SCIENTIFIC REPORT

of the implementation of the research project

COLLECTIVE DYNAMICS, DISSIPATION AND FRAGMENTATION IN QUANTUM MESOSCOPIC SYSTEMS

(DINAMICA COLECTIVA, DISIPARE SI FRAGMENTARE IN SISTEME MEZOSCOPICE CUANTICE)

for the period october 2011 – december 2014

In this scientific report we present the most significant achievements in the research activity performed within the above-mentioned project in connection with the main tasks included in the proposal

For WP1. Objective: *Insight into the features of collective modes and of entrance channel dynamics in dissipative reactions with exotic nuclei*

In 2011, based on an analytic, schematic shell model in a harmonic oscillator potential we separated two independent dipole modes in neutron rich nuclei. One is associated to the out of phase oscillations of protons and neutrons which belongs to the nuclear core. The second corresponds to the vibrations of the excess neutrons against the (more) symmetric core. We started from a model developed by David Brink having the Hamiltonian:

$$H_{sm} = \sum_{i=1}^{A} \frac{\vec{p}_i^2}{2m} + \frac{K^2}{2} \sum_{i=1}^{A} \vec{r}_i^2$$

and performed the separation:

$$H_{sm} = H_{n\ int} + H_{p\ int} + H_{CM} + H_D$$

Here the first two terms are associated to the intrinsic motions of the protons and the neutrons while the term

$$H_D = \frac{A}{2mNZ} \vec{P}^2 + \frac{KNZ}{2A} \vec{X}^2$$

will correspond to the dipole vibration which describes the Giant Dipole Resonance. Finally the Hamiltonian

$$H_{CM} = \frac{1}{2Am} \vec{P}_{CM}^2 + \frac{KA}{2} \vec{R}_{CM}^2$$

characterizes the (spurious) Center of Mass motion. If X indicates the collective coordinates associated to the dipolar motion, representing the distance between the protons center of mass and neutrons center of mass respectively (all protons moves against all neutrons) then the canonically conjugated momentum for this coordinate is:

$$\vec{P} = \frac{NZ}{A}(\frac{1}{Z}\vec{P}_Z - \frac{1}{N}\vec{P}_N)$$

From TRK sum-rule is obtained the total cross section for Giant Dipole Resonance as:

$$\begin{aligned}\sigma_D = \int_0^{\infty} \sigma(E)dE = \frac{4\pi^2 e^2}{\hbar c}\sum_i E_i |\langle i|D|0\rangle|^2 = \\ \frac{4\pi^2 e^2}{\hbar c}\frac{1}{2}\langle 0|[D,[H_{sm},D]]|0\rangle = \\ \frac{2\pi^2 e^2}{\hbar c}\langle 0[D,[H_D,D]]0\rangle = \\ \frac{2\pi^2 e^2}{\hbar c}\frac{NZ}{A} = 60\frac{NZ}{A} mb\ MeV\end{aligned}$$

By introducing the pygmy dipole motion defined above we can generalize this result. If Y is the collective coordinate describing the position of the excess neutrons relative to the core center of mass while Xc is the distance between the CM of core and core neutrons respectively then the following relations are valid:

$$\vec{X} = \frac{N_e}{N}\vec{Y} + \frac{N_c A}{N A_c}\vec{X}_c$$

$$\vec{X}_c = \vec{R}_{p_c} - \vec{R}_{n_c} \quad \vec{Y} = \frac{N_c}{N_c + Z_c}\vec{R}_{n_c} + \frac{Z_c}{N_c + Z_c}\vec{R}_{p_c} - \vec{R}_{n_e}$$

$$\vec{X} = \vec{R}_{p_c} - \vec{R}_n = \vec{R}_{p_c} - \frac{N_e}{N}\vec{R}_{n_e} - \frac{N_c}{N}\vec{R}_{n_c}$$

The shell model Hamiltonian can be decomposed as follows:

$$\begin{aligned}H_{sm} = H_{n_c\ int} + H_{p_c\ int} + H_{e\ int} + \\ \frac{1}{2Am}\vec{P}_{CM}^2 + \frac{KA}{2}\vec{R}_{CM}^2 + \\ \frac{A_c}{2Z_c N_c m}\vec{P}_c^2 + \frac{KN_c Z_c}{2A_c}\vec{X}_c^2 + \\ \frac{A}{2A_c N_e m}\vec{P}_y^2 + \frac{KN_e A_c}{2A}\vec{Y}_e^2 = \\ H_{n_c\ int} + H_{p_c\ int} + H_{e\ int} + H_{CM} + H_c + H_y\end{aligned}$$

The canonically conjugated momentum associated to the collective coordinate defined above are given by:

$$\vec{P}_c = \frac{N_c Z_c}{A_c}\left(\frac{1}{Z_c}\vec{P}_{Z_c} - \frac{1}{N_c}\vec{P}_{N_c}\right)$$

$$\vec{P}_y = \frac{N_e A_c}{A}\left(\frac{1}{A_c}(\vec{P}_{Z_c} + \vec{P}_{N_c}) - \frac{1}{N_e}\vec{P}_{N_e}\right)$$

$$\vec{P}_{CM} = \vec{P}_Z + \vec{P}_{N_c} + \vec{P}_{N_e}$$

This treatment allows us to determine, for the first time, the upper limit of the fraction of cross section exhausted by Pygmy Dipole mode as is proved below:

$$\sigma_y = \int_0^\infty \sigma_y(E)dE = \frac{4\pi^2 e^2}{\hbar c}\sum_i E_i |\langle i|D_y|0\rangle|^2 =$$
$$\frac{4\pi^2 e^2}{\hbar c}\frac{1}{2}\langle 0|[D_y,[H_{sm},D_y]]|0\rangle =$$
$$\frac{2\pi^2 e^2}{\hbar c}\langle 0|[D_y,[H_y,D_y]]|0\rangle =$$
$$\frac{N_e Z_c}{N A_c}\frac{2\pi^2 e^2}{\hbar c}\frac{NZ}{A} = \frac{N_e Z_c}{N A_c}\sigma_D$$

For example in the case of Tin nucleus having 82 neutrons to the pygmy dipole can be ascribed 19.5 % of the total cross section. Analogously in the case of 68Ni isotope some one find 11%. Such estimates are also very useful for the experiments since they provide a first guess of what should be expected when pygmy response is investigated.

The next step of our study concerning the dipolar collective response in exotic nuclei was to compare the predictions of the schematic model discussed above with more realistic calculations based on transport equations of Boltzmann-Nordheim-Vlasov (BNV) type

$$\frac{\partial f_q}{\partial t} + \frac{\mathrm{p}}{m}\frac{\partial f_q}{\partial \mathrm{r}} - \frac{\partial U_q}{\partial \mathrm{r}}\frac{\partial f_q}{\partial \mathrm{p}} = I_{coll}[f]$$

These equations represent the semi-classical limit of the Time-Dependent Hartree-Fock (TDHF) equations and therefore are appropriate to explore the collective features of nuclear systems. A new numerical code was developed in order to explore the dynamics of pygmy dipole mode, to calculate the strength function and transition densities and to observe the influence of the symmetry energy on its features.

In the same time new analytical calculations were initiated aiming to test various pictures for this motion corresponding to a microscopic analog of the hydrodynamical approaches proposed until now.

In 2012, the theoretical investigations based on this numerical program provided several indications about the manifestation of the pygmy dipole resonance in neutron rich nuclei as a collective mode with an energy centroid well below the GDR peak. For 132Sn the PDR position was identified around 8.5 MeV, weakly influenced by the dependence with the density of the symmetry energy as is seen from the figure below (V. Baran et al., Phys. Rev C 85, 2012).

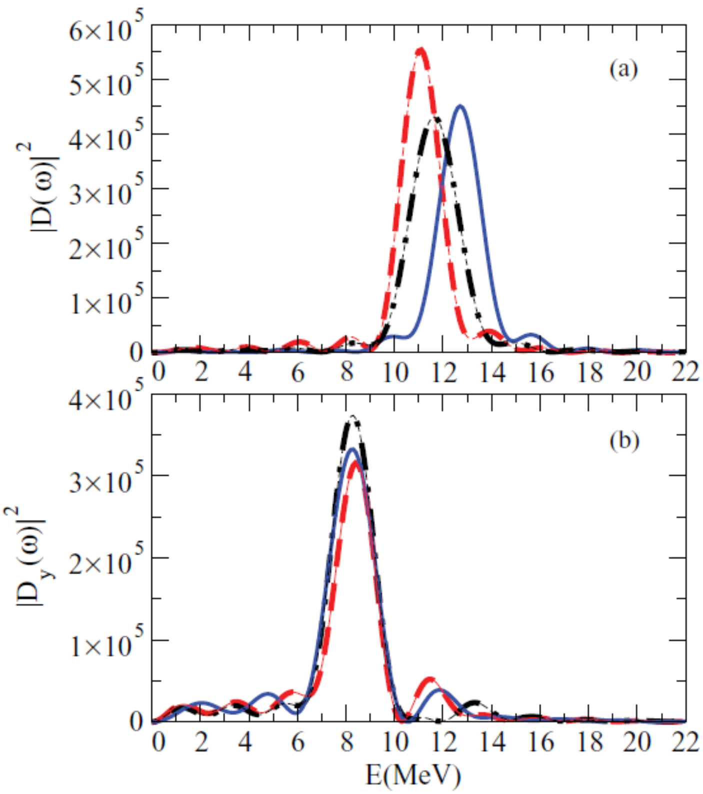
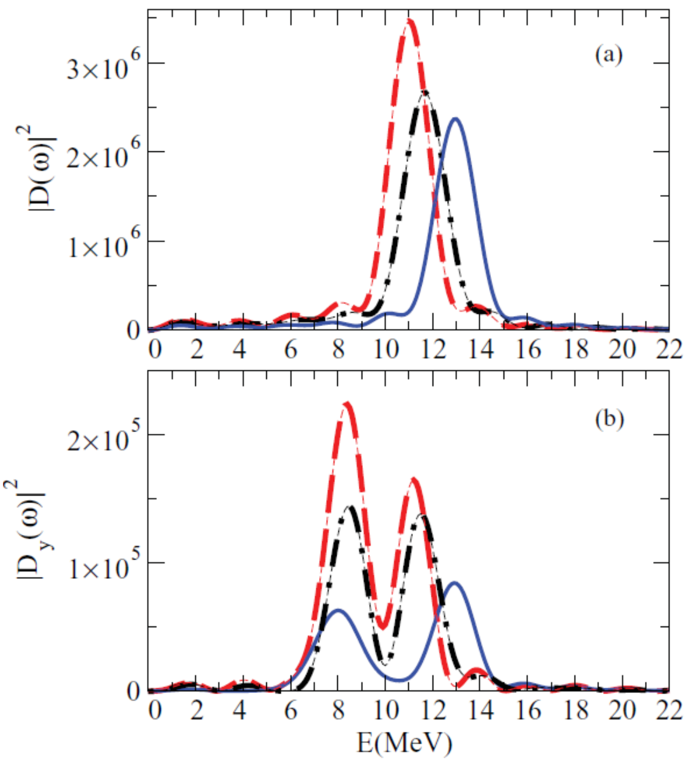


FIG. 3. (Color online) The power spectra of total dipole (a) and dipole D_y (b) (in fm^4/c^2) for asysoft [the blue (solid) lines], asystiff [the black (dot-dashed) lines], and asysuperstiff [the red (dashed) lines] EoS. Pygmy-like initial conditions.

On the other hand the Energy-Weighted Sum Rule is strongly influenced by the slope parameter L which characterizes the symmetry energy dependence with density around saturation. For Tin 132 we obtained a fraction of EWSR exhausted by pygmy mode between 2.8 % and 4.6 % when we pass from asy-soft to asy-superstiff EOS, in nice agreement with the experimental information reported about this system. It was demonstrated that not all excess neutrons are involved in the pygmy mode, part of them being blocked by the core as can be seen from the power spectrum of pygmy dipole Dy in the next figure:



This behavior can explain way the exhausted sum-rule is smaller than the upper limit predicted by the molecular sum-rule in the schematic model discussed above. The original results of our studies were published in Physical Review C (as Rapid Communication), in Romanian Journal Of Physics and were presented at some international conferences.

