scale and average asymptotic Φ_{plane} value are consistent with the collective rotation of an iper-deformed and expanded PLF in a di-nuclear configuration.

M.Papa et al;PHYSICAL REVIEW C 75, 054616 (2007)

Symmetry energy dependence of long timescale isospin transport (MSU)

^{64}Zn+^{64}Zn at 45 MeV/nucleon

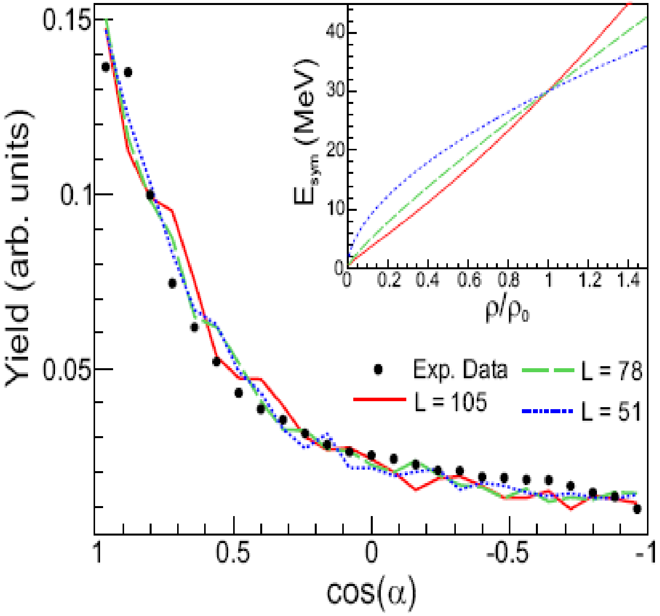
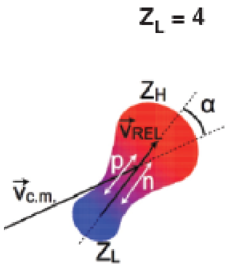


FIG. 1. (Color online) Cos(α) distribution from the experiment (solid black circles) and CoMD simulation (lines) for events with $Z_H > 11$ and $Z_L = 4$. All results are normalized to a total integral of 1. The three different forms of the density dependence of the symmetry energy used within the CoMD calculations are shown in the insert.



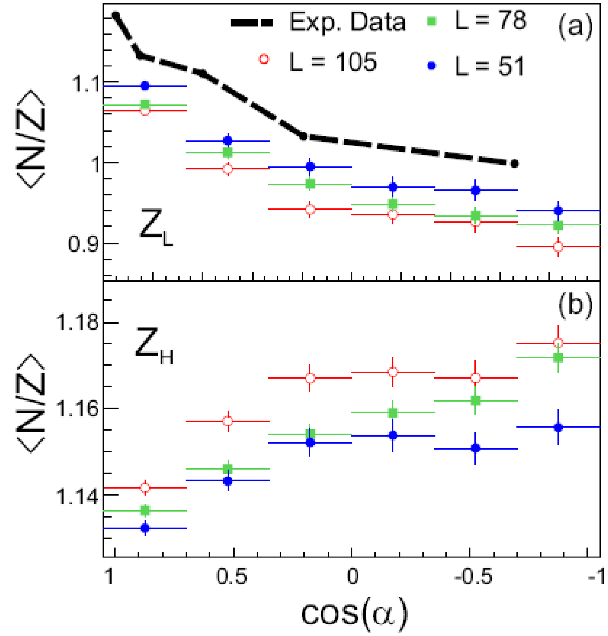
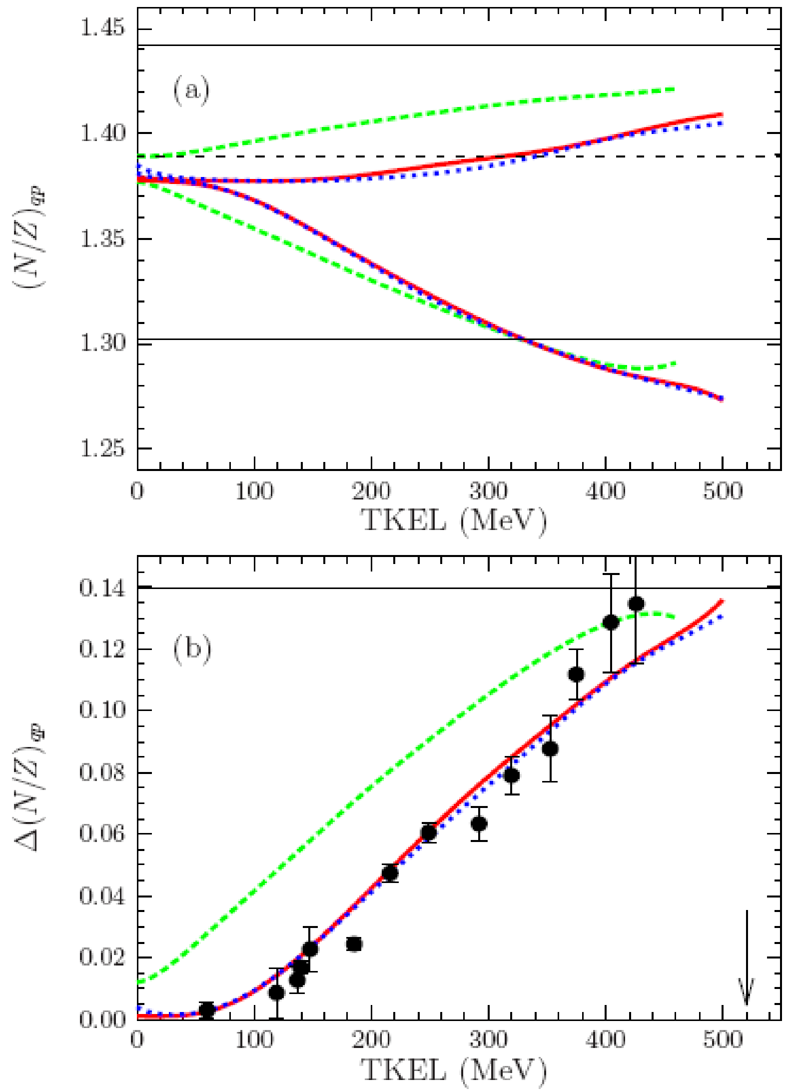


