Project description

HEAVY ION OPTICAL POTENTIALS FOR EXOTIC NUCLEI IN ASTROPHYSICAL UCLEAR REACTIONS

Introductory Remarks

The study of the microscopic optical model potential (OMP) of nucleus-nucleus scattering, relevant for understanding the reaction dynamics, is one of the fundamental subjects in nuclear physics. The large amount of experimental data made available in last two decades regarding the reactions with unstable (exotic) nuclei proved to be a real challenge for the existing optical potentials. The microscopic OMP is also an efficient tool for the study of colliding systems for which the elastic scattering measurements is absent or difficult, such as in the case of neutron-rich or proton-rich β-unstable nuclei. For this reason designing reliable OMP in nuclear reactions taking place in the Cosmos or induced by radioactive beams in laboratories is requested in investigations on nuclear structure of exotic nuclei or nucleosynthesis in stars. It is the main purpose of the present proposal to lay on a more firm basis the foundations of the OMP, by obtaining a better approximation of the exchange part, to diminish the arbitrariness in the imaginary part of the potential and to thus to analyse various nuclear reactions relevant in astrophysical context such as the alpha capture reactions or one-proton removal reactions, but also fusion reactions at sub-barrier energies, providing valuable informations on the direct reactions mechanism or alpha-alpha scattering reactions that can offer clues on the putative Bose-Einstein condensation in alpha nuclei or alpha clusters matter. This project is to a certain extent a prolongation of other two projects PN-II:

1. PN-II, ID-696/Ctr. 49/ Reactii de fuziune la energii extrem sub-barierice(Fusion Reactions at Extreme Sub-Barrier Energies-FUSBAR) by Dr. habil.S. Misicu.
2. PN-II, ID-765/Ctr. 258/Studiul materiei nucleare la linia de stabilitate prin reactii nucleare de interes astrofizic (Investigation of Nuclear Matter at the Drip Line by Nuclear Reactions of Astrophysical Interest), by Dr. F. Carstoiu

Since the elaboration of these two projects, four years ago (2007), new experimental data and new theoretical developments accumulated. The first project (I will make reference to it using the acronym FUSBAR) was aiming to obtain a description of several colliding and fusing systems at energies below the Coulomb barrier. The adopted approach consisted in applying the coupled-channel(CC) method with appropriate boundary conditions and nuclear structure input of the projectile and of the fragment. This heavy-ion potential used in the CC calculation was obtained in the Double-Folding (DF) form and the project proposed a new approach for its derivation. Thus the knock-on exchange part was estimated by taking the Perrey-Saxon approximation in order to localize the nonlocal kernel, and the recoil contributions were included. Density-dependent Skyrme (zero-range like) and Gogny (finite-range like) interactions were included as effective *N-N* forces with some of their modern parametrizations used especially in nuclear structure applications. Also the densities, which subsequently are folded with this effective interaction in the DF method, were calculated in the framework of the Hartree-Fock-Bogoliubov mean-field theory with same type of microscopic forces, i.e. Skyrme. The most important results obtained in this project are the description of several fusion reactions displaying hindrance (see the discusion below on this phenomenon). First the reactions ^{28}Si+^{28}Si and ^{28}Si+^{30}Si were nicely explained by introducing couplings to *n*-phonon vibrational states and adding to the DF potential a repulsive potential whose strength is fixed by equation-of-state of asymmetric nuclear matter. Next, the very recent (2007) fusion data for ^{16}O+^{208}Pb were explained by including also neutron-transfer channels. The project also attempted to give an answer to the conjecture launched by C.L. Jiang and collab. that the hindrance phenomenon will play a crucial role in the astrophysical reactions ^{12}C+ ^{12}C, ^{12}C+^{16}O and ^{12}C+^{16}O. We answered this dilemma by explaining the below barrier evaporation cross-section data for these last three reactions without a shallow potential.

After ending the project new data on extreme sub-barrier fusion was made available by the Legnaro group regarding reactions with ^{48}Ca projectiles. We analyzed and sent for publication the cases ^{48}Ca+ ^{48}Ca, ^{48}Ca+ ^{36}S and ^{48}Ca+ ^{96}Zr. I should mention that the new method to compute the DF potential in the project FUSBAR was applied also to the fusion of spherical ^{16}O and ^{48}Ca on heavy deformed targets and the fusion on halo nuclei.