In 2013, we explored the mass dependence of the collective pygmy response and the role of the neutron skin on its dynamics. As we shall show later, following our investigations, a very interesting correlation between PDR and the development of neutron skin was clearly evidenced. The neutron skin thickness can be determined once the one-body distribution functions for protons and neutrons are calculated. Indeed the local densities are

$$\rho_q(\vec{r}, t) = \int \frac{2d^3\mathbf{p}}{(2\pi\hbar)^3} f_q(\vec{r}, \vec{p}, t)$$

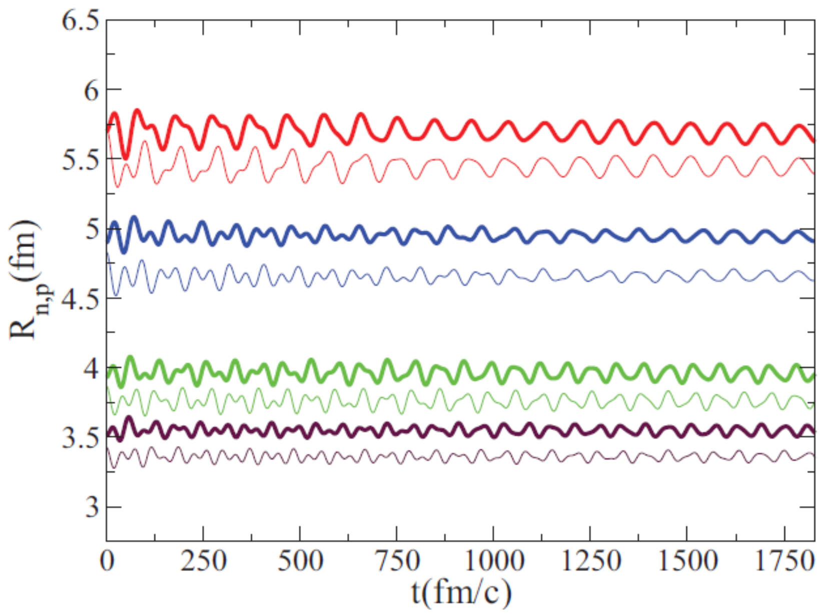
and the size of neutron skin is obtained as:

$$\Delta R_{np} = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle} = R_n - R_p$$

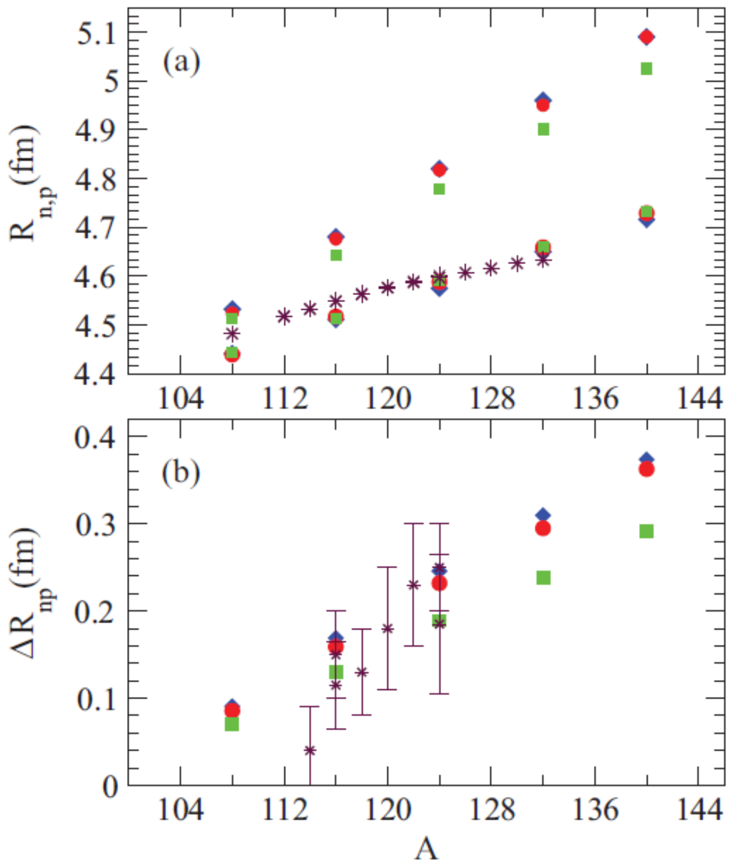
where:

$$\langle r_q^2 \rangle = \frac{1}{N_q} \int r^2 \rho_q(\vec{r}, t) d^3\mathbf{r}$$

A possible method to obtain the neutron and proton mean square radius is by observing their small oscillations about the equilibrium value. For 208Pb, 132Sn, 68Ni si 48Ca these quantities are plotted in the Figure which follows (V. Baran et al. Phys. Rev C 2013).



In next Figure, for a chain of Sn isotopes are plotted the experimental values (stars) of proton mean square radius as well as the mean square radii determined numerically considering three different asy-EOS.



We notice a reasonable agreement between the proton mean square radius determined with our method and experimental data.

Then the dipolar response for all considered systems was obtained considering a GDR-like excitation:

$$V_{\text{ext}} = \eta\delta(t - t_0)\hat{D} \text{ at } t = t_0$$

The strength function:

$$S(E) = \sum_{n>0} |\langle n|\hat{D}|0\rangle|^2 \delta(E - (E_n - E_0))$$

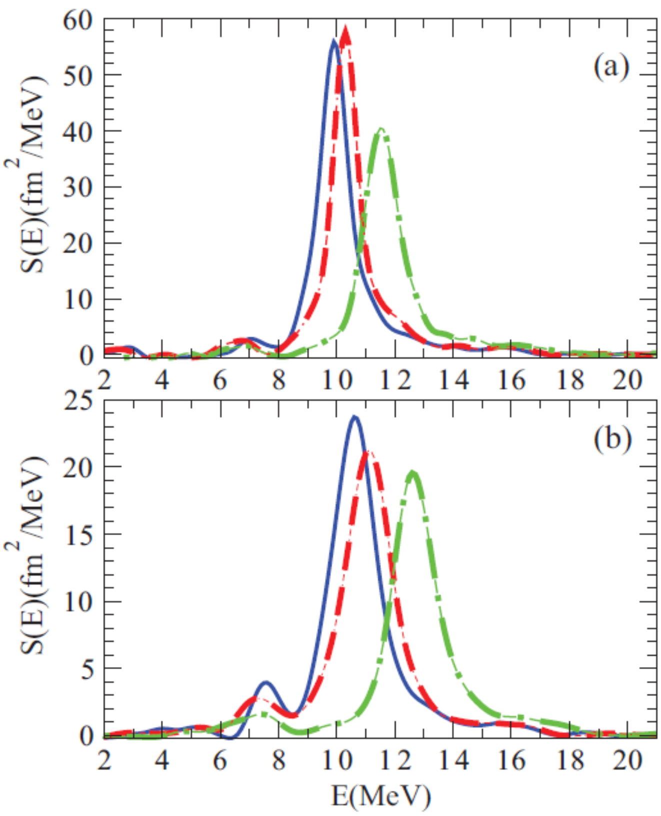
is obtined from the Fourier transform of the dipole moment:

$$S(E) = \frac{\text{Im}(D(\omega))}{\pi\eta\hbar}$$

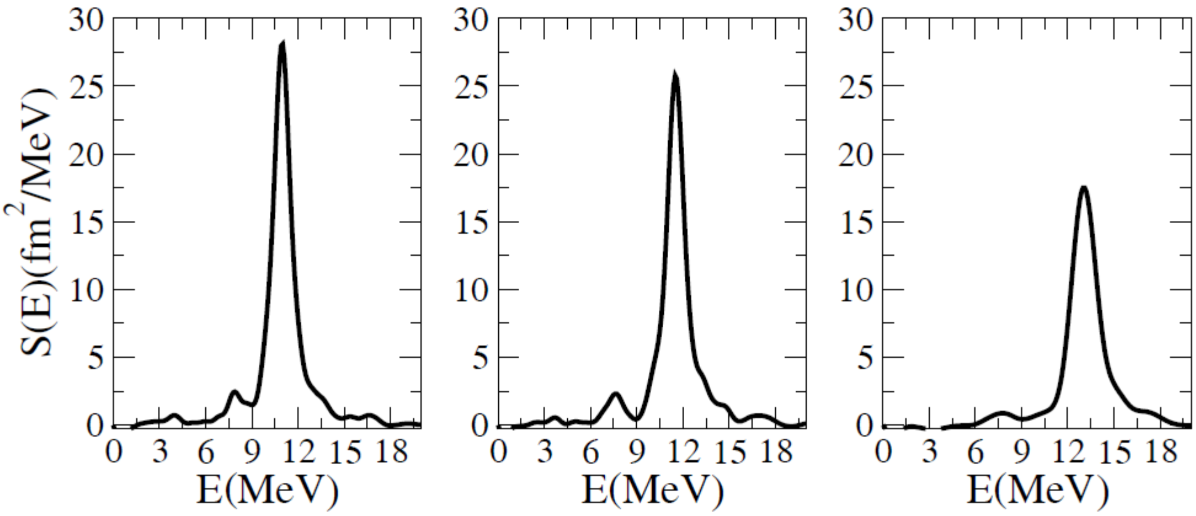
where:

$$D(\omega) = \int_{t_0}^{t_{\max}} D(t)e^{i\omega t}dt$$

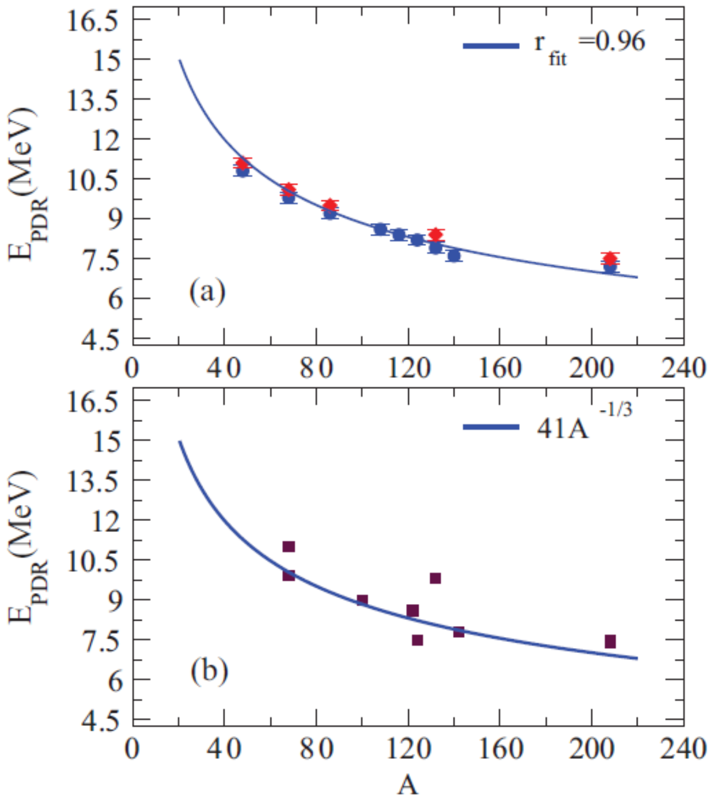
In the case of 208Pb si 140Sn the results of this analysis are presented for the three parametrizations with density of the symmetry energy:



From the strength function for 132Sn (see the next Figure) derived in this way is possible to identify a peak associated with the collective response at 7.5-8 MeV. This response we associate with Pygmy Dipole Resonance (PDR) Rezonanta Dipolara Pygmy (PDR).



Plotting the PDR energy centroid as a function of mass (red and blue symbols in the figure below) we observe a good agreement with experimental data (maroon squares).