FIG. 3. (Color online) Relationships between the $\langle N/Z \rangle$ and cos(α) for the Z_L fragment and the Z_H fragment extracted from the CoMD simulation are shown in panels (a) and (b), respectively. Experimental data for the Z_L fragment is included for comparison.

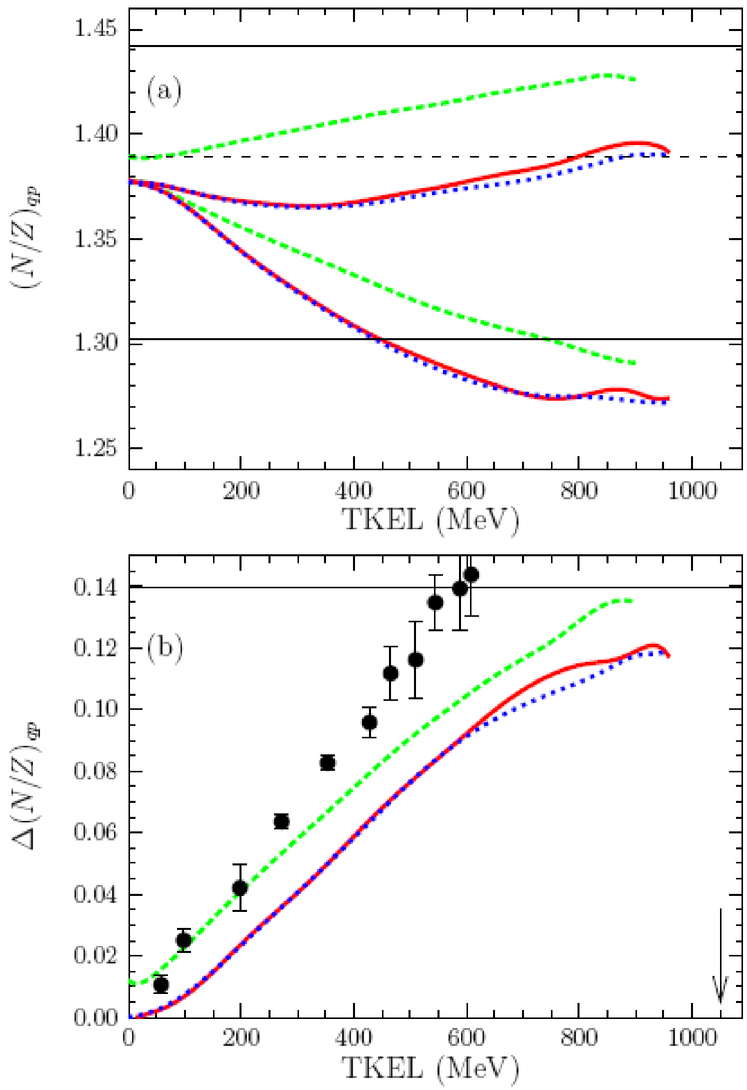
K. Stiefel et al PHYSICAL REVIEW C 90, 061605(R) (2014)

Isoscaling of heavy projectile residues and *N/Z* equilibration in peripheral heavy-ion collisions below the Fermi energy (TAMU)

^{86}Kr(15MeV/nucleon) + ^{124,112}Sn



^{86}Kr(25MeV/nucleon) + ^{124,112}Sn



G.Soliutis et al;PHYSICAL REVIEW C 90, 064612 (2014)

Isospin Dependence of Incomplete Fusion Reactions at 25 MeV/Nucleon (LNS).

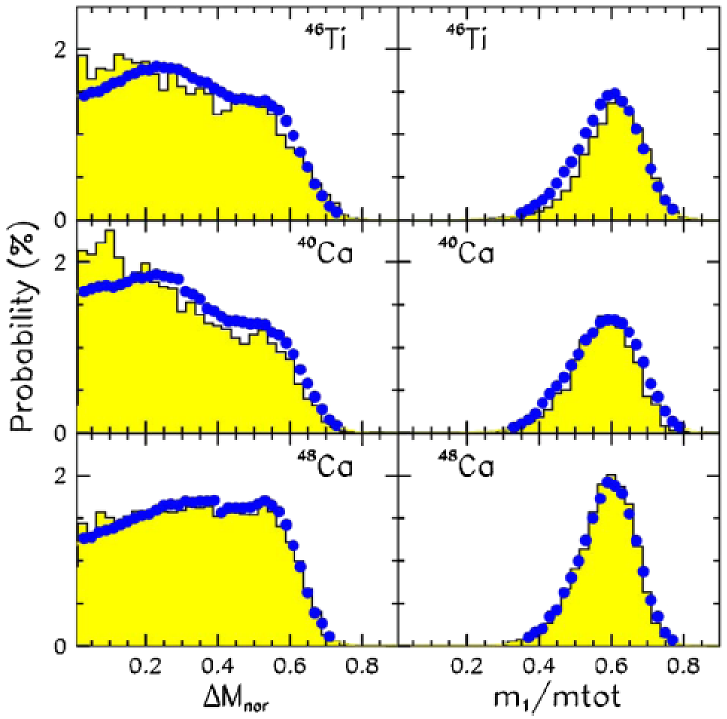


FIG. 2 (color online). Dot histograms: Probability plots of $m_1 - m_2$ and m_1 normalized to the total mass for the studied reactions. Shaded histogram: CoMD-II + GEMINI calculations. See text for details.