In the second project (I will make reference to it using the acronym ID-765) exotic neutron-rich nuclei from the *psd*-nuclei were investigated. For ^{23}Al, where all shell-model calculations indicated a dominance of *d*-states together with important contributions from the excited states of the core, the calculations reported in the project ID-765 confirmed the spin 5/2 and the parity + of the g.s. The adopted semiclassical Glauber model for break-up reactions in weakly bound neutron-rich nuclei was extended to the description of proton removal in proton-rich nuclei with inclusion of final state interactions. In this framework the *S*-matrix was obtained by solving numerically the Schrödinger equation with DF heavy-ion potentials and JLM effective *N-N* interactions. Before applying this model to the recent data on proton removal from RIKEN the model was tested on a wide number of available elastic scattering data.

<u>Based on the results and the experience gained in these previous two projects we propose a new project which aims to calculate the optical heavy-ion potential, by improving the approximation leading to the localization of the nonlocal exchange kernels, enlarging the number of employed G-matrix interactions,</u>

such as the Jeukenne-Lejeune-Mahaux (JLM), inclusion of three-body forces in the G-matrix used in double-folding calculations and inclusion of the imaginary part in a consistent way via the JLM folding model or Feshbach theory of the optical potential nuclear reactions. As applications the present proposal targets towards reactions relevant for nuclear astrophysics such as those induced by alpha particles on nuclei of various masses, 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.

1. **Heavy ion optical potentials from fundamental effective interactions**

The double-folding model (DFM) is a notorious practical tool for constructing the OMP between reacting nuclei. In this approach the nucleon-nucleon (*NN*) effective interaction in the nuclear medium is folded twice with the nuclear densities of the projectile and target nuclei. One of the most widespread effective *NN* interactions used for the OMP construction is the so-called M3Y *G*-matrix interaction. Originally this interaction was proposed in a density-independent form by Bertsch et collab., with the most popular two parametrizations being based on the 1) Reid soft core *G*-matrix elements in the even channels and Elliott ones in the odd channels [1] and 2) Paris forces in both even and odd channels [2]. Shortly after, a density- and energy-dependent generalization of the M3Y interaction was proposed [3], which provided a good of the scattering from various targets of α-particles with bombarding energies from 6 to 43 MeV per nucleon. We have already developed in the previous project two FORTRAN codes, 1) FINRAN, providing the DF nucleus-nucleus potential using density-independent M3Y, the density-dependent Gogny forces (D1, D1S and D1N parametrizations) as well other less popular forces (Migli, Sprung, M3Y-P1,2,3, Sopper) and 2) DFSKYRME using the zero-range, momentum and density-dependent Skyrme forces (over 20 parametrizations!). Presently we extend the FINRAN code to include density-dependent interactions of M3Y type such as BDM3Y, CDM3Y as well the recent version which incorporates three-body effects(TBF) CEG07b+TBF [4]. Since the interaction is dominated by the exchange, we provided an improved evaluation of the knock-on exchange component. Within the code FINRAN the exchange component is estimated from the local equivalent of the resulting nonlocal kernels, using the lowest order of the Perey- Saxon approximation.
We already included in this code recoil effects which are important in the case of light particles and we intend to treat the exchange part in a better way by solving the nonlocal equations corresponding to the existence of the nonlocal potential. To accomplish this last task we shall adopt an approximate method for solving the nonlocal equations by expanding the nonlocal potential in a small parameter s/a (the range of nonlocality over the characteristic length of the diagonal part of the integral kernel). The

formalism is likely to provide an accurate and simple method for numerical applications that goes beyond the severe approximation implied by the Perey-Saxon localization.

The DF model with these various M3Y forces provides us only with the real part of the OMP and in many situations the imaginary potential is added by hand, normally by taking a functional form similar to the real potential but with different parameters and strength in order to reproduce the experimental elastic scattering data. For this reason we propose to derive the imaginary potential within two folding approaches. In the first folding model the real and imaginary parts of the OMP are obtained with the same degree of consistency. Customarily this folding model is known as the JLM folding model [5]. Therefore, within our proposal we are going to include the JLM interaction that presently is used only for scattering of nucleons and light nuclei on nuclei of various masses. As a parametrization of the JLM effective NN interaction we resort to a newly one, derived from the relativistic Dirac-BHF.

In the second approach we adapt the Feshbach theory of nucleon-nucleus OP to heavy ion scattering. We include second order terms treated in the WKB approximation and therefore obtain non-vanishing contributions to the imaginary part of the potential.