Our fit provides a mass dependence of PDR energy centroid with mass:

$$E_{\text{PDR}} = 41 A^{-1/3}\ \text{MeV}$$

which describes quite well the experimental data (V. Baran et al. Phys. Rev. C 2013). Once the strength function was determined the EWSR exhausted by PDR is obtained as:

$$m_{1,y} = \int_{\text{PDR}} E S(E) dE$$

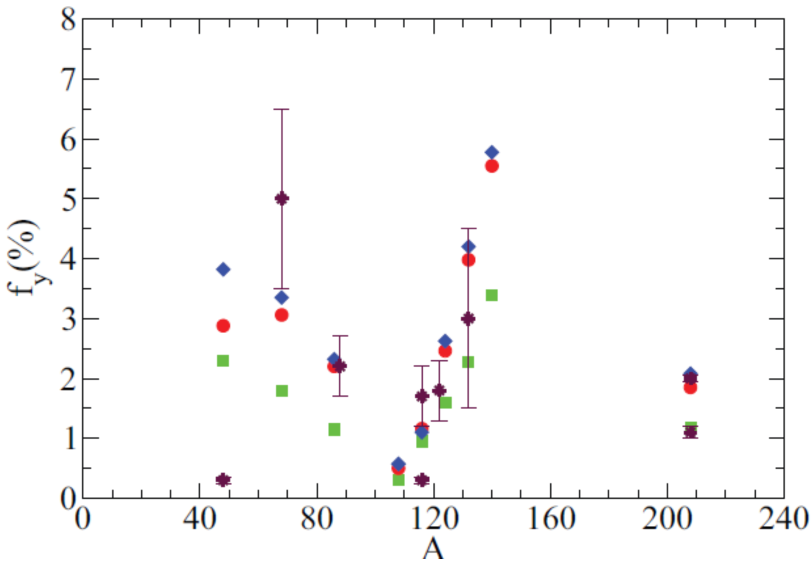
The corresponding fraction is calculated as the ratio:

$$f_y = \frac{m_{1y}}{m_1}$$

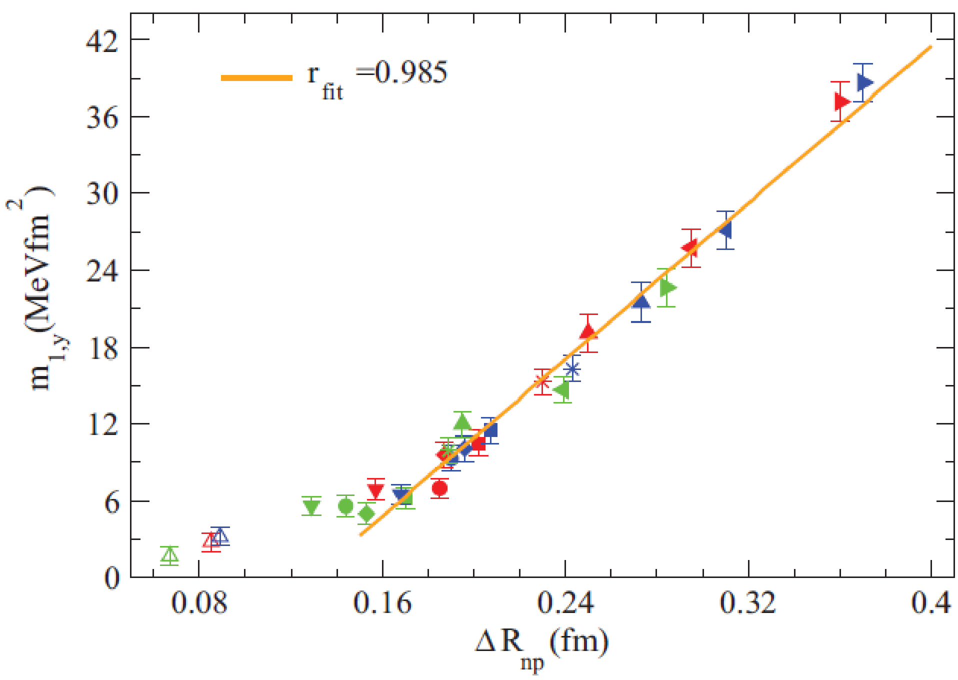
where

$$m_1 = \int_0^\infty E S(E) dE$$

Our microscopic transport study of PDR provides also for this quantity (green squares asy-soft, red circles asy-stiff, blue diamonds asy-superstiff) a good agreement with the experimental data available in the literature (the stars in the next figure) in all mass regions.



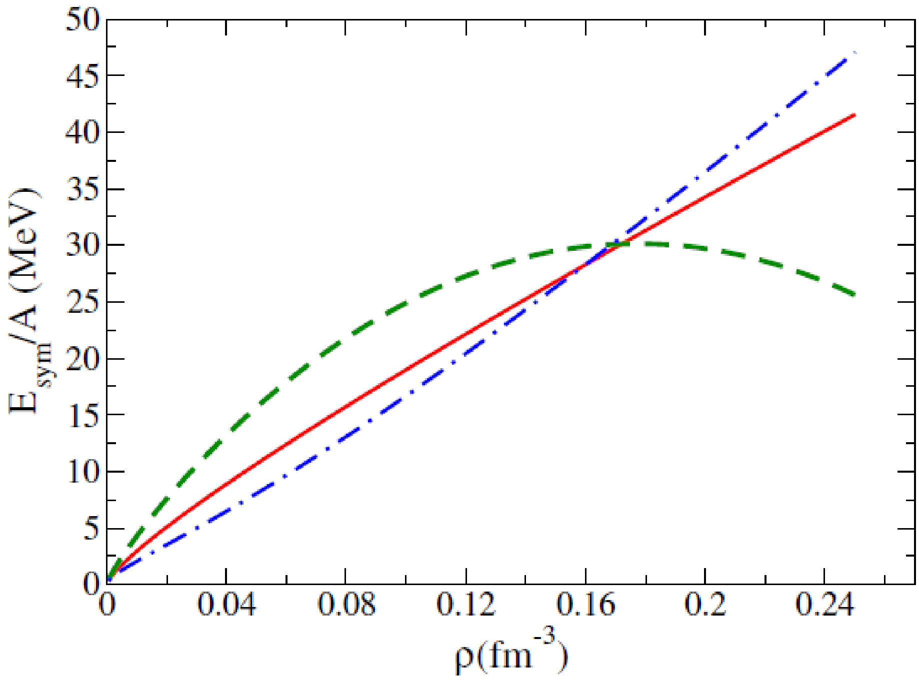
Our analysis suggests a new correlation between the EWSR exhausted by PDR and the neutron skin thickness. An universal linear correlation with a slope 150MeV fm is evidenced for systems with neutrons skins greater than 0.15fm as is seen from the figure below (V. Baran et al. Phys. Rev. C 2013).



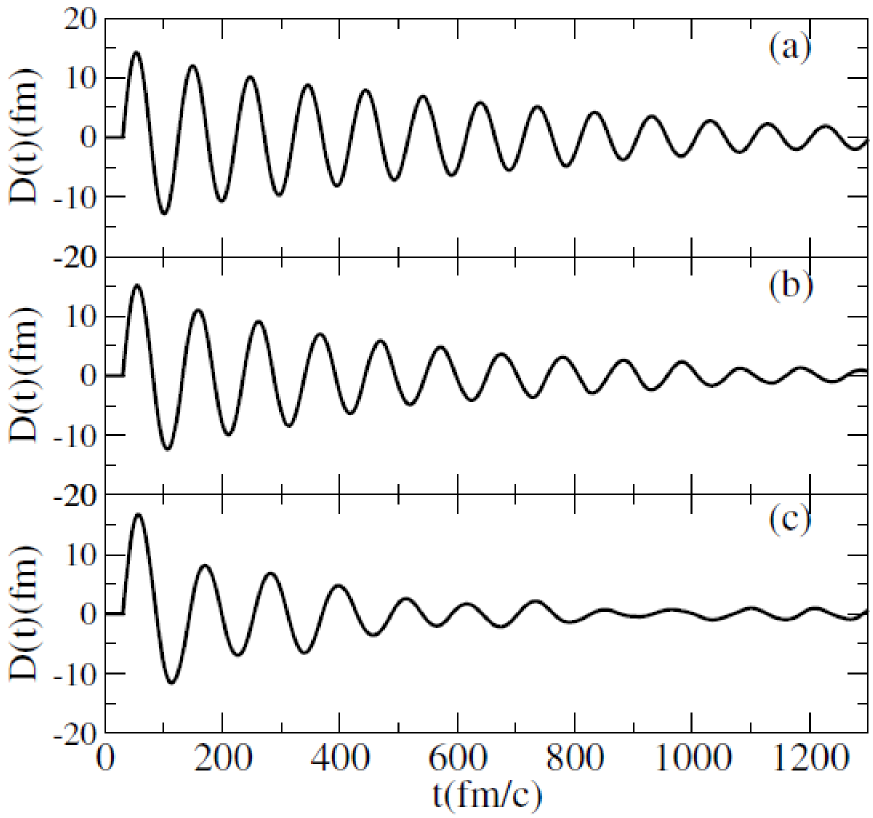
We also elaborated a new schematic model which will allow for additional analytical results which, we hope, will clarify some of the features unveiled by the numerical studies. We intend to have a manuscript containing these results in 2014.

In 2013 the original results related to these arguments were published in the journals Physical Review C and Romanian Journal of Physics and were reported at several international conferences as can be seen from the list at the end of this report. We underline that these investigations are relevant for the future experiments which are expected at the Extreme Light Infrastructure-Nuclear Physics (ELI-NP) facility.

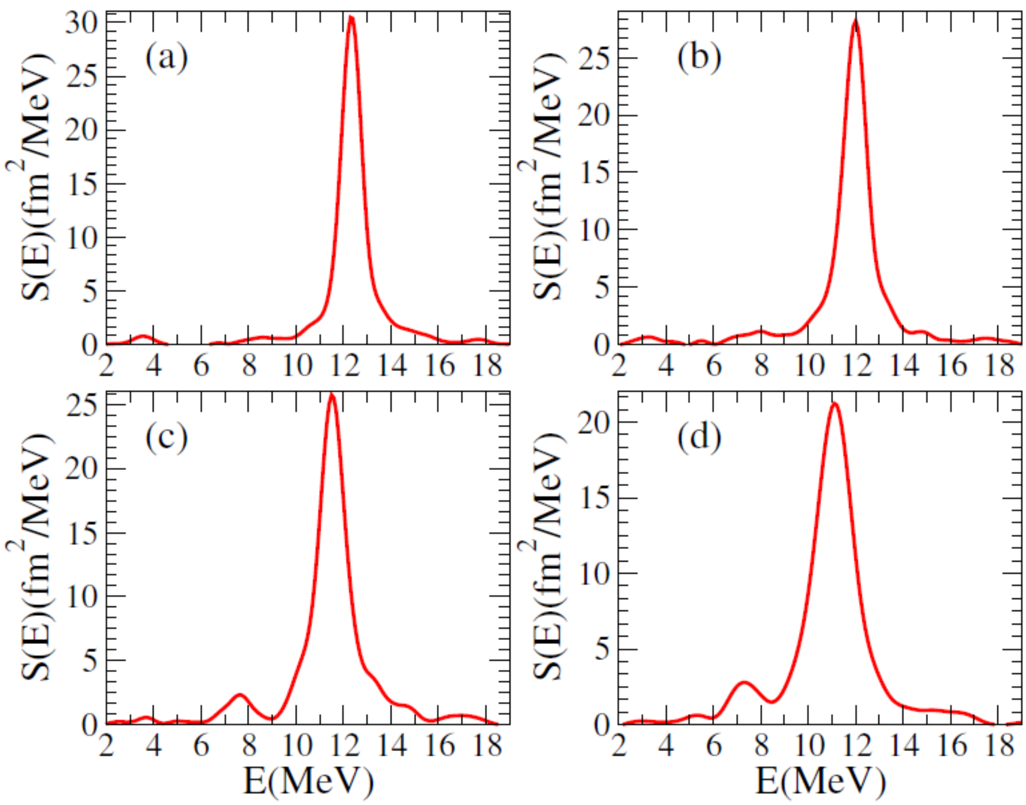
In 2014 we extended the investigations of the dipolar response to the dipolar polarizability. In the following we present the new results published in European Physical Journal D (2014). We consider for the symmetry energy three parameterizations with density providing similar values at saturation but which manifest very different slopes around this point (see the figure below). In this way we can explore how the slope parameter L affects the collective response of finite nuclear systems.



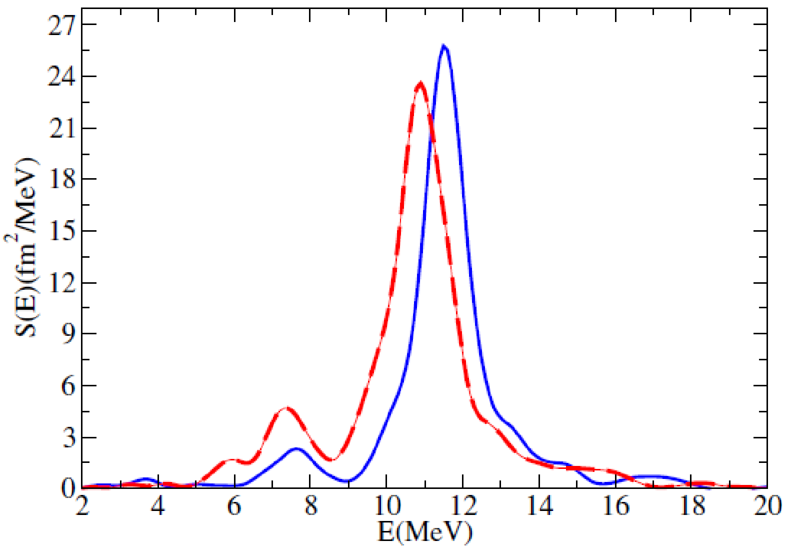
The time evolution of the dipole moment following a GDR-like initial condition for 108Sn (a), 124Sn (b) and 148}Sn (c) is shown for asystiff EOS in the next figure below.