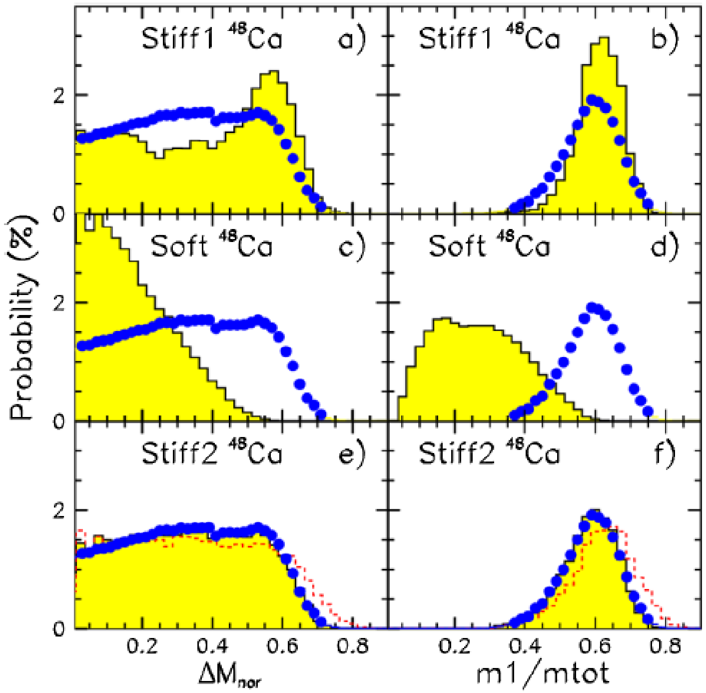


FIG. 3 (color online). CoMD-II + GEMINI calculations (shaded area histogram) and experimental results (dotted histograms) for the ^{48}Ca case for (a),(b) Stiff1 parametrization; (c),(d) Soft parametrization; (e),(f) Stiff2 parametrization, dashed line CoMD-II calculations, without the GEMINI stage.

F.Amorini et al PRL 102, 112701 (2009)

I.Lombardo et al.,Phys. Rev. C. 82, 014608 (2010).

G.Cardella et al.,Phys. Rev. C. 85, 064609 (2012)

Cluster formation in CoMD and the EoS (T=0)

- The pre-conditions which allow for the spontaneous formation of Clusters in these kind of approaches are the many-body correlations of the model and the use of localized nucleonic wave-packets.
- To reproduce the standard properties of Nuclear Matter at the saturation density, these correlations make necessary the changes of the parameter values describing the effective interaction with respect to the values obtained in Mean-Field approaches.

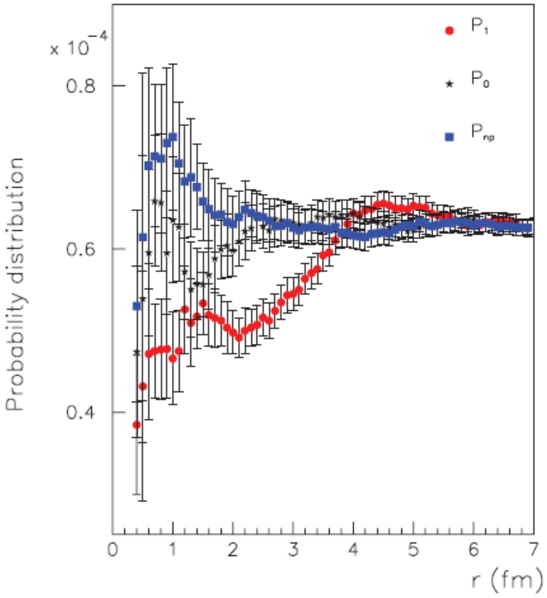


FIG. 2. (Color online) Probability distribution P_1 to find two identical nucleons at a relative distance r. In the same figure P_0 represents the probability evaluated for neutron and proton couples with opposite spin. Finally, P_{np} indicates the probability obtained for neutron-proton couples.

$$V(\mathbf{r},\mathbf{r}') = V^{(2)}\delta(\mathbf{r}-\mathbf{r}') = \frac{T_0}{\rho_0}\delta(\mathbf{r}-\mathbf{r}') + \frac{2T_3\rho^{\sigma-1}}{(\sigma+1)\rho_0^{\sigma}}\delta(\mathbf{r}-\mathbf{r}') + \frac{T_4}{\rho_0}F'_k(2\delta_{\tau,\tau'}-1)\delta(\mathbf{r}-\mathbf{r}'). \quad (1)$$

M.F. limit of the simple Skyrme interaction

$$E_{\rm pot} = U_{\rm twb} + U_{\rm trb} + U_{\rm asy} = \frac{1}{2}V^{(2)}\rho = \frac{1}{2}\frac{T_0\rho}{\rho_0} + \frac{T_3\rho^{\sigma}}{(\sigma+1)\rho_0^{\sigma}} + \frac{1}{2}T_4F_k(\rho)\beta^2,$$