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2. Consistent Description of Hindrance at Sub-Barrier Energies.

In a series of papers [1,2,3,4,5], the director of the present proposal and collab. proposed an explanation of the hindrance phenomenon occurring in several medium-light and medium-heavy systems [6]. The basic idea consists in using a heavy-ion potential modified in such a manner that a strong overlap between the nuclear matter distributions tails of the projectile and target is prevented. For such configurations, especially in the inner part of the barrier, additionally to the standard direct and exchange components of the ion-ion potential, a strongly repulsive potential is acting. In the project FUSBAR we introduced within the DF method other effective *NN* forces such as Skyrme and Gogny. We tested the Gogny interaction in its three parametrizations (D1, D1S and D1N) for fusion reactions at sub-barrier energies and found that in some cases they offer an better description of the data compared to M3Y forces.

We therefore intend to prepare a review paper dedicated to the DF potential based on Gogny forces in low-energy nuclear reactions. Apart of the papers we already published regarding the applications of Gogny forces for astrophyisical reactions $^{12}C+^{12}C$, $^{12}C+^{16}O$ and $^{12}C+^{16}O$ [7,8] we have unpublished calculations on alpha-alpha scattering reactions at low energies. We also prepared a study on the equation-of-state with Gogny forces where we conclude that like the DDM3Y forces the saturation properties of symmetric nuclear matter are reproduced. Very recently the fusion excitation function of $^{36}S+^{48}Ca$ was experimentally investigated at Legnaro and cross sections as low as ∼ 600 nb were attained [9]. Along with this case the Legnaro group reinvestigated the system $^{48}Ca+ ^{48}Ca$ down to ∼ 500 nb [10] . These authors remarked that although the logarithmic derivative (slope) after a sharp increase below the Coulomb barrier saturates (level off), these two reactions still bear hindrance features. This conclusion is in disagreement with Jiang and collab. who analyzed several other projectile/target combinations [6] displaying hindrance. According to these authors a signature for the onset of hindrance is the apparent occurrence of a maximum in the *S*-factor and consequently a steep increase of the slope well below the Coulomb barrier.

To explain the data, the Legnaro group assumed an abnormally large diffuseness parameter (a=0.9 fm) in the Akyuz-Winther potential that is customary used in the coupled-channel (CC) analysis of medium heavy nuclei fusion data. For the reaction $^{96}Zr+^{48}Ca$ reported earlier by the Legnaro group the same conclusion was reached, i.e. saturation of the slope and the need of a large diffuseness to explain the data [11]. In two very recent publications [12,13] the Legnaro group reported further measurements on the medium-light systems, $^{58}Ni+ ^{54}Fe$ and $^{36}S+^{64}Ni$, and showed that an even larger diffuseness parameter (a=1.2 fm) is necessary in order to fit the data. The assumption of a large diffuseness of the potential to explain the large slope at deep sub-barrier energies for the case $^{58}Ni+ ^{58}Ni$ was used earlier by Hagino et al. [14], but had been dismissed by us in ref. [1,2].

We therefore undertake the task to analyze the 5 fusion reactions for which there are new measurements at energies deep under the barrier. We focus our analysis on the three fusion reactions, mentioned above, and demonstrate that the data can be described by using exactly the same nuclear structure input for ^{48}Ca. For the other two nuclei the nuclear structure input used in our investigation is close to the one used by Stefanini et al. for ^{36}S , ^{96}Zr . The single particle densities entering the folding integrals are prescribed according to the Density Matrix Expansion Method. Each case is tested with four different types of *NN* effective forces : the two standard parametrizations of the density independent M3Y force (Reid and Paris) and two parametrizations of the density-dependent Gogny force (D1S and D1N). A consistent description of all three reactions is obtained by keeping fixed the nuclear structure input for ^{48}Ca. The inclusion of 2^+ and 3^- phonon states in the coupled-channel calculation, within an energy excitation window identical for all three reactions explains better the hindrance in extreme sub-barrier fusion cross sections. The interactions providing the best fit to the data are not pointing to a possible maximum in the astrophysical *S*-factor thereby confirming the conclusion reached by the Legnaro group for these cases.

A similar analysis will concern the other two reactions , ^{58}Ni+ ^{54}Fe and ^{36}S+^{64}Ni. Here, like in the case of the reactions with ^{48}Ca we seek to invalidate the conjecture of a large diffuseness of the potential.

