Scientific Report 2011-2014

Implementing the project ***PN-II-ID-PCE-2011-3*** *entitled*

HEAVY ION OPTICAL POTENTIALS
FOR EXOTIC NUCLEI IN ASTROPHYSICAL NUCLEAR REACTIONS

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1. Introductory considerations

The main scope of this project is the derivation of a quality Optical Model Potential for various nuclear systems interacting at low energies, which for example can be found in the stellar environment. We carried out the heavy-ion OMP calculation by improving the approximation leading to the localization of the nonlocal exchange kernels, enlarging the number of employed G-matrix interactions, such as the Gogny, Skyrme, Argonne. As applications this proposal focused on reactions relevant for nuclear astrophysics such as those induced by alpha particles on nuclei of various masses (capture reactions), analysis of the most recent fusion data of medium nuclei displaying hindrance, deeply bound proton removal reactions from neutron rich nuclei around Z=16,N=28 and the determination of Asymptotic Normalization Coefficients and spectroscopic factors of proton halo nuclei in one-proton break-up reactions.

2. Consistent description of sub-barrier fusion (2011)

In order to calculate the excitation functions we employed the coupled-channel method (CC) with appropriate boundary conditions and nuclear structure input (low-lying vibrational modes) of both traget and projectile. The heavy-ion potențial (HIP) was calculated within our improved double-folding method. The exchange term of the of the HIP is described later (in the next section reported în 2012). Aș effective N-N forces we employed the traditional Michigan-3-Yukawa (M3Y) in both parametrizations (Paris and Reid), as well the density-dependent interaction of Gogny in its three parametrizations (D1,D1S,D1N) . The one-body densities were obtained within the self-consistent Hartree-Fock-Bogoliubov approximation or from the Density Matrix Expansion method.

In the summer of 2011, we published our analysis on the fusion reactions ^{48}Ca+^{36}S,^{48}Ca,^{96}Zr [1] and we obtained a very good agreement to the experimental data [2,3,4]. We also investigated the ^{40}Ca+ ^{40}Ca reaction [5] and we explained the data from [6] by including in the CC formalism two-phonon states for the quadrupole 2+ and octupole 3- bands and one-phonon for the 5- band. Using the rotating-frame-approximaton we included up to 17 chanels in the CC scheme. The deformations parameters were extracted from the transition probabilities B($E\lambda$) for the multipolarities λ=2,3,5. In Fig.1 we compare the cross-sections calculated by us with experimental data from ref.[6].