By employing the procedure described before we calculated the strength function and followed the development of the pygmy response when the number of neutrons in excess increases as is shown below for 108Sn (a), 116Sn (b), 124Sn (c) and 132Sn (d) systems.



The comparison between the strength function for 132Sn [the blue (solid) lines] and 148Sn [the red (dashed) lines] in the figure below demonstrates very clearly the role of neutrons in excess upon the pygmy dipole response.



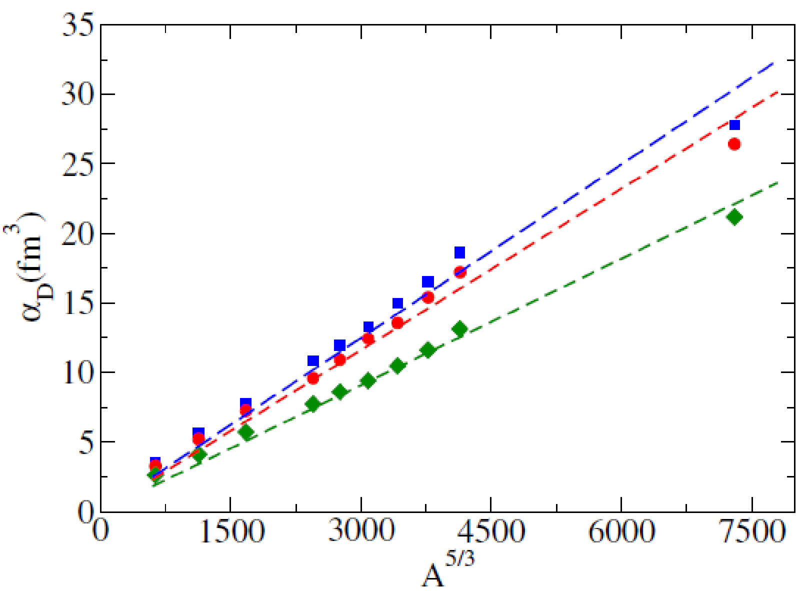
Let us observe that from S(E) one can determine the nuclear dipole polarizability:

$$\alpha_D = 2e^2 \int_0^\infty \frac{S(E)}{E} dE$$

The Migdal estimation of polarizability, valid for large systems, provides a A^(5/3) dependence with mass:

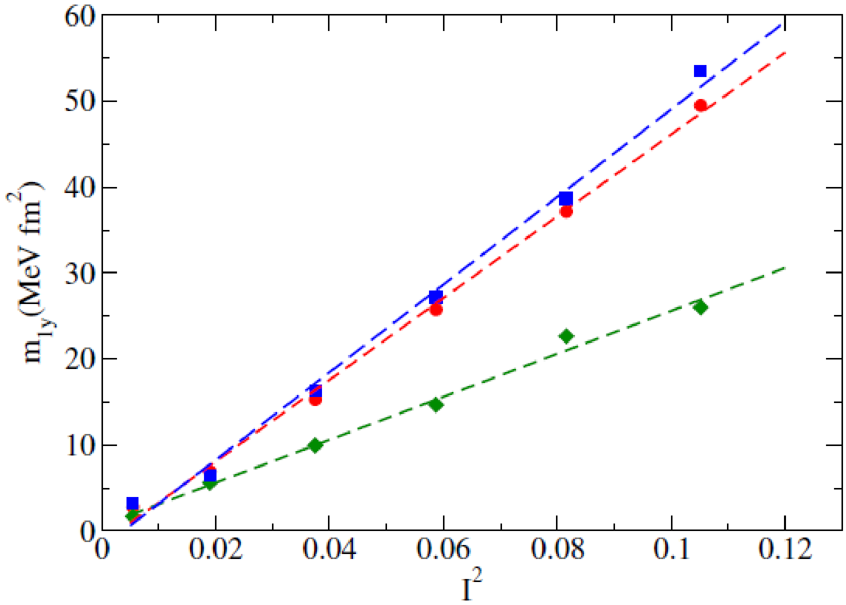
$$\alpha_D = \frac{e^2 A < r^2 >}{24\epsilon_{sym}} = \frac{1.44e^2}{40\epsilon_{sym}} A^{\frac{5}{3}}$$

As the next figure below shows



the linear correlation with A^(5/3) is quite well verified. Nevertheless a clear dependence of the slope with asy-EOS is evidenced. This can be related to the surface effects and the interplay between surface and volume symmetry energy, expected to manifest in finite systems and which will be influenced by the symmetry energy slope parameter L (V. Baran et al. Eur. Phys. J. D (2014)).

Moreover, from our calculations for Sn isotopes, a quadratic correlation appears to describe quite well the observed dependence of EWSR exhausted by PDR with the isospin parameter I. We remark that, as in the case of polarization, the linear correlation between m_{1,y} and I^2 is influenced by the symmetry energy slope parameter L. We can therefore conclude that polarization effects in the isovector density play an important role in the dynamics of Pygmy Dipole Resonance.



In the final section of this chapter we present new calculations on the dipole response within a generalized schematic model based on the Tamm-Dancoff Approximation and the Random-Phase Approximation with separable interactions. If we relax the condition to have only one coupling constant for the separable interaction the TDA equations becomes (see V. Baran et al. arXiv:1411.9665v1):

$$\epsilon_i X_i^{(n)} + \lambda_1 Q_i \sum_{j \le i_c} Q_j^* X_j^n + \lambda_2 Q_i \sum_{j > i_c} Q_j^* X_j^n = E_n X_i^{(n)} \quad \text{if} \quad i \le i_c, \qquad (9)$$

$$\epsilon_i X_i^{(n)} + \lambda_2 Q_i \sum_{j \le i_c} Q_j^* X_j^n + \lambda_3 Q_i \sum_{j > i_c} Q_j^* X_j^n = E_n X_i^{(n)} \quad \text{if} \quad i > i_c, \qquad (10)$$

with the solutions

$$X_i^{(n)} = \frac{N^c}{E_n - \epsilon_i} Q_i \quad if \quad i \leq i_c,$$
$$X_i^{(n)} = \frac{N^e}{E_n - \epsilon_i} Q_i \quad if \quad i > i_c.$$

Here the normalization factors are given by

$$N^c = \lambda_1 \sum_{j \leq i_c} Q_j^* X_j^n + \lambda_2 \sum_{j > i_c} Q_j^* X_j^n,$$
$$N^e = \lambda_2 \sum_{j \leq i_c} Q_j^* X_j^n + \lambda_3 \sum_{j > i_c} Q_j^* X_j^n.$$

and satisfy the homogeneous system of equations:

$$\Big(\lambda_1 \sum_{i \leq i_c} \frac{|Q_i|^2}{E_n - \epsilon_i} - 1\Big) N^c + \lambda_2 \sum_{i > i_c} \frac{|Q_i|^2}{E_n - \epsilon_i} N^e = 0,$$
$$\lambda_2 \sum_{i \leq i_c} \frac{|Q_i|^2}{E_n - \epsilon_i} N^c + \Big(\lambda_3 \sum_{i > i_c} \frac{|Q_i|^2}{E_n - \epsilon_i} - 1\Big) N^e = 0.$$

If we resume to the degenerate case, the condition to have nontrivial solutions

$$(E_n - \epsilon)^2 - (\lambda_1 \alpha + \lambda_3 \beta)(E_n - \epsilon) + (\lambda_1 \lambda_3 - \lambda_2^2)\alpha\beta = 0,$$

we obtain the TDA collective energies

$$E_n^{(1)} = \epsilon + \frac{(\lambda_1 \alpha + \lambda_3 \beta)}{2} \left(1 + \sqrt{1 - \frac{4(\lambda_1 \lambda_3 - \lambda_2^2)\alpha\beta}{(\lambda_1 \alpha + \lambda_3 \beta)^2}}\right)$$
$$E_n^{(2)} = \epsilon + \frac{(\lambda_1 \alpha + \lambda_3 \beta)}{2} \left(1 - \sqrt{1 - \frac{4(\lambda_1 \lambda_3 - \lambda_2^2)\alpha\beta}{(\lambda_1 \alpha + \lambda_3 \beta)^2}}\right).$$

If

$$\lambda_1 \alpha >> \lambda_3 \beta:$$

simple expressions for the two energies are obtained:

$$E_n^{(1)} \approx \epsilon + (\lambda_1\alpha + \lambda_3\beta),$$
$$E_n^{(2)} \approx \epsilon + \frac{(\lambda_1\lambda_3 - \lambda_2^2)\alpha\beta}{(\lambda_1\alpha + \lambda_3\beta)}.$$

One of the solutions is closer to the value associated to the collective mode obtained in the usual TDA approach while the other one is much closer to unperturbed value. It is interesting to observe that now the strength of all the transition probabilities towards the unperturbed states is distributed only between these two states:

$$|\langle n_{c,1}|Q|0\rangle|^2 + |\langle n_{c,2}|Q|0\rangle|^2 = \alpha + \beta = \sum_i |Q_i|^2.$$

Including ground state correlations the RPA calculations leads to the energies:

$$E_{n,RPA}^{(1)2} = \epsilon^2 + 2\epsilon(E_{n,TDA}^{(1)} - \epsilon) = \epsilon(2E_{n,TDA}^{(1)} - \epsilon),$$
$$E_{n,RPA}^{(2)2} = \epsilon^2 + 2\epsilon(E_{n,TDA}^{(2)} - \epsilon) = \epsilon(2E_{n,TDA}^{(2)} - \epsilon),$$

It is interesting to notice that within the RPA treatment the total EWSR is shared only by these two states

$$E_{n,RPA}^{(1)}|\langle n_{c,1}|Q|\tilde{0}\rangle|^2 + E_{n,RPA}^{(2)}|\langle n_{c,2}|Q|\tilde{0}\rangle|^2 = \sum_i \epsilon|Q_i|^2,$$

Therefore both of them manifest a collective nature. We discuss the predictions of these schematic models for two specific nuclear systems 68Ni and 132Sn. We determined the position of the energy centroids corresponding to the two collective states both in TDA (black lines) and RPA (red lines) calculations see the next figure. For 68Ni two values were chosen for the number of excess neutron, namely N_e=12 which corresponds to the extreme case N_e=N-Z (dashed lines) and N_e=6 (solid lines). We observe that the ground state correlations are influencing stronger the GDR peak and that the RPA predictions are closer to the experimental values (around 17.8 MeV). The PDR energy centroid does not change too much when we modify the value of N_e, nor when we include the ground state correlations. The experimental value recently reported is E_{PDR,exp}=9.55 MeV. In the case on 132Sn for N_e=12 the position of the PDR energy centroid changes from E_{PDR}=8.5 MeV to 7.5 MeV when the coupling constant is varied. A steeper decrease is observed for a greater value of N_e.

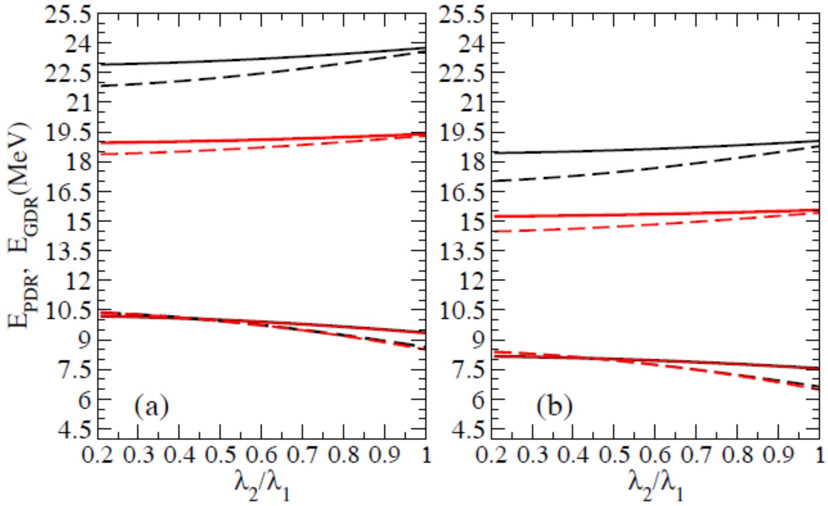


FIG. 1: (Color online) The GDR and PDR energy centroids as a function of the ratio λ_2/λ_1. The black lines refers to the TDA while the red lines to RPA calculations. (a) For ^{68}Ni the solid lines correspond to $N_e = 6$; the dashed lines corresponds to $N_e = 12$. (b) For ^{132}Sn the solid lines correspond to $N_e = 12$; the dashed lines corresponds to $N_e = 32$.

We also investigated the evolution the EWSR exhausted by the two collective modes when the coupling constant is changed. A stronger coupling reduces the fraction ascribed to pygmy dipole mode.