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3. Nonlocal exchange kernels for *α*-nucleus interaction.

The influence of the Pauli principle in scattering, reactions and *α*-decay is one of the most challenging subjects in the field of nuclear physics which is not yet fully understood. The microscopic treatment of interactions between composite nuclei comprises laborious work, most of which is required to derive the nonlocal exchange kernels resulting from the antisymmetrization procedure dictated by the Pauli principle. The difficulties of the microscopic theory of composite particle interactions have mostly a technical character. The procedure of antisymmetrizing the wave function of dinuclear (projectile/target or cluster/mother nucleus) systems with respect to any nucleon permutation is in principle straightforward but in most cases leads to very complicated equations. The numerical calculation of the microscopic integral kernels are laborious (time-consuming, round-off errors,etc.).

The main purpose of this part of the proposal is to develope a convenient approach which removes part of the computational difficulties for the OMP *α*-nucleus. The effort will foccus towards obtaining expressions for the integral kernels and next solve the equation of motion of the nuclear system. The study will mainly concern spherical nuclei but we intend to discuss also the case of a deformed target.

Many astrophysical applications involve *α*-radiative captures, *α*-decays and *α*-transfer reactions. The corresponding reaction rates are still highly uncertain due to the poor knowledge of the α-nucleus OMP, especially at extreme sub-barrier energies. There have been several works dedicated to the construction of a global α-optical potential that takes into account the strong energy dependence (especially coming from the imaginary part) and nuclear structure effects that characterize the α-nucleus interaction. The compilation [1] calculates the real part of the potential using only the direct part of the DF potential with DDM3Y-Reid effective NN interactions and succeeds to reproduce well the bulk experimental data on (α,γ), (α,n), (α,p) and (n,α) reactions as well existing scattering data at energies of relevance to astrophysical applications (E<12 MeV). The compilation [2] introduce also the exchange term via the knock-on approximation but no recoil effects are accounted for. The analysis is extended to the alpha-particle scattering data on nuclei in the range A~50-120 and energies from ~13 to 50MeV.

Compared to these contributions we plan to extend the study of the α-nucleus OMP first by including in the analysis various parametrizations of the Gogny forces and the Skyrme forces. We are also going to treat the nonlocal exchange kernel according to the above outlined new procedure. Another point that we would like to approach is related to the imaginary part of the OMP. For this reason we are going to apply the JLM folding model which provides both real and imaginary part of the OMP thereby reducing drastically the number of parameters in the model. With the corresponding computer code developed in the first part of the proposal we will carry out extensive calculations for the microscopic OMP for alpha-nucleus elastic scattering.

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4. Asymptotic Normalization Coefficients from one-proton removal breakup reactions

A long term program of reaction studies at the RIKEN RIBF facility is initiated by a large international collaboration involving Texas A&M Univ.,IFIN-HH Bucharest, and others institutions from France, Japan, Italy and UK. The initial focus will be on the extraction of Asymptotic Normalization Coefficients (ANCs) from one proton removal breakup reactions. These experiments will provide important information about rates of nuclear reaction that occur in stellar explosions. They will be carried out using the Zero-Degree Spectrometer with fragmentation beams from the BigRIPS projectile separator at RIBF. In the longer term, both proton and neutron one nucleon removal reactions will be studied using a new spectrometer, SAMURAI. It will have focal plane detectors for light and heavy ions and for neutrons. Funds are provided by DOE/Office of Science Program Office to build a silicon detector array that would go just after the target and in front of SAMURAI. The silicon array would be used to measure the angles of protons and heavy-ions following a reaction in the target. The goal of the future experiments is to obtain information about (*p*,*γ*) and (*n*,*γ*) reaction rates at stellar energies for nuclei far from stability. Analysis of the data and the extraction of spectroscopic information will require a close interplay between experiments and advances in reaction theory. Romanian collaborators on this proposal (from IFIN-HH) will develop the theoretical tools needed to describe the data resulting from the measurements of breakup reaction cross sections of the proton-halo candidates ^{9}B, ^{9}C and ^{27}Al. The main task is represented by the determination of ANCs and, where appropriate, spectroscopic factors. The *S*-matrix elements defining the transition operators for breakup stripping, nuclear and Coulomb dissociation will be derived from an eikonal expansion up to second order from the microscopically calculated OMP developed in the first part of the proposal (see section 1)