Fig.1

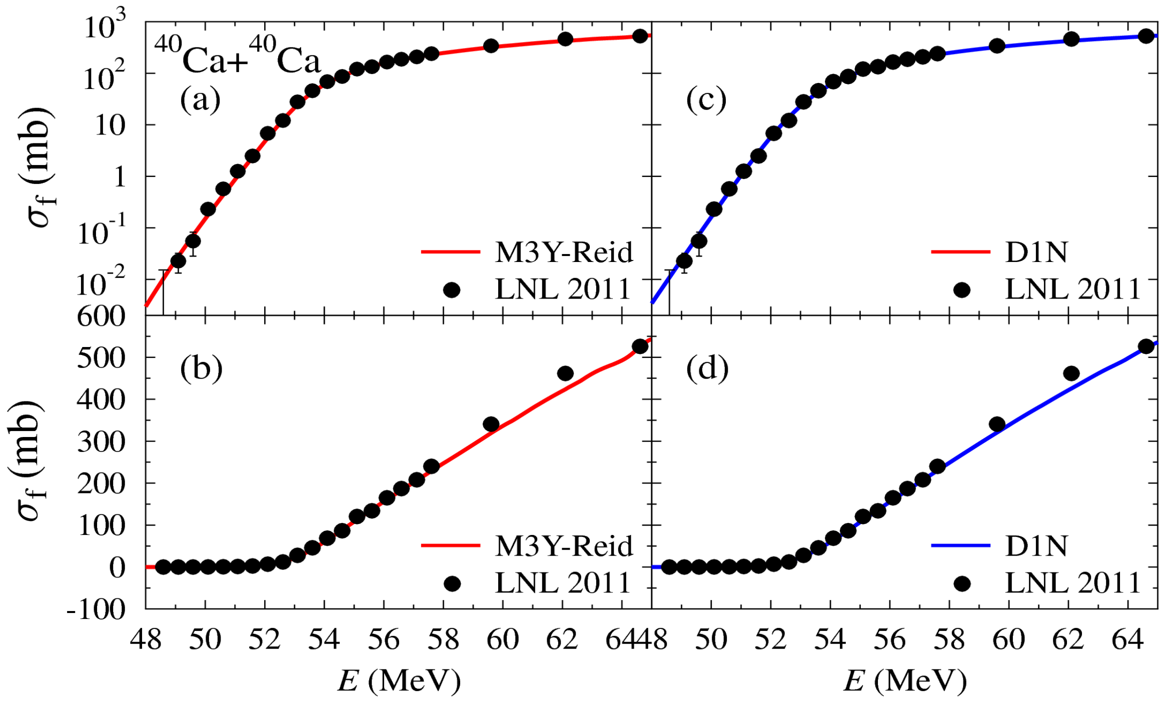

Fig.1

The astrophysical factor $S(E)=E\ \sigma_f \exp(\eta-\eta_0)$ in logarithmic scale ($\eta=Z_1Z_2e^2/\hbar v$ and η_0 is the value of η at a fixed reference energy) is displayed in Fig.2. This quantity steadily increases below the lowest recorded bombarding energy and therefore we cannot conclude the existence of a maximum as speculated by the Legnaro group.

The logarithmic derivative, $L(E)=d\ \ln(E\ \sigma_f)/dE$, as can be deduced from Fig.3, do not display a divergent behavior in a clear manner at the lowest measured energy. The last two experimental points deviate from the smooth behavior of L. However the theoretical curves seem to display a plateau at very low energies. Under these circumstances we refute the conjecture of Rowley and Hagino which states that the intensity of the octupolar phonon is responsible for the irregularitries observed in the experimental data at the lowest energies. We checked this hypothesis and consequently we carried out a study with the aim to separate the dependence of L on the intensity of the octupole phonon. A large value of β_3 triggers mainly a smooth increase of the cross-section without producing irregularities in the extreme sub-barrier region.

In conclusion at very low energies the fusion cross-section of the reaction ^{40}Ca+^{40}Ca has a faster decrease than the one expected from the extrapolation of older experimental data and therefore the dynamical model used at this moment by us confirms the same behavior as for other symmetric fusing systems, e.g. ^{58}Ni+^{58}Ni, ^{64}Ni+^{64}Ni, ^{28}Si+^{64}Ni, ^{100}Mo+^{64}Ni, ^{16}O+^{208}Pb, ^{28}Si+^{30}Si, ^{48}Ca+^{36}S,^{48}Ca,^{96}Zr. The analysis carried out by us in 2011 and published in [8,13] excludes the occurrence of a maximum of S in the close proximity of the last experimental point.