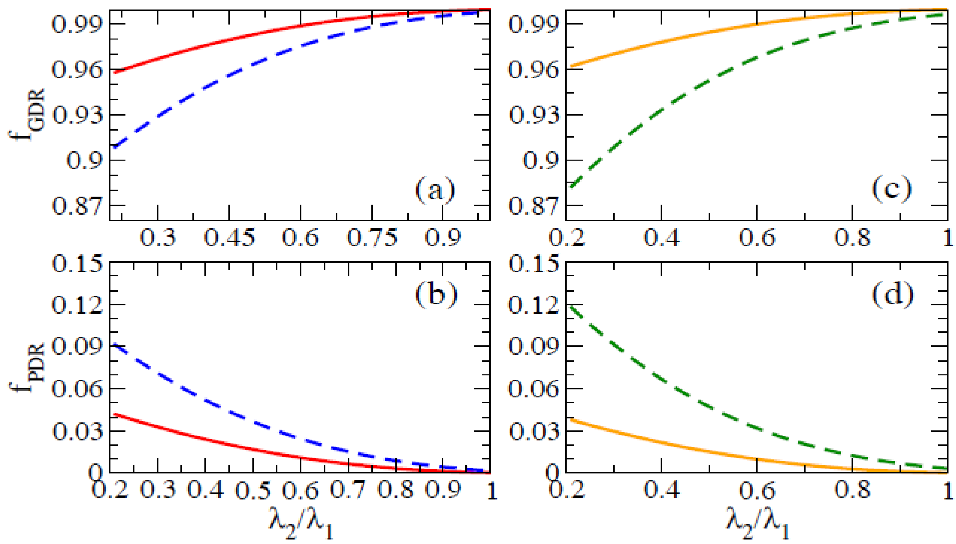
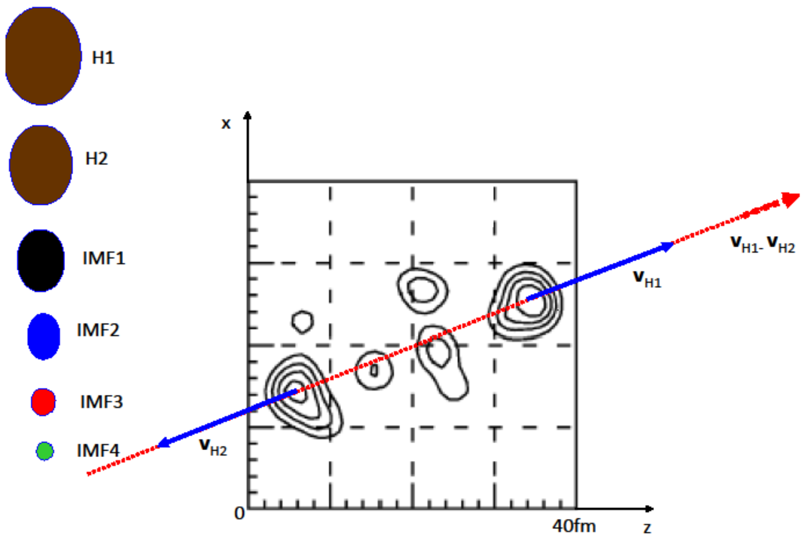


FIG. 2: (Color online) (a) The EWSR fraction exhausted by GDR in RPA calculations for ^{68}Ni. $N_e = 6$ (red solid lines) and $N_e = 12$ (blue dashed lines). (b) The EWSR fraction exhausted by PDR in RPA calculations for ^{68}Ni. $N_e = 6$ (red solid lines) and $N_e = 12$ (blue dashed lines). (c) The EWSR fraction exhausted by GDR in RPA calculations for ^{132}Sn. $N_e = 6$ (orange solid lines) and $N_e = 12$ (blue dashed lines). (d) The EWSR fraction exhausted by PDR in RPA calculations for ^{132}Sn. $N_e = 6$ (orange solid lines) and $N_e = 12$ (green dashed lines).

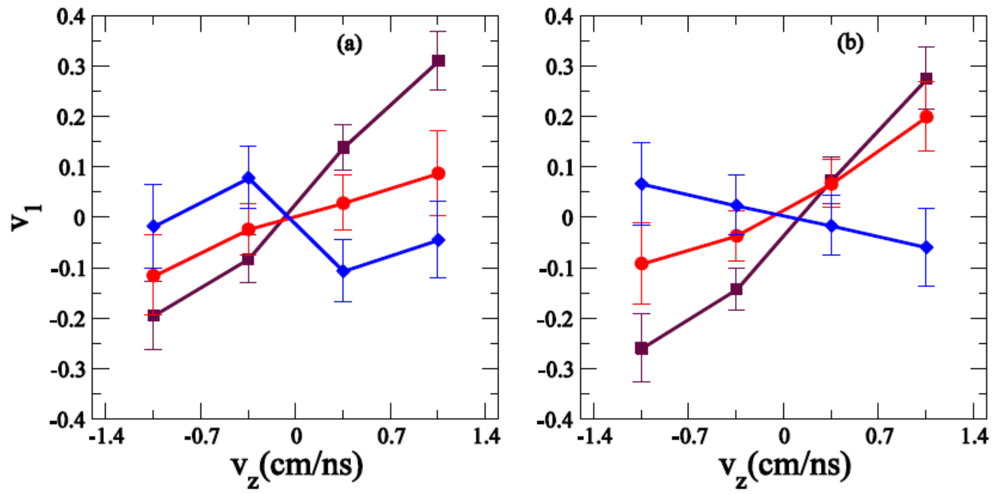
For WP2. Objective: ***Advanced investigations on the fragmentation mechanisms at Fermi energies.***

During the years 2011 and 2012, in the framework of a microscopic transport model based on the Boltzmann-Nordheim-Vlasov, Stochastic Mean Field (SMF), was studied the fragmentation process of the systems Sn124+Sn124 la 50AMeV at 50AMeV and impact parameter b=4fm, Sn124+Ni64 and Sn112+Ni58 at impact parameter b=6fm and 35A MeV energies. In the isospin channel were employed two different parameterizations with density.

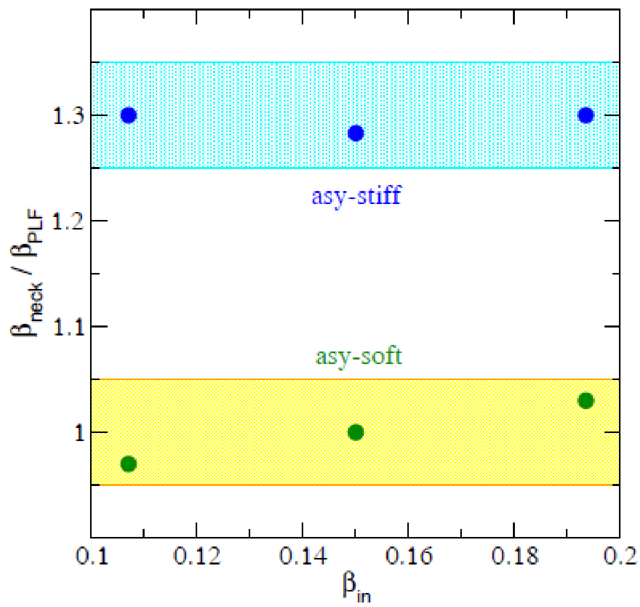


An important result regarding the nuclear fragmentation at Fermi energies was the calculation of collective flow parameters v1 and v2 respectively for the Intermediate Mass Fragments at the transition from the multifragmentation to neck fragmentation, more precisely at impact parameter b=4fm. Was concluded that certain specific signatures of fragmentation dynamics are reflected in the dependence of v1 on the longitudinal velocity and the dependence of v2 on transverse momentum.

We shall extend this analysis to a broader range of of impact parameters (between 3fm and 5 fm) which corresponds to the transition from multifragmentation to neck fragmentation, a transition insufficiently explored until now. We also intend to improve the statistics by a factor ten, which now is possible as a result of the computational facilities which this grant made possible. This allows a more detailed analysis of various correlations between kinematic observables and isospin degree of freedom, of interest for the future experiments at various facilities over the world.

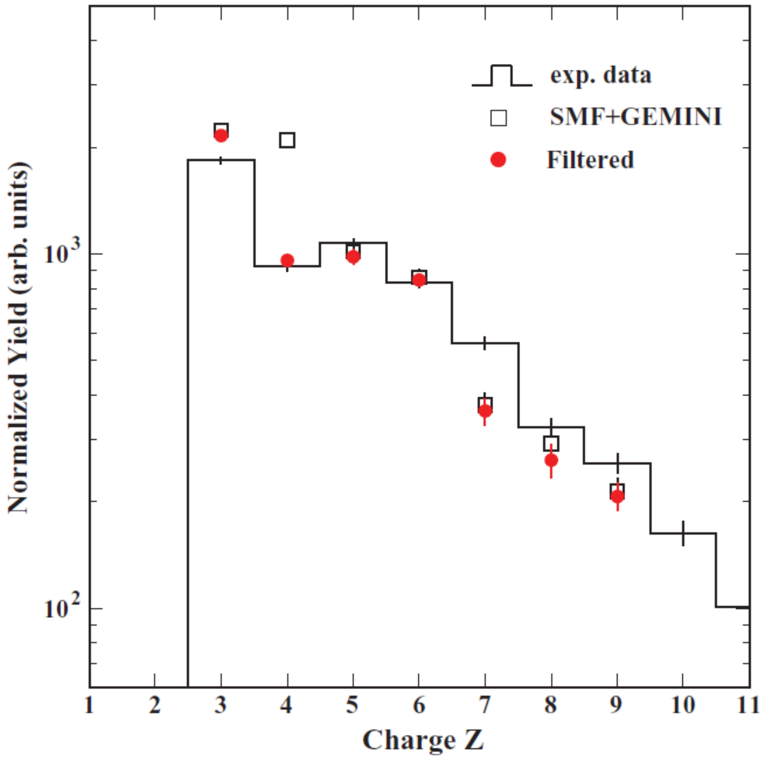


The observed kinematic properties of the produced fragments, including velocity and angular distributions, are quite well reproduced in the case of Sn+Ni reactions. From the distribution of the average value of the ratio N/Z (N is the neutrons number, Z is the protons number) as a function of the angle between the separation axis and fragmentation axis, is observed that the asy-stiff equation of state provide results closer to the experiments.



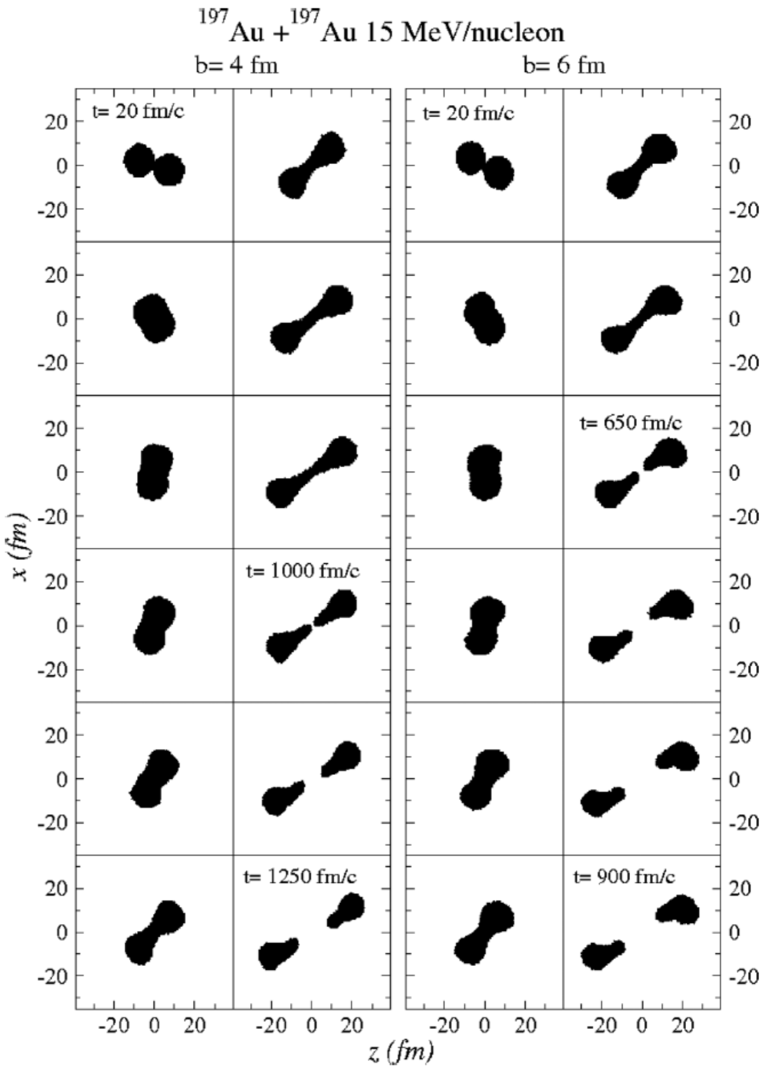
For a proper comparison with experimental data was also included the effect of the secondary decays. These in general are reducing the sensitivity to the symmetry energy. Nevertheless the proposed observables are providing robust information about the neck fragmentation at intermediate energies and the isospin dynamics. Moreover they allow a clear separation of the effects associated with the non-equilibrium, early stages of the reaction.