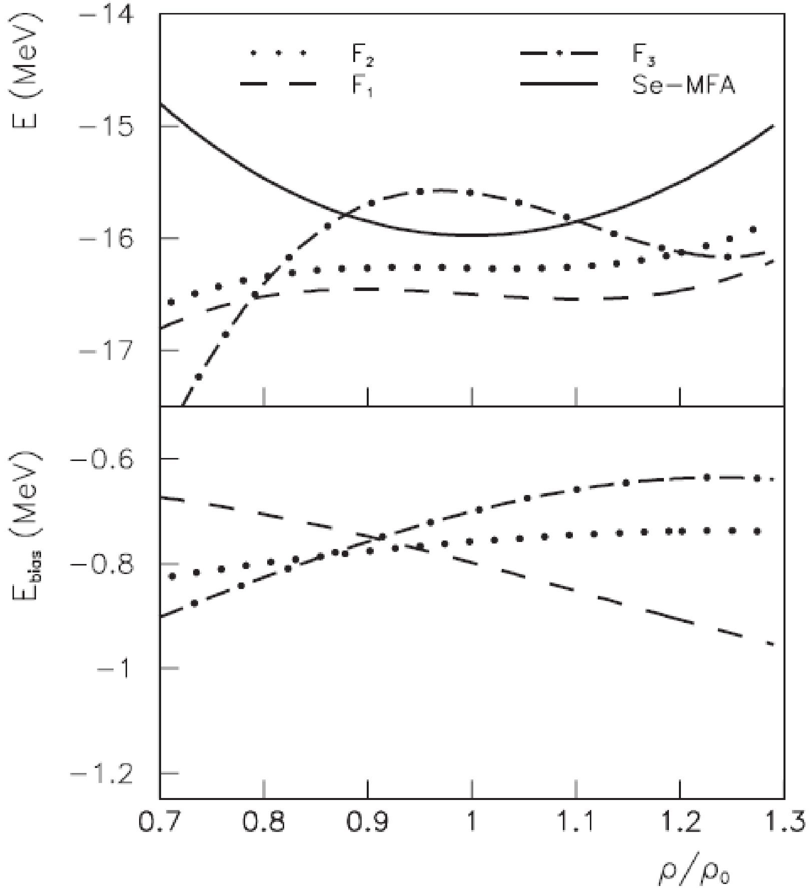
$$F_k = (\rho/\rho_0)F'_k,$$
$$F'_1 = \frac{2(\rho/\rho_0)}{1+\rho/\rho_0},$$
$$F'_2 = 1,$$
$$F'_3 = (\rho/\rho_0)^{-1/2},$$
$$F'_4 = (\rho/\rho_0)^{\gamma-1},$$

T_0(M.F.)=-263 MeV; T_3(M.F.)=208 MeV σ(M.F.)=1.25

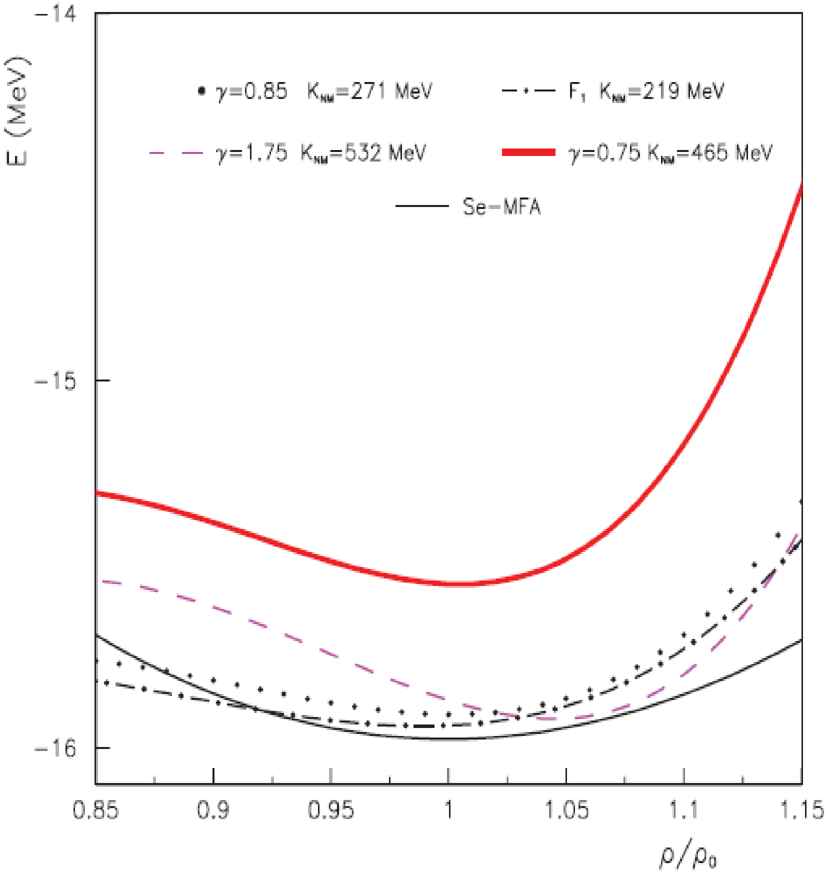
M.Papa,PHYSICAL REVIEW C 87, 014001 (2013)

M.Papa,PHYSICAL REVIEW C 87, 014001 (2013)