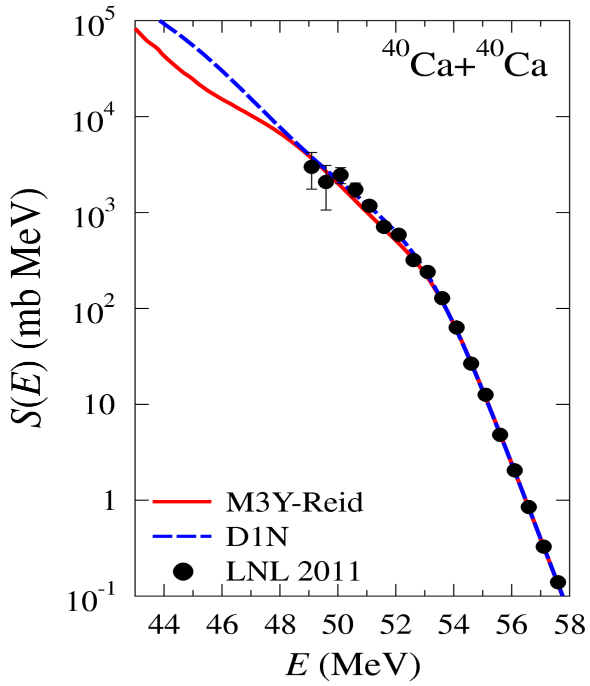

Fig.2

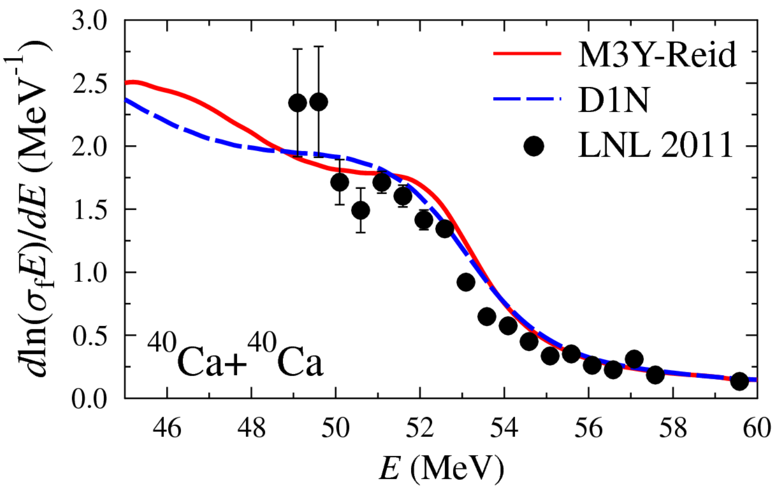

Fig.3

3. Heavy-ion potentials obtained from fundamental effective interactions (2012)

We introduced for the first time in double-folding calculations the Argonne force. This is a type of N-N interaction used succesfully in describing the spectra of light nuclei in Green functions Monte Carlo calculations. The Argonne force AV18 is probably one of the most realistic in this class of N-N forces. In Fig.4 we compare various Argonne parametrizations employed in the OPM with a phenomenological potential for three systems. For the $\alpha + \alpha$ system we use a phenomenological potential that reproduces the phase-shift data and the resonant state 0^+ in ^{8}Be. For the α+^{40}Ca system we use a global fit potential, whereas for the ^{40}Ca+^{40}Ca system we employ a potential reproducing the fusion data. We conclude that for all three cases we obtain the same hierarchy of the Argonne potentials, i.e. the simpler the force the more shifted to the right is the peak of the fusion barrier. The most elaborate Argonne potential (AV18) resembles the most to the phenomenological potential, a fact that we deem to be remarkable. We also noted that the heavier the system the OMP employing the AV18 force becomes more repulsive and displays a higher barrier.

The conclusion of this analyis is that the use of the Argonne force is feasible and therefore the corresponding OPM should be constructed as an interpolation between AV18 which is a bit to repulsive and AV4 which is a bit to attactive. Apparently, by removing tensor terms from AV4 the OPM becomes to attractive and underestimates the fusion barrier. It seems that the dissapearence of the coupling between the $^3S_1$ and $^3D_1$ channels and the degradation of the $^3P_{0,1,2}$ channels is responsible for this behavior.