To exemplify, a nice agreement between the theoretical predictions and experimental data was revealed for the charge distribution of the intermediate mass fragments as is seen from the figure below.

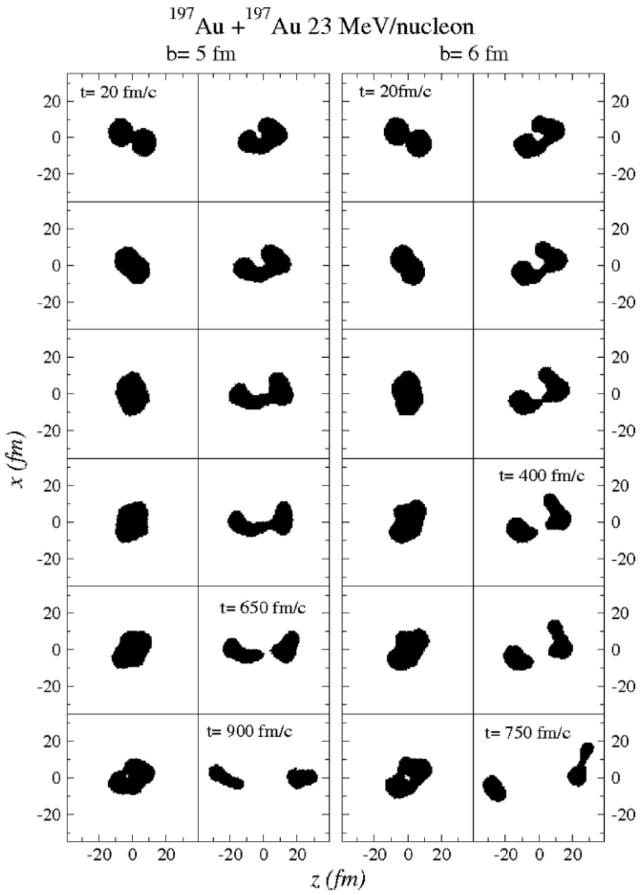


The original results of these investigations were included in two papers published in 2012 in Physical Review C and in a work which appeared in The European Physical Journal A in 2014.

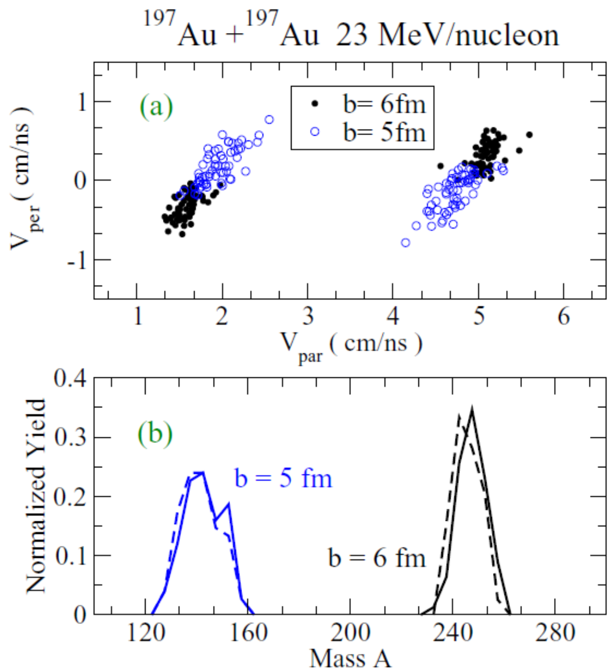
In 2014 the ternary events in the heavy ion collisions at energies between 10 AMeV and 30 AMeV were studied within the Stochastic Mean Field model. These events have a dynamical origin and occur in semi-central collisions where the formation of excited systems in various conditions of shape and angular momentum is observed. This fragmentation mode may emerge from the combined action of surface (neck) instabilities and angular momentum effects. We focus first on the study of the 197Au+197Au reaction at 15 AMeV at semi-central impact parameters which manifest as a strongly damped reaction having predominantly a binary character. However, break-up events into three or four massive fragments of comparable mass are also reveled. The ternary events are dominated by configurations where the heaviest fragment, close to the 197Au mass is recognized as the remnant of the projectile (PLF) or the target (TLF), while the other two fragments, denoted as F1 and F2, are generated by the subsequent break-up of TLF or PLF. The contour plots of the density projected on the reaction plane, calculated with SMF at 15AMeV at several times are plotted in the figure below for two values of the impact parameters b=4fm (left panel) and b=6fm respectively (right panel). In this window of impact parameters the reaction is rather dissipative and an intricate neck dynamics is already perceveid, leading eventually to the possibility of observing multiple breakups on longer time scales. The neutron-rich neck region connecting the two reaction partners survives quite a long time, 500-1000 fm/c, favoring the development of surface instabilities and mean-filed fluctuations, leading to a variety of configurations for the reaction outcome.



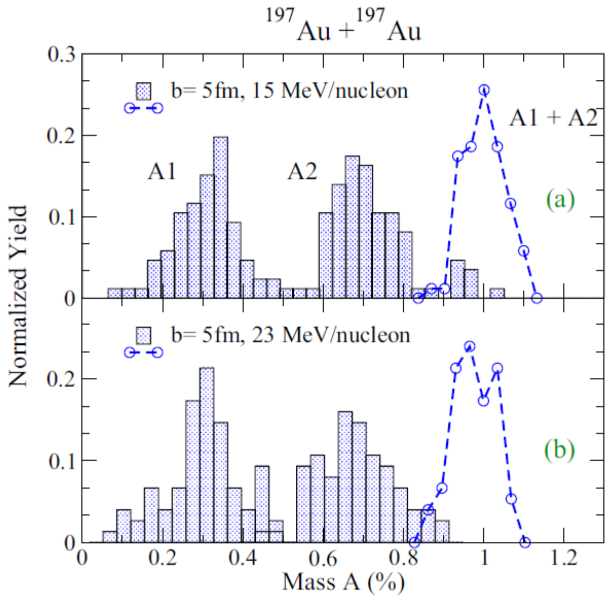
Rather deformed primary PLF-TLF are observed, which may split, by further breakup, into massive fragments of comparable size. This effect is quite pronounced in the impact parameter window considered, whereas for more central or more peripheral collisions, rather compact PLF-TLF fragments are emerging from the reaction path. The next figure shows density contour plots obtained for the same reaction but at 23 AMeV and impact parameters b=5, 6 fm. Is observed that now the fragmentation times become shorter and the neck region is mostly absorbed by one of the two initial,excited fragments (PLF or TLF) inducing the formation of a rather elongated object, which may eventually break up, accompanied by a fragment of more compact shape.



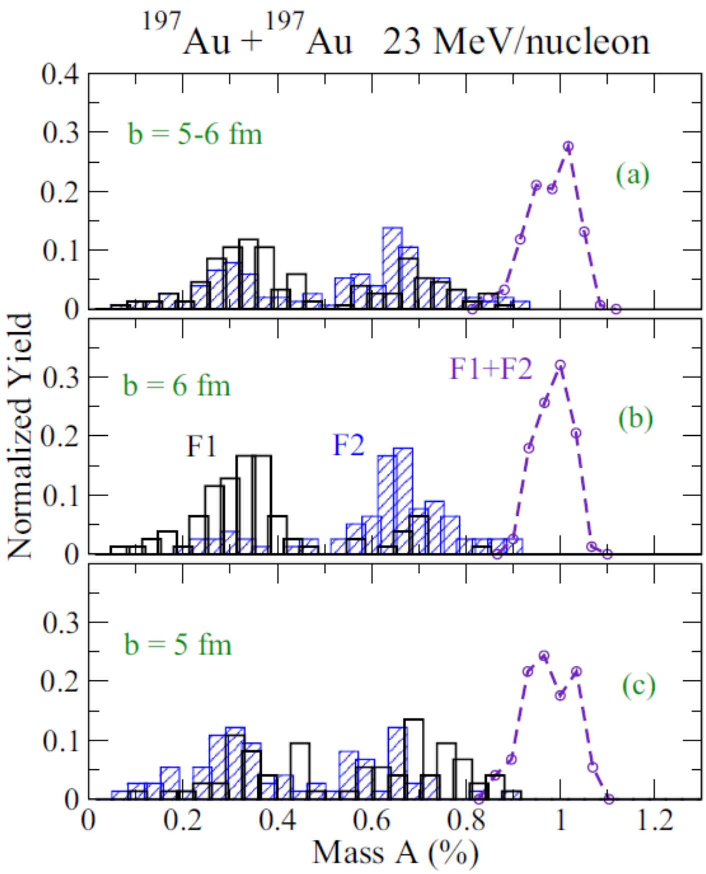
In the next figure we show the distribution of parallel and transverse velocities for the reaction at 23 AMeV for b=5 and 6 fm (a) as well as the mass distribution normalized to the number of events, of Deformed Fragment (DF, full line) and Spherical Fragment (SF, dashed line) fragments. For the reaction at b=6fm the fragment masses are shifted by 100 units for a better visibility.



For ternary events in the next figure at 15MeV (a) and 23 AMeV (b) shows the mass distribution of the lightest, A1, and heaviest, A2, fragments identified with the method proposed in the paper (C. Rizzo et al. PRC2014) for the impact parameter b=5fm. Once the masses are normalized to the average mass of the DF fragments, results look close to the experimental distributions.



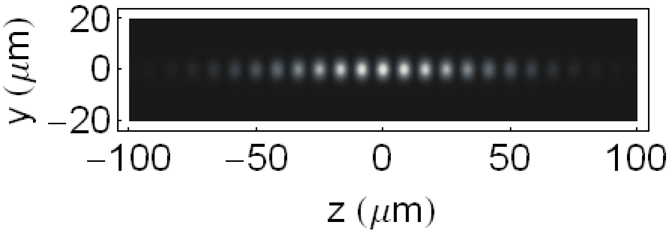
To establish a closer connection with the experimental analyses in the fragment recognition procedure we identify as F1 the fragment which is located on the external side of DF fragment and as F2 the other one. The corresponding mass distribution is shown in the following figure.



The simulations show an interesting evolution, with the impact parameter, towards the features observed experimentally. Indeed, whereas at b=5fm the fragment F1 exhibits a wider mass distribution while at b=6m it is mostly located in the low-mass region. All these results point to the occurrence of a reaction mechanism, neck rupture coupled to angular momentum effects, which could explain the experimental observations.

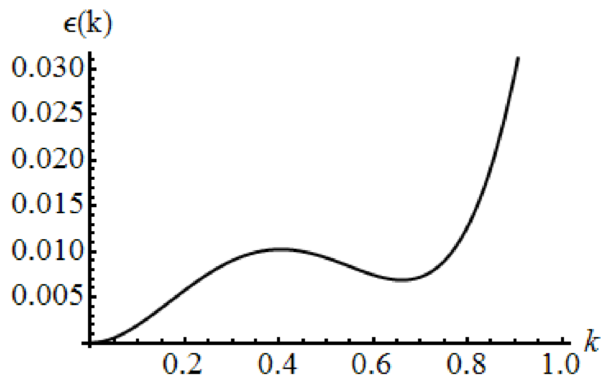
For WP3. Objective: ***Collective dynamics and fragmentation in BEC within the Gross-Pitaevskii-Boltzmann formalism***

Following the experimental observation of Faraday waves in (pure) Bose-Einstein condensates subjected to parametric excitations on the strength of the radial component of the magnetic trap (see P. Engels *et al.*, Phys. Rev. Lett. **98**, 095301 (2007)) and the theoretical formalism which describes the fragmentation of Bose-Einstein condensates through a Faraday type of modulational instability (see A.I. Nicolin, Phys. Rev. E **84**, 056202 (2011)) which is illustrated in the figure below,



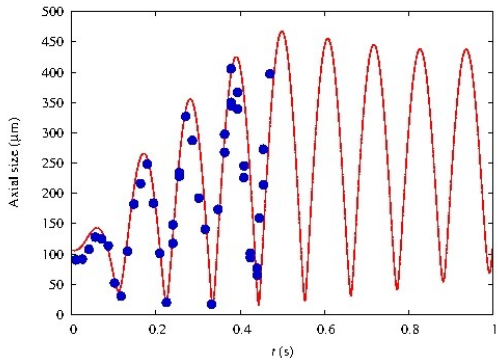
it appears to be of utmost importance to study the impact of the thermal cloud on the fragmentation of a Bose-Einstein condensate. The existing literature indicates that the ideal theoretical tool consists of a hybrid system of equations in which the Gross-Pitaevskii equation (which describes the O K dynamics of the condensate) is coupled self-consistently with the Boltzmann equation (which describes the thermal cloud). We have started to implement numerically the collision integral for bosons and we are now considering the implementation of the equations of motions based on the density dependent mean fields.