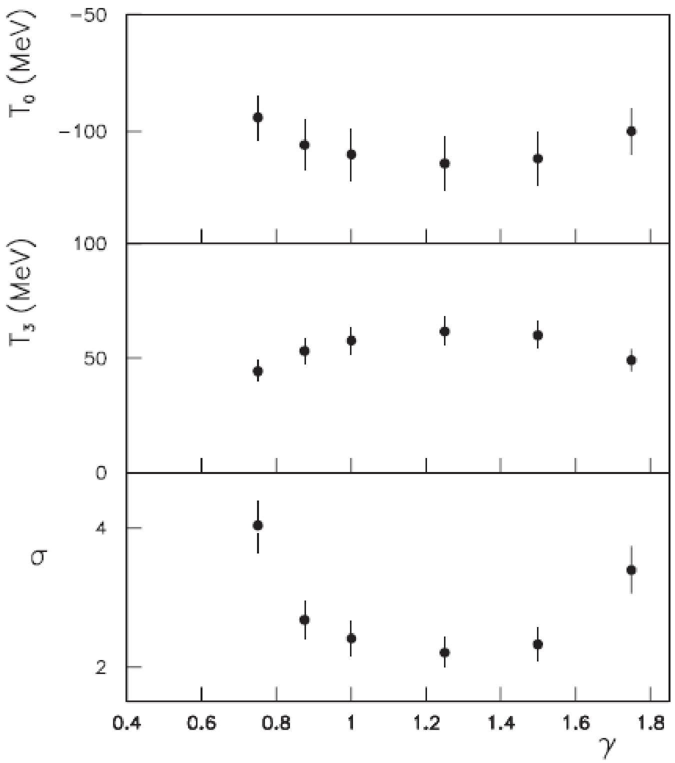
EoS using the same parameters as obtained from the M.F.approximation

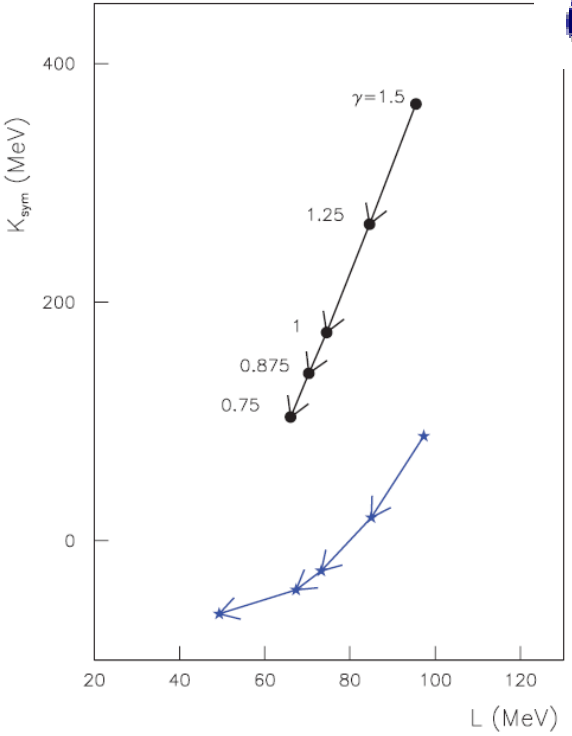


EoS with K_{nm}≈220-300 MeV with new parameters after the self-consistent procedure



T_0(M.F.)=-263 MeV; T_3(M.F.)=208 MeV σ(M.F.)=1.25





M.Papa,PHYSICAL REVIEW C 87, 014001 (2013)

CoMD-III

Dipolar degrees of freedom and Isospin Equilibration processes in Heavy Ion Collisions

M. Papa and the EXOCHIM collaboration

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ASY-EOS 2015 International Workshop on Nuclear Symmetry Energy and Reaction Mechanisms

3-6 March 2015 Piazza Armerina (En) Italy

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 can not describe the system during its overall time evolution ($\Upsilon_n \approx 2500$ fm/c T=2MeV)

- The observed data should be described phenomenological via a fast pre-equilibrium stage described using dynamical models , and later-stage processes described by statistical decay models (different explored densities).

- A phenomenon closely linked to the iso-vectorial forces is the well-known process leading to the redistribution in momentum-space of the charge/mass excess $\beta = (N-Z)/A$ of the emitted particles and fragments (complex phenomenon) (see diffusion effect in [1])

- In particular, in the last stage the iso-spin and excitation energy dependencies of the level density formula play a key role and are currently under investigation .

- When clearly identified, the attempt to measure observables in principle closely linked to only one of the two regimes is therefore very useful.

[1] M.B.Tsang et al; PRL 062701 (2006);PRL 102 122701(2009).

Time Derivative of the total dipole

$$<\vec{D}> = <\sum_{i=1}^{m} Z_i(\vec{V}_i - \vec{V}^{cm})>_K$$

A) because of the symmetries of the statistical decay mode, <*D*> is not affected by the statistical emission of all the produced sources in the later stages [1].

B) as shown in [2], this quantity is closely linked to the charge/mass equilibration process.

$$<\vec{D}> \propto \sum_{Z,A} \frac{Z}{A} <m_{Z,A}><\vec{P}^{cm}_{Z,A}> C^{Z,A}_{\vec{P}}$$

$$C^{Z,A}_{\vec{P}^{cm}_{Z,A}} = \frac{<m_{Z,A}\vec{P}^{cm}_{Z,A}>}{<m_{Z,A}><\vec{P}^{cm}_{Z,A}>}$$

Isospin Equilibration according to the Rami definition $\longrightarrow$ $<\vec{D}> = 0$

On the contrary if $<\vec{D}> \neq 0$ $\quad <\vec{D}> = <\vec{D}_m> = \frac{1}{2}\mu(\beta_T - \beta_P)(\vec{V}_p - \vec{V}_T)$