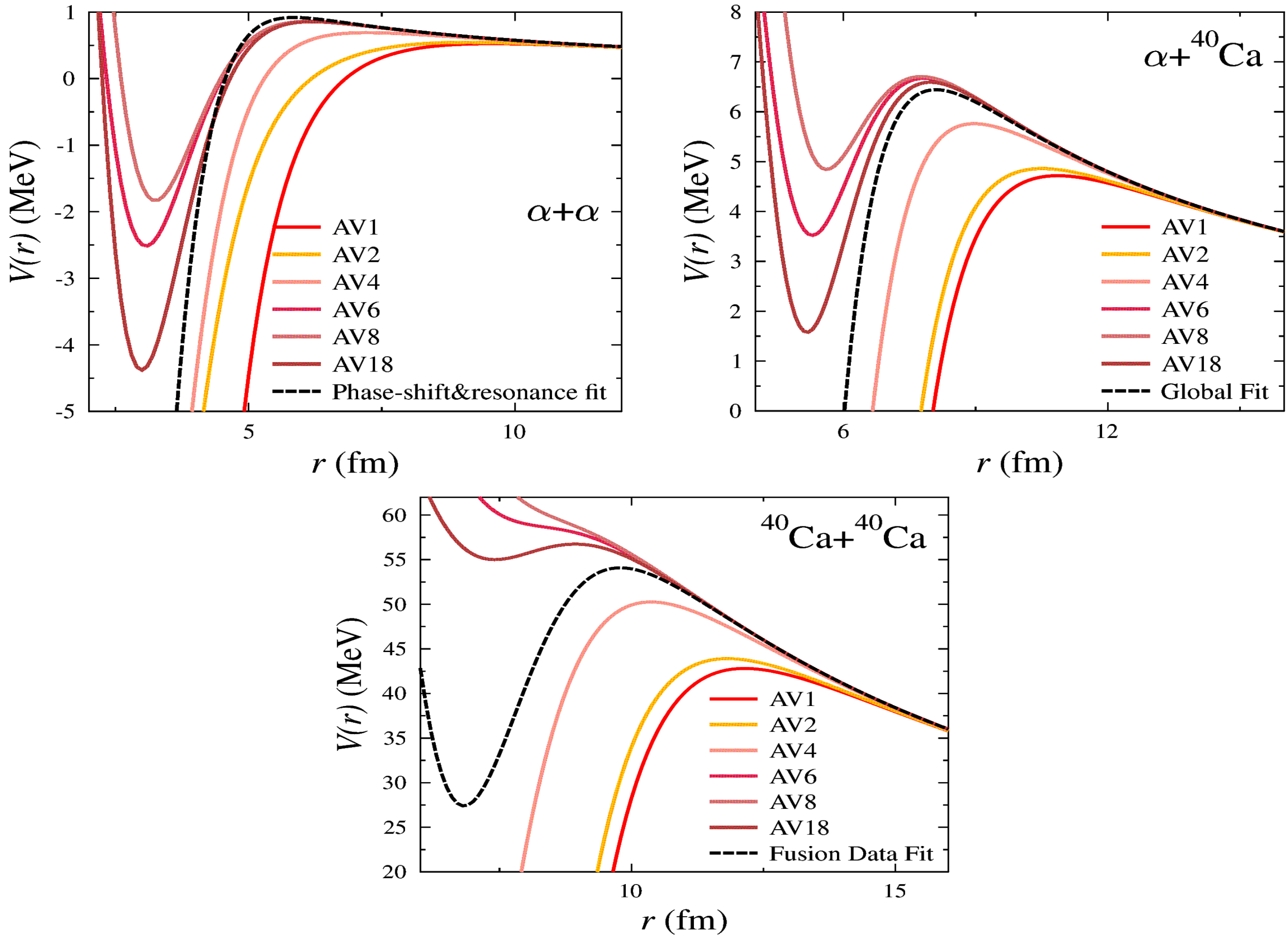

Fig.4

4. Nonlocal exchange kernels for alpha-nucleus interactions (2013)

In this stage we developed a calculation scheme for the calculation of the α-nucleus non-local part of the OMP. We obtained the integral kernel of the exchange potential and then we carried out a localization procedure in terms of the center-of-mass energy. Finally we solved the Schroedinger equation corresponding to the nuclear scattering process. We applied the method for a large variety of N-N forces such as : M3Y, Gogny, Brink-Boeker, Soper, Serber and Argonne [7]. In Fig.5 we illustrated the energy dependence of the AV18 OMP (right panel) and its exchange part (left panel) for the system α+^{40}Ca for a selection of 4 energies (E=0,5,10,50 MeV). We concluded that the height of the barrier varies slightly with E, whereas the central part of the potential is strongly affected for overbarrier bombarding energies. At higher energies the exchange potential becomes less attractive.

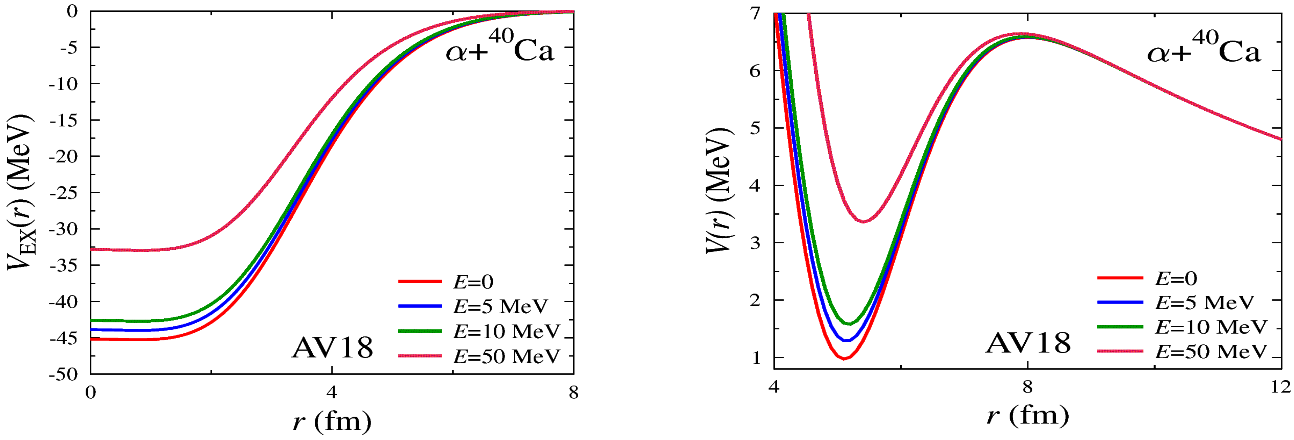

Fig.5

5. Clusters of antimatter în critical fields. Part I : Relativistic mean-field formalism for systems of alpha-like nuclei. (2014)

At this stage of the project we extended the Relativistic Mean-Field (RMF) model for standard nuclear matter such that along with baryons of the Fermi type (protons and neutrons) interacting via scalar and vector meson fields, we include also a complex scalar Bose field with self-interactions with the aim to describe alpha particles. The equations of motion of this quantum field are derived from the Euler-Lagrange equations of the total Lagrangean (nucleons,alphas,mesons) and first we calculated the level $\varepsilon_\alpha(k=0)$ where α particles accumulate due to the Bose-Einstein condensation (BEC). In Fig.6 we ploted this state as a function of the baryon(vector) density ρ_V for standard nuclear matter for various RMF parametrizations without self-interactions. Due to the repulsive character of the vector meson mean-field potential, the saturation is predicted for all forces like in the case of Fermi baryon levels.