5. Deeply bound proton removal reactions from neutron rich nuclei around *Z*=16,*N*=28

Nucleon removal at intermediate energies (from 50 to several 100 MeV/nucleon) is a key direct reaction frequently used to populate hole states in exotic nuclei and access information on their wave function from the measured cross sections. These studies performed at low-energy beam fragmentation facilities are unique to tackle the question of shells and single-particle properties of unstable nuclei. In the foreseeable future the following problems are intended to be solved : (i) solve long-standing issues concerning nucleon removal reactions, (ii) develop new microscopic approaches to calculate cross sections for one- or two-nucleon removal using relativistic-energy beams, (iii) develop a coherent description of hydrogen and heavy-ion induced removal reactions. Generally, experimental and theoretical approaches aim at extending our knowledge of nucleon-removal reactions and their interplay with nuclear structure, beyond the present state-of-the art, mainly based on the Glauber approximation. Nucleons in atomic nuclei experience a shell structure that evolves within the nuclear landscape [1], revealing a new picture of shell closures for some exotic nuclei compared to the sequence first established by Goeppert-Mayer and Jensen. Our understanding of nuclear structure far from stability relies on experiments based on the use of radioactive beams and nuclear reactions in inverse kinematics. Shell occupancies in ground-state wave functions can be revealed by analyzing cross sections of direct stripping reactions such as low-energy transfer or knockout reactions. The measured absolute cross sections lead to the determination of shell occupancies through the extraction of spectroscopic factors as well as the Asymptotic Normalization Constant (ANC) in the ground state and from there the direct component of the astrophysical S factor for the corresponding radiative capture reactions. The parallel momentum distribution of the residue is sensitive to the intrinsic angular momentum L of the removed nucleon. Transverse momentum distribution of the heavy fragment have been proved as a powerful tool for the spectroscopy of loosely bound nuclei. Recent studies indicate that two-nucleon removal may be sensitive to pair correlations. The predicted cross sections are found to be systematically too high for deeply-bound nucleons by a factor of 3-4. Up to now, no quantitative explanation has been provided. It was first suggested that deeply -bound nucleons experience additional correlations, not taken into account in mean-field or shell-model calculations, which may lead to an unexpected strong shell depletion [2], but modern Green's function calculations predict only a moderate increase of short range correlations for deeply-bound nucleons [3]. This discrepancy between theory and experiment for deeply-bound nucleon stripping has been investigated via low-energy transfer reactions in the Argon isotopic chain from ^{46}Ar to ^{34}Ar: a weak dependence of correlations on neutron-proton asymmetry has been suggested [4]. The quasielastic assumption is found to be relatively valid with structureless probes such as electrons or protons when restricted to certain kinematical regions. In the case of inclusive heavy-ion induced nucleon-removal reactions, multiple re-interactions of nucleons inside the projectile or excitations of the residual nucleus during the reaction may blur the simple picture of a single nucleon ejected from a frozen nucleus, with no other collision. A recent study of deeply-bound nucleon removal reactions allowing core excitations via a Monte-Carlo based approach suggests that core excitations occurring in the collision may play a role in the observed “reduction” of experimental cross sections compared to eikonal ones [5]. Unexplained large momentum tail and non-eikonal distortions have been observed in the momentum distributions of the residual nucleus showing that dissipation in such fast collisions is not understood yet [6]. A coherent set of nuclear structure information coming from all facilities requires a joined effort towards a good understanding of direct reaction mechanisms. Neutron-rich nuclei in the neighborhood of ^{44}S have attracted much attention in recent years. The question whether the high degree of collectivity observed for ^{42,44}S is due to a breakdown of the N = 28 neutron-magic number or the collapse of the $Z = 16$ proton subshell gap at neutron number 28 is much discussed in the literature . The vanishing of the $Z = 16$ subshell closure was inferred from the near-degeneracy of the proton $s_{1/2}$ and $d_{3/2}$ orbitals in the chain of *K* isotopes as $N = 28$ is approached. The reaction mechanism will be discussed in terms of a complex *G*-matrix interaction which include three body effects obtained from Brueckner theory of nuclear matter. We believe that it is crucially to test this interaction in proton removal reactions in order to asses the importance of three body effects. We propose to go beyond the eikonal model by calculating *S*-matrix elements in the impact parameter space by an exact continuation method based on Calogero equation. We propose also to include final state interactions effects in calculating parallel momentum distributions of the heavy residue in nuclear dissociation. Coulomb amplitudes for proton removal will be calculated as usual in the first order of the perturbation theory.

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