Impinging nuclei with different charge/mass asymmetries: during the pre-equilibrium stage the Z/A are redistributed in momentum-space and $|<\vec{D}>| \rightarrow 0$

[1]M.Papa et al PHYSICAL REVIEW C 72, 064608 (2005)

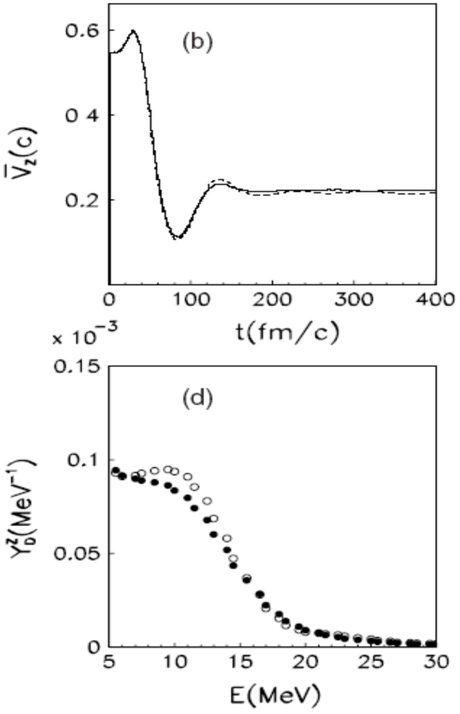
[2] M.Papa M and G.Giuliani, Journal of Physics: Conference Series 312 082034(2011).

Therefore,<*D*>is a rather well-suited global variable for selecting dynamical effects related to the iso-spin equilibration process.

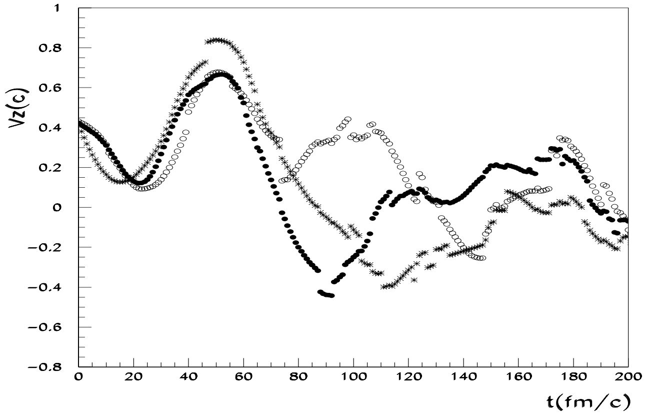
In the following, we assume that its value is a measure of the degree of isospin equilibration reached by the system due to the dynamics of the process.

Only a look to the time dependence of the dipolar signal CoMD-II calculations

^{40}Ca+^{48}Ca 45MeV/nucleon b=6fm



The pree-equilibrium γ-ray emission is a furhter "marker of the isospin-equilibration processes. The related spectral properties contains a direct information about the time of the processes



G.Giuliani and M.Papa PHYSICAL REVIEW C 73, 031601(R) (2006)

M.Papa et al PHYSICAL REVIEW C 72, 064608 (2005)

M.Papa et al;PHYSICAL REVIEW C 68, 034606 (2003)

^{48}Ca+^{27}Al 40 MeV/Nucleon investigated with the multi-detector CHIMERA at LNS

^{27}Al+^{48}Ca, auxiliary system- ^{27}Al+^{40}Ca Isospin-quasi-symmetric partner 40 MeV/A

$$<\vec{D}>=<\sum_{i=1}^{m} Z_i(\vec{V}_i-\vec{V}^{cm})>_K$$

K ≡ Z_b,TKEL

Evaluation/correction of uncertainty

Good reconstruction of events:

$m \geq 2$, $Z_{tot}^{d}=33$ $P_{tot}^{d} \geq =0.7 P_{tot}$,

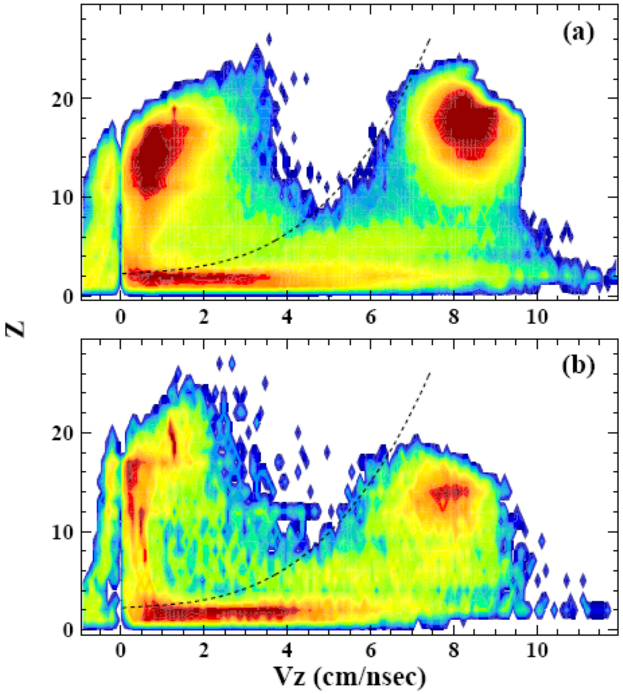
$62 \leq m_{tot}^{d} \leq 78$

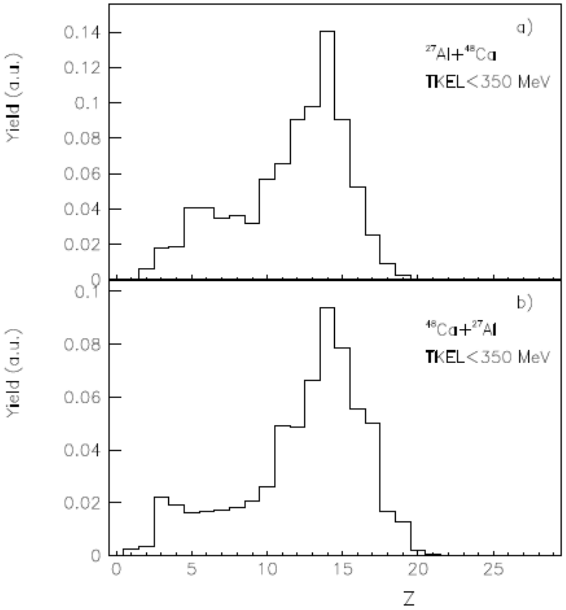
a) Random uncertainty (zero average) can be very small δ<D>≈1/sqrt(N)

b) Eventual systematic uncertainty on charges an velocities $\Delta_Z<D>$, $\Delta_V<D>$

the main system and the auxiliary one

$\Delta_Z<D> \leq 0.2$ cm/nsec TKEL≤350 MeV





A.Pagano et al.,Nucl.Phys A734 504(2004);A.PAgano, Nucl.Phys.NEws 22 25(2012).

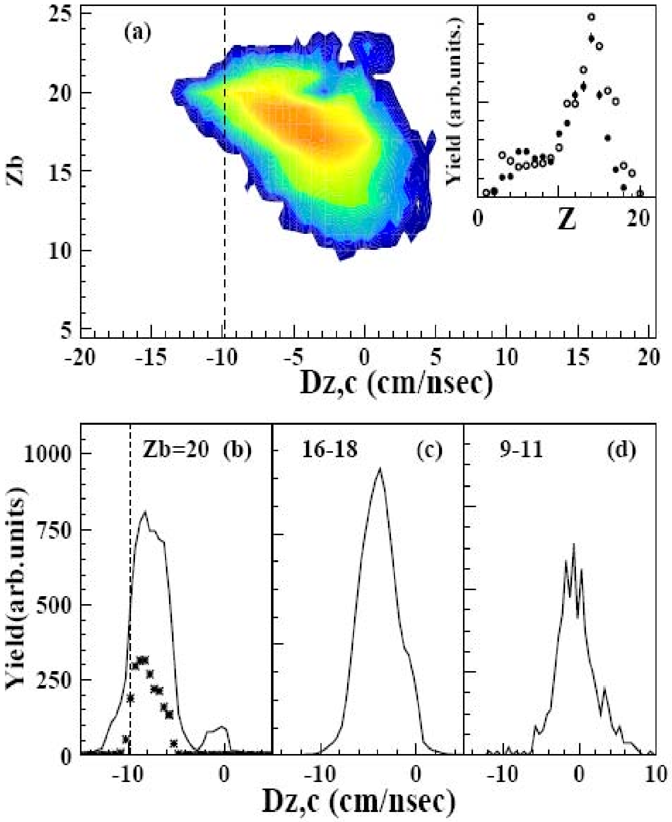
We will focuse on the beam axis component of <D>

$$< D_Z^c > = < \sum_{i=1}^{m} Z_i (V_Z^i - V_Z^{cm,d}) >_K$$

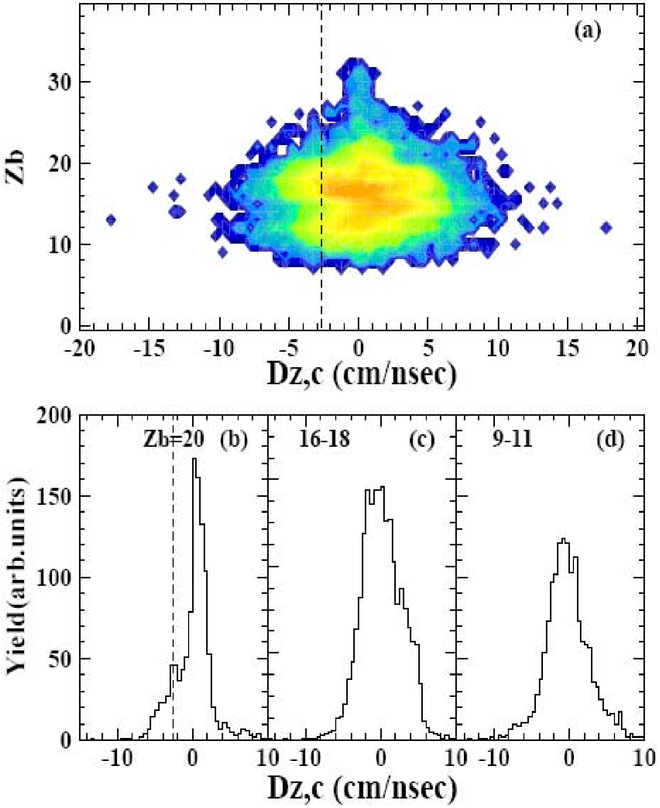
We correct for systematic errors on the velocity by using $V_Z^{cm,d}$ instead of V_Z^{cm}

$<D_Z^c>$ represents a partial dipolar signal related to the intrinsic motion of the subsystem formed by all the charged particles.