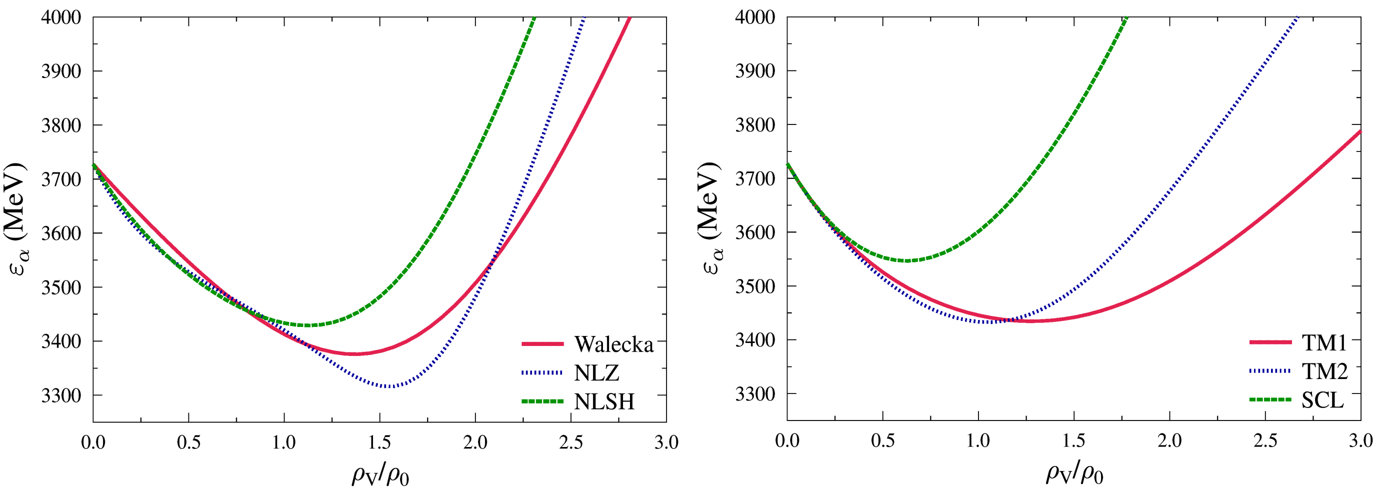

Fig.6

In the case of pure alpha matter (ρ_V=0) we calculated the very same level this time as a function of α particle density ρ_α (Fig.7) with and without self-interactions. It is worthwhile to note that in the absence of self-interactions of the α -field (g_2=0) the BEC is overbound whereas for a positive quartic self-interaction (g_2>0), the level raise in the upper continuum for oversaturation densities. These results are presented in ref.[8].