In the first part **of 2012** we have focused on the emergence of density waves in dipolar Bose-Einstein condensates and have obtained analytically, based on detailed variational calculations, the roton-maxon dispersion relation which is showed below. These results are presented at large in Proceeding of the Romanian Academy – Series A **14**, 35 (2013).



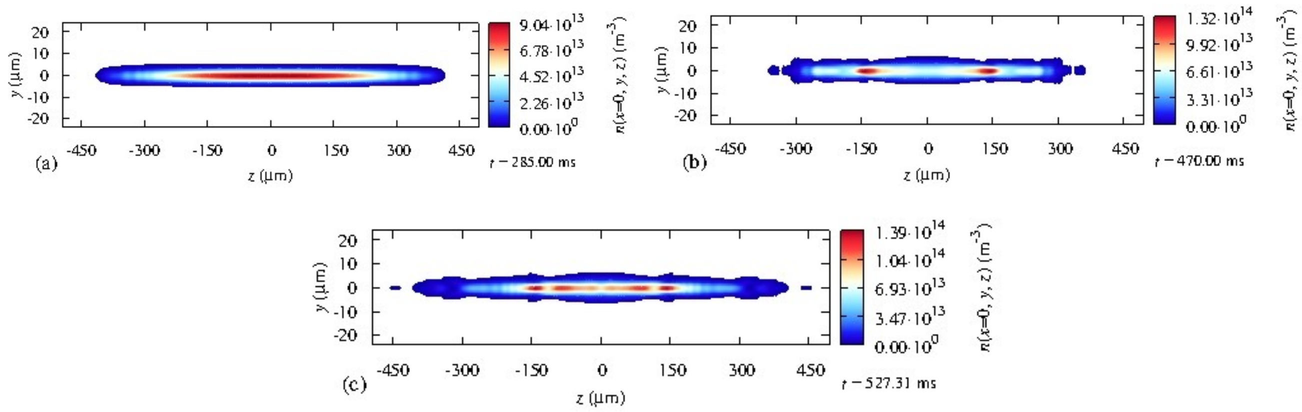
Dispersion of density waves in a dipolar Bose-Einstein condensate. Notice the maximum-minimum structure which is typical for systems with non-local interactions.

Motivated by the recent experiments on the fragmentation of a Bose-Einstein condensate subjected to parametric excitations on the two-body scattering length reported by the group of Prof. Randall G. Hulet from RICE University (see Phys. Rev. A **81**, 053627 (2012)), we have investigated by analytical and numerical means the fragmentation process using solely the Gross-Pitaevskii equation. Our preliminary results show that the fragmented state is in fact a hybrid state that consists of a collective mode and a resonant density wave. In the following figure we depict the time dependence of the width of the condensate to illustrate the quantitative agreement between our numerical results and the existing experimental data.



Time dependence of the width of the condensate subjected to parametric excitation applied on the two-body scattering length. The experimental data (blue full circles) are drawn from Phys. Rev. A 81, 053627 (2012), while the full red line shows the numerical simulations.

In the following figures we show the time evolution of the density profile of the condensate (which corresponds to the experimental setup in Phys. Rev. A 81, 053627 (2012)) to show how the fragments are formed at the border of the condensate.



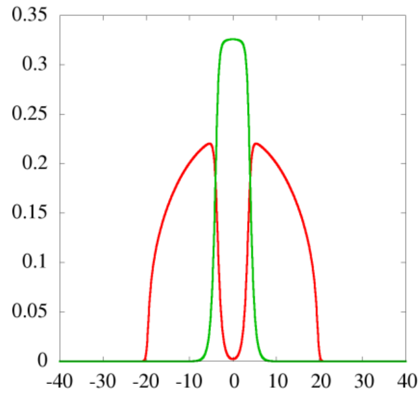
Time evolution of the density profile of a Bose-Einstein condensate subjected to parametric excitation of the two-body scattering length. The first density profile corresponds to the ground state of the condensate, while the other two capture the density profile at two subsequent times. We emphasize that two small fragments take of from the border of the condensate.

The results of our investigations based on the Gross-Pitaevskii equation were published at Springer as a book chapter in a collective volume dedicated to forefront achievements in nonlinear science (namely *Localized excitations in nonlinear complex systems. Current state of the art and future perspectives.* Eds. R. Carretero-Gonzalez *et al.*). A detailed analysis of the experimental data shows that the number of atoms in the condensate suffers significant fluctuations which makes is necessary to couple self consistently the Gross-Pitaevskii with the Boltzmann equation (which describes the thermal cloud in which all atoms expelled from the condensate are present) for long-time simulations.

In 2013 and 2014 we have made the first steps towards modeling the interaction of a Bose-Einstein condensate with the surrounding cloud by modifying locally the two-body interaction due to fluctuations in the density of the condensate. This regime (known in the literature as the *collisionally inhomogeneous regime*) offers a first description of the non-equilibrium effects, the quality of the theoretical model relying on the spatial modulation of the scattering length. In Romanian Reports in Physics **65**, 820 (2013) we have showed that for quasi-one-dimensional condensates the emergence of longitudinal density waves excited through parametric means (which eventually lead to the fragmented state of the condensate) is not substantially modified by the spatial modulation of the scattering length, thereby emphasizing the robustness of this nonlinear effect.

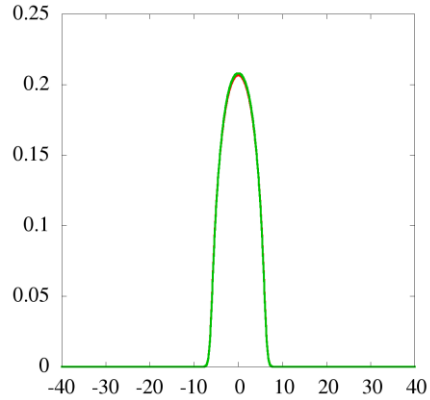
There are, however, a series of qualitative modifications that concern the emergence of *resonant* waves that are substantially slowed down when the scattering length reaches a prominent maximum in the center of the trap and is otherwise small. As we have shown in Phys. Rev. A **89**, 023609 (2014), as the strength of two-body scattering length reaches a prominent maximum the condensate approaches an effectively linear regime in which all nonlinear effects slow down.

The miscibility of ultra-cold quantum gases is a problem of maximum interest, both theoretically and experimentally, as no serious investigation into the dynamics of the condensed state is impossible without a detailed structure of the ground state. To this end, we have investigated in Phys. Rev. A **89**, 023609 (2014) the ground state of a binary condensate (*e.g.*, two hyperfine states of the same atomic species, say Rubidium) shaped as a cigarette (*i.e.*, quasi one-dimensional structure) whose two-body scattering length varies from a constant (which is typical for pure condensates) to Delta-function-shaped interaction (which is typical for a small condensate immersed in a thermal cloud). Detailed numerical studies based on two coupled Gross-Pitaevskii equations have showed us the transition of the ground state from the symbiotic, non-miscible, soliton-like configuration (depicted below), in which one component effectively traps the other,



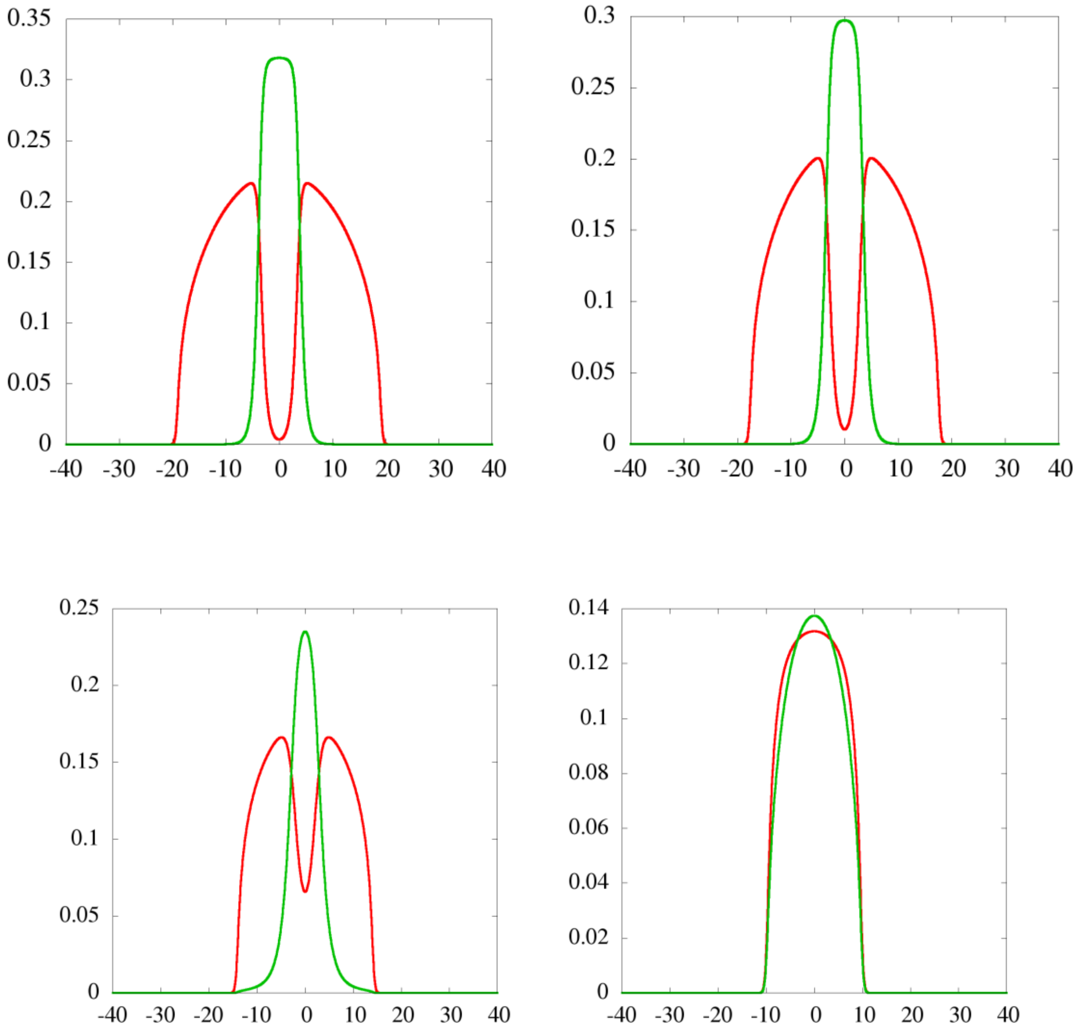
Longitudinal (radially integrated) density profile of a binary, cigar-shaped, non-miscible condensate with a constant two-body scattering length.

towards a perfectly miscible configuration in which the two components are located in the center of the magnetic trap (see the figure below).



Longitudinal (radially integrated) density profile of a binary, cigar-shaped, miscible condensate whose two-body scattering length is shaped as a Delta-function located at the center of the magnetic trap which confines the condensate.

The transition between the two states is depicted in the following figure, the intermediate ground states illustrated there being of substantial experimental interest.



Longitudinal (radially integrated) density profile of a cigar-shaped condensate whose scattering length varies from a constant value (upper left plot) to a Delta-function positioned in the center magnetic trap (lower right plot).

The main conclusion that can be drawn from the numerical results is that the miscibility of the ground state depends strongly on the level of spatial homogeneity of the two-body interaction. The second conclusion is that the Gross-Pitaevskii alone cannot describe the dynamics of a condensates immersed in a thermal cloud because the thermal cloud modifies locally the two-body interactions and it is therefore mandatory to couple self-consistently the Gross-Pitaevskii equation (which describe the condensed cloud) with the Boltzmann equation (which describes the thermal cloud). This hybrid model is currently implemented numerically.