^{48}Ca+^{27}Al



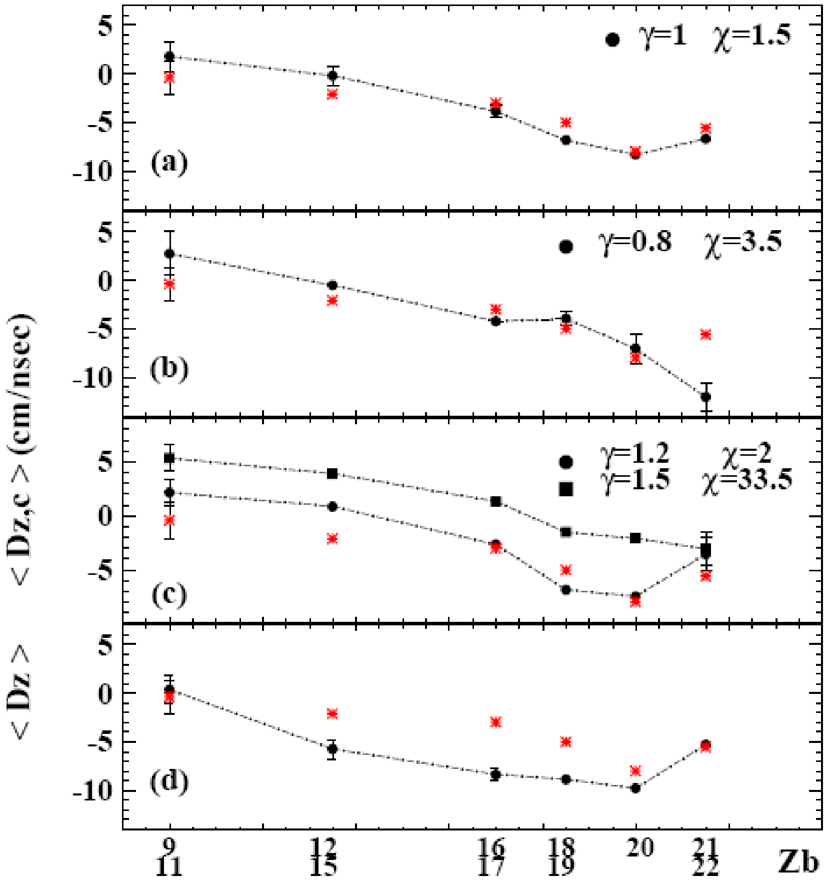
^{27}Al+^{40}Ca



Experimental Data and CoMD-III+Gemini+filter calculation

$\gamma = 0{:}8(L \simeq 79MeV)$, $\gamma = 1(L \simeq 90MeV)$, $\gamma = 1{:}2(L \simeq 100MeV)$, $\gamma = 1{:}5(L \simeq 114MeV)$ and $E_{sym} \approx 32$ MeV

$$< D_Z > \approx < D_Z^c > + Z_{tot}^d (V_Z^{cm,c} - V^{cm})$$



We observe:

For $\gamma \neq 0.8$ and $Z_b \neq Z_P$ $|\overline{D}_Z^c| < |\overline{D}_Z^c(Z_P)|$

we obtain that $V_Z^{cm,c} < V^{cm}$ therefore $V_Z^{cm,N} > V^{cm}$ and more neutron emission from PLF region more charge/mass symmetric fragments.

For $\gamma = 0.8$ and $Z_b > Z_P$ $|\overline{D}_Z^c| > |\overline{D}_Z^c(Z_P)|$

we obtain that $V_Z^{cm,c} > V^{cm}$ therefore $V_Z^{cm,N} < V^{cm}$, more neutron emission from TLF and mid-rapidity region.

In this case, a closer look to the fragments shows an almost complete disassembly of the light partner (TLF).

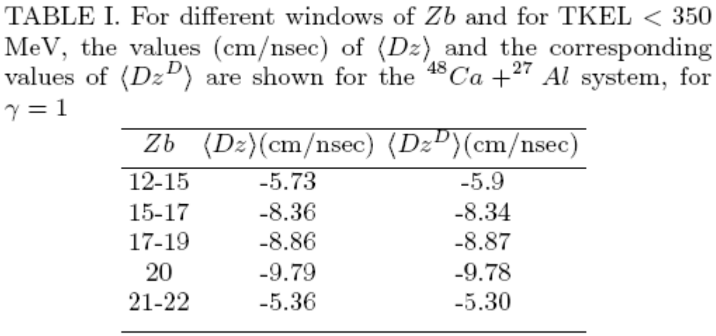


TABLE I. For different windows of Zb and for TKEL < 350 MeV, the values (cm/nsec) of $\langle Dz \rangle$ and the corresponding values of $\langle Dz^D \rangle$ are shown for the $^{48}Ca +^{27} Al$ system, for $\gamma = 1$

Zb	$\langle Dz \rangle$(cm/nsec)	$\langle Dz^D \rangle$(cm/nsec)
12-15	-5.73	-5.9
15-17	-8.36	-8.34
17-19	-8.86	-8.87
20	-9.79	-9.78
21-22	-5.36	-5.30

Concluding remarks

- Further experimental investigation should involve different systems and different reaction mechanisms ($\gamma<1$).

-In particular, a next step forward in these kind of measurements would require a more detailed investigation, including a reliable estimation or minimization of systematic uncertainty on the velocity of the charged particles. This would permit a direct experimental estimation of $\langle D_z \rangle$, allowing for a corresponding experimental estimation of the global effect associated with the dynamically-emitted neutrons.

-Now we have the possibility to use in an extended way the Pulse-Shape discrimination on the Silicon detector for slow particles.

-Longer measurements involving targets and projectiles with same charge/mass and mass asymmetry. (vanishing values of $\langle D_Z \rangle$ independently from the reaction mechanism) could be very useful.