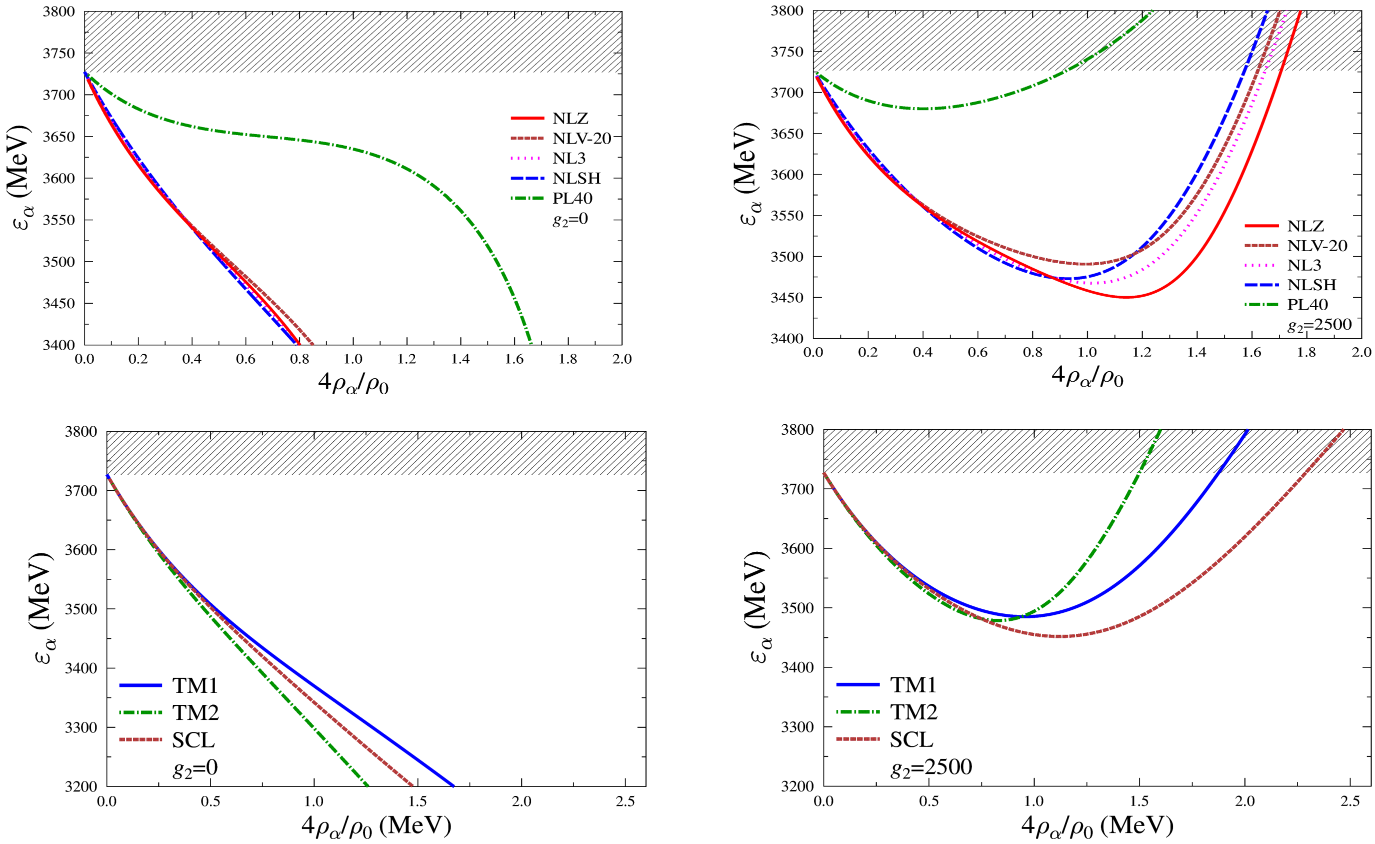

Fig.7

6. Foundations of rational continuum mechanics of nuclear matter. Part I. Elaborating the energy density functional for a composite nuclear medium. (2014)

In this stage of the project we layed the foundations of the Rational Continuum Mechanics of Nuclear Matter (RCMNM) based on the elastic behavior of large nuclear systems when subjected to external perturbations. Inspired by the well elaborated formalism of continuum mechanics of classical macroscopic bodies we introduced as a fundamental relations the so-called constitutive or material behavior laws. These relations are expressing the diversity of responses of deformable bodies (nucleus is deformable as well!) due to mechanical loads or electromagnetic fields. In the case of nuclei we deal with the elastic response to external electromagnetic (electrons, photons) or hadron (p, α ,etc.) probes. In the ideal case this law consists of a one-to-one relation between the stress tensor and the body's deformation. Using the particle number and total energy conservation and expanding the internal energy density (elastic energy density functional) in terms of a displacement field $\boldsymbol{u}$ induced by the external perturbation we can derive the elastic constants (Lame coefficients) for any type of energy functional (Skyrme,Gogny,etc.). For asymmetric nuclear systems (disbalance between the density of protons and density of neutrons) we deal with an elastic mixture. Thus both isoscalar and isovector nuclear modes are possible and their frequencies are determined by the elastic coefficients, thus by the material law. As a first example considered the Unitary Fermi Gas which is the unitary limit of a proton-neutron system interacting via short-range forces such that its scattering length a is much larger than the nuclear radius r_0 .

References

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