For WP4. Objective: ***Transport description of collective features and dissipation in QGP***

In 2011 we performed the numerical simulations and analysis for sets of 8000 events with a code able to describe the expansion of the quark-gluon plasma at RHIC conditions. The dynamics has as option the inclusion of the Nambu-Jona-Lasinio (NJL) interaction which induces the spontaneous breaking of chiral symmetry. Therefore first task was to observe the effects of the spontaneous breaking of chiral symmetry on some collective features of QGP. The expansion dynamics was studied at RHIC conditions corresponding to the impact parameter b=6fm following an comparative approach, in the absence and in the presence of NJL term respectively. Was obtained the radial dependence of the effective mass of the quarks at different times, the time dependence of the elliptic flow parameter v2 at mid-rapidity as well as a functions of transverse momentul. We intend to improve the statistics in order to extend the analysis to the flow parameter v4. Latter we shall explore the role of the fluctuations in the initial conditions of the collective features of the expansion of quark-gluon plasma. The results obtained until now were published in a work which appeared in Journal of Physics: Conference series, 2012.

In 2012 we extended the numerical code devoted to describe the dynamics of quark-gluaon plasma by including an additional interaction term, of vectorial type. During the next year we shall perform several tests aiming to confirm that the new version will open the possibility to extend the investigations at nonzero baryonic densities at energies correspondint to RHIC energy scan.

In 2013 and 2014, in collaboration with theory group from Catania University the numerical code was upgraded in order to reduce the numerical fluctuations due to a finite (small) number of test particles per quark. More precisely, from 5-10 test-particles per quark now the number of test particles was rise to 150-200 when are considered two flavours. Was also tested the consistency of the results obtained with the actual code with the data as well as with the previous results obtained numerically in similar physical conditions.

The present systematic investigations are looking to the effects of hot and cold spots (amplitudes, number) generated in the initial density distribution upon collective evolution and the values of parameters v2, v3, v4. The analysis is performed for both conditions: in the absence and in presence of NJL term in order to clarify the role of chiral symmetry breaking on the effects induced by the initial fluctuations.

During these 36 months of research activity the references about the subjects under investigation were permanently updated. We shall notice that our articles already were cited for more than 80 times. The scientific directions which emerged as a result of our studies were adopted by master students and PhD students which recently decided to follow the Theoretical and Computational Physics Master or Doctoral direction in Theoretical Physics which are organized at Physics Faculty of University of Bucharest.

Summarizing, the original scientific results of our research activities on subjects related to the grant arguments were published in 15 articles which appeared in ISI journals, all with Acknowledgements and visible in ISI Web of Science, in 4 articles which appeared in Romanian ISI journals while a book chapter was published at Springer. The members of the project participated with 20 oral presentations at various international conferences.

Articles published in international ISI journals:

2012

1) *Pygmy dipole resonance: collective features and symmetry energy effects*
Autori: V.Baran, B. Frecus, M. Colonna, M. Di Toro
Physical Review **C 85**, 051601 (2012) (ISI impact factor 3.7)

2) *From multifragmentation to neck fragmentation: Mass, isospin and velocity correlations*
Autori: V.Baran, M. Colonna, M. Di Toro, R. Zus
Physical Review **C 85**, 054611 (2012) (ISI impact factor 3.7)

3) *Correlations between emission timescale of fragments and isospin dynamics in Sn124+Ni64 and Sn112+Ni58 reactions at 35 A MeV*
Autori: E. De Filippo, A. Pagano, …V.Baran,…..
Physical Review **C 86**, 014610 (2012) (ISI impact factor 3.7)

2013

4) *Connecting the pygmy dipole resonance to the neutron skin*
Autori: V.Baran, M. Colonna, M. Di Toro, A. Croitoru, D. Dumitru
Physical Review **C 88**, (2013) (ISI impact factor 3.88)

2014

5) *Theoretical predictions of experimental observables sensitive to the symmetry energy*
Autori: M. Colonna, V.Baran, M. Di Toro
The European Physical Journal **A 50,** 30 (2014) (ISI impact factor 2.42)

6) *Faraday waves in collisionally inhomogeneous Bose-Einstein condensates*
Autori: A.Balaz, R. Paun, A. I. Nicolin, S. Balasubramanian, R. Ramaswamy
Physical Review **A 89**, 023609 (2014) (ISI impact factor 3.00)

7) *Connecting the pygmy dipole resonance to the neutron skin*
Autori: C. Rizzo, M. Colonna, V. Baran, M. Di Toro
Physical Review **C 90**, 054618 (2014) (ISI impact factor 3.88)

8) *Nuclear collective dynamics within Vlasov approach*
Autori: V.Baran, M. Colonna, M. Di Toro, B. Frecus, A. Croitoru, D. Dumitru
The European Physical Journal **D 68** , 356 (2014) (ISI impact factor 1.40)

Lucrari in reviste din tara cotate ISI:

2012

1) Collective dipole modes in nuclear systems
Autori: V.Baran, B. Frecus, M. Colonna, M. Di Toro, R.Zus
Romanian Journal of Physics **57**, 36-48, (2012) (ISI impact factor 0.526)

2013

2) Density waves in dipolar Bose-Einstein condenstates
Autori: A. Nicolin
Proceedings of the Romanian Acad. Series **A 14**, 35 (2013) (ISI impact factor 1.15)

3) From neutron skin to pygmy dipole resonance: the roles of symmetry energy in a transport approach
Autori: V.Baran, B. Frecus, M. Colonna, M. Di Toro, A. Croitoru, D. Dumitru
Romanian Journal of Physics **58**, 1208 (2013) (ISI impact factor 0.745)

4) Density waves in dipolar Bose-Einstein condenstates
Autori: A. Nicolin
Romanian Reports in Physics **65**, 820 (2013) (ISI impact factor 1.137)

Articles published in the ISI Proceedings of International Conferences:

2012

1) *Kinetic approaches to phase transitions in strongly interacting systems*
Autori: V.Baran, M. Colonna, M. Di Toro, R. Zus
Journal of Physics: Conference Series vol. **338**, 012020, (2012)

2013

2) *Exploring the nuclear matter phase diagram with heavy ion reactions*
Autori: M. Colonna, V.Baran, M. Di Toro, C. Rizzo
Journal of Physics: Conference Series vol. **413**, 012018, (2013)

3) *Reaction mechanisms in transport theories: a test of the nuclear effective interaction*
Autori: M. Colonna, V.Baran , M. Di Toro, B. Frecus, YX Zhang
Journal of Physics: Conference Series vol. **420**, 012104, (2013)

4) *Collective flow properties of intermediate mass fragments and isospin effects in fragmentation at Fermi energies*
Autori: V.Baran , M. Colonna , M. Di Toro, R. Zus
AIP Conference Proceedings **1564**, 150 (2013)

2014

5) *Collective features of nuclear dynamics with exotic nuclei within microscopic transport models*
Autori: V.Baran , M. Colonna, M. Di Toro, A. Croitoru, D. Dumitru
EPJ Web of Conferences **66**, 03004 (2014)

6) *News on the equation of state from heavy ion reactions*
Autori: M. Colonna, V.Baran , M. Di Toro
Journal of Physics: Conference Series vol. 527, 012009 (2014)

7) *Mass and isospin dependence of the dipole response in a microscopic transport approach*
Autori: V.Baran , M. Colonna , M. Di Toro, A. Croitoru, A.I. Nicolin
AIP Conference Proceedings (in press, 2014)

Book chapters

Fragmentation of a Bose-Einstein Condensate Through Periodic Modulation of the Scattering Length
Autori: A. Balaz, A. Nicolin
In the volume: *Localized Excitations in Nonlinear Complex Systems*
Springer, 2013

Participations at Conferences

2012:

1./ The 8th General Conference of Balkan Physical Union (Universitatea Ovidius, Constanta, 5-7 iulie 2012) cu posterul "*A novel non-polynomial Schrodinger equation for high-density cigar-shaped condensates*" in care apare proiectul apare in acknowledgement, sustinut de drd. Carina Raportaru.

2./ Conferinta Nationala de Fizica (Universitatea Ovidius, Constanta, 8-10 iulie 2012) cu posterul "*Formation of Faraday and resonant waves in driven Bose-Einstein condensates*" in care apare proiectul apare in acknowledgement, sustinut de drd. Carina Raportaru

3./ International Student Conference of Balkan Physical Union (Universitatea Ovidius, Constanta, 10-13 iulie 2012) cu posterul "*Noise-driven transitions in nonlinear lattices*" in care apare proiectul apare in acknowledgement, sustinut de drd. Carina Raportaru.

4./ ICT-Innovations 2012 (Ohrid, 12-15 septembrie 2012) cu colocviul "*Nonlinear dynamics of Bose-Einstein condensates by means of symbolic computations*". Lucrarea aferenta colocviului urmeaza sa fie publicata in proceedings-ul conferintei, ca Web Proceedings, si cuprinde proiectul in acknowledgement, sustinuta de drd. Carina Raportaru.

5./ Conferinta Nationala de Fizica (Universitatea Ovidius, Constanta, 8-10 iulie 2012), invited talk "*Resonant waves in Bose-Einstein condensates*" , Dr. A. Nicolin.

6./ 2nd Conference on Localized Excitations in Nonlinear Complex Systems (LENCOS 2012, Sevilla, 9-12 iulie 2012), cu colocviul *"Variational treatment of surface waves in Bose-Einstein condensates*" dr. A. Nicolin.

7./ TIM 12 (Universitate de Vest din Timisoara, 27-30 noiembrie 2012) "*Faraday waves in binary nonmiscible Bose-Einstein condensates*" , invited talk, dr. Alexandru Nicolin.

2013

8./ International Nuclear Physics Conference 2013 (INPC2013), Firenze 2-7 iunie, Italy, *"Collective features of nuclear dynamics with exotic nuclei within microscopic transport models*",
Invited Talk, Virgil Baran.

9./ ELI-NP Workshop "Towards TDR of experiments with brilliant gamma-ray beam at ELI-NP", 25-26 June 2013, Bucharest, "*Skins, dipole polarizability and pygmy resonances:mass dependence and symmetry energy effects in a microscopic transport approach*" Oral Presentation, sustained by Virgil Baran.

10./ The 13th International Balkan Workshop on Applied Physics, 4-6 July 2013, Invited Speaker, "*Nuclear Dipole Dynamics within microscopic transport models*", sustained by Virgil Baran.

2014

11./ The 14 th International Balkan Workshop on Applied Physics, 2-4 July, Constanta, Romania, 2014
„ *Analytical description of the nonlinear dynamics of Bose-Einstein condensates by means of genetic algoritms*", sustained by Dr. Carina Raportaru.

12./ 6th ICT Innovations Conference 2014, 9-12 September, Ohrid, R. Macedonia
"*Thermal transitions in non-linear lattices*", sustained by Dr. Carina Raportaru.

13./ TIM 14 Physics Conference- *Physics without frontiers*, 20-22 November 2014, Timisoara, Romania
„High-Perfomance Computing algorithms for the nonlinear dynamics of Bose-Einstein condensates",
sustained by Dr. Carina Raportaru

14./ CIIT 2014 (Bitola, Macedonia), "*Symbolic computing for the nonlinear dynamics of Bose-Einstein condensates*", oral presentation, dr. A.I. Nicolin.

15./ RO-LCG 2014 *"Grid, cloud and high-performance computing in physics research"* Bucharest, Magurele "*Symbolic and numerical computing for Bose-Einstein condensates*" – sustained by A.I. Nicolin, vice-chairman of the conference

16./ TIM 14 Physics Conference- *Physics without frontiers*, 20-22 November 2014, Timisoara, Romania
„Symbolic and numerical computing for Bose-Einstein condensates", invited talk, A.I. Nicolin

17./ The 14 th International Balkan Workshop on Applied Physics, 2-4 July, Constanta, Romania, 2014

"Isospin and mass dependence of pygmy resonance in neutron rich nuclei"
invited talk, V. Baran

18./ Carpathian Summer School of Physics 2014, Sinaia, Romania 2014
"*Mass and isospin dependence of the dipole response in a microscopic transport approach"*
invited talk, V. Baran

19./ Advanced many-body and statistical methods in mesoscopic systems II, 1-5 September, Brasov,
"Pygmy *dipole response in a schematic model"*, Oral presentation, A. Croitoru

20./ Advanced many-body and statistical methods in mesoscopic systems II, 1-5 September, Brasov,
"*Collective dynamics and fragmentation in nuclear systems"*, Invited talk, V. Baran

Were elaborated two PhD theses having scientific arguments related to the research directions of the present grant:

"*Collective nuclear motions within a microscopic transport model"* sustained by Bogdan Frecus (September 2012).

"Studiul comportamentului neliniar si stochastic al condensatelor Bose-Einstein", sustained by Mihaela Carina Raportaru (October 2012).

Director proiect,

Prof.univ.dr. Virgil Baran