Proposal for an INFN Research Project (Iniziativa Specifica)

Section I:

Title:

MOdeling Nuclear STructure and REactions

Acronym:

MONSTRE

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Keywords

Nuclear Structure – Nuclear Reactions – Many-body methods - Density functionals

Abstract

The main goal of our collaboration is to implement an integrated framework for the physics of atomic nuclei, nuclear reactions, and strongly interacting matter. We aim to match the development of nuclear structure and reaction theory with the experimental progress currently underway in areas like the production of rare isotopes, dark-matter detection, and the physics of electroweak interactions, including neutrino-oscillation and double-beta decay. The recent progress in gravitational-wave detection also calls for a better understanding of the nuclear interactions aiming to reconcile terrestrial nuclear physics observations with the new constraints of astrophysical origin. We will not disregard also important applicative aspects like those related to nuclear medicine.

Different complementary aspects in the field will be tackled by networking the combined expertise of the various units, who are active in developing a set of advanced and complementary many-body analytic and computational methods. We plan to use our experience in a concerted way in the effort of bridging the gap between the different scales involved in a modern nuclear physics research program.

Specific research paths that will be explored include:

- Modern interactions derived from nuclear effective field theories will be implemented in the light and medium mass sectors, and in infinite matter using *ab initio* techniques, investigating in particular the role of the three-body force. Consistent nuclear currents derived within the same framework, and describing the interactions of nucleons with electromagnetic and weak probes, will allow us to quantitatively understand nuclear effects relevant to experiments like neutrino oscillations, radiative capture, single- and double-beta decay.
- Many-body methods including the nuclear shell-model, density functional theory, optical potentials, and algebraic models will be employed in the calculation of bulk, spectroscopic, and decay properties in finite nuclei throughout the mass table. We will improve these methods by constraining the effective interaction against *ab initio* calculations. Our goal is to achieve a coherent picture of the role of short- and long-range correlations in nuclei across the nuclear chart.
- The consistent merging of structure and reaction theories will offer the opportunity to directly compare theoretical calculations with data obtained from experiments employing probes and reactions for nuclear systems under extreme conditions. In particular, we plan to study weakly bound systems at the edge of nuclear stability, as well as new nuclear excitations and, based on dissipative heavy-ion collisions, nuclear matter in different density conditions.

We plan to strengthen our connections with the experimental INFN committees, also through the organization of joint thematic workshops. Our network will provide a perfect scientific environment for the training and mobility of Ph.D. students in the field of low-energy nuclear theory. The collaboration aims at proposing courses at the Ph.D. level shared by the different Units.

Composition of the participant Research Units:

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- **INFN Section Catania**
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Section II:

Status of the relevant research field; scientific context, objectives and envisaged achievements of the proposed program

Modern nuclear physics aims at achieving a unified description of extremely complex phenomena occurring at different scales of energy and size. Topics like the connection between QCD and nuclear forces, the description of nuclear reactions in exotic nuclei, heavy-ion collisions, and the physics of neutron stars used to be the work fields of different communities, each one developing methodologies targeted to specific classes of problems.

We envision establishing a synergistic framework that connects all these diverse research areas, capitalizing on the specific expertise of each community. Recent experimental advancements have clearly pointed out the need for such a strategic agenda. For example, the direct observation of gravitational waves has spurred the demand for a fully quantitative understanding of the nuclear equation of state (EoS). This fact has, in turn, triggered a number of experiments addressing the physics of hypernuclei, directly related to the high-density part of the EoS, and further revived the community involved in the physics of rare ions and heavy-ion collisions. In both cases, experiments need to be accompanied by a substantial theoretical effort that can reconcile modern theories of the nuclear interaction at low and intermediate energies with astrophysical observations. Similar scenarios have consistently emerged also in the field of neutrino physics, dark matter detection experiments, and rare ion beams.

Over the last decades, nuclear effective field theories have established themselves as the general paradigm to devise nuclear interaction and consistent electroweak currents. This has rekindled the interest for analyzing the existing theoretical tools to provide a unified pattern leading from few-body systems to heavy nuclei and to the EoS. A bright example in this context was given by the US nuclear physics community, which launched several years ago the UNEDEF initiative, now turned to the NUCLEI initiative.

Another important aspect is related to the continuous development of theoretical methods that capitalize on high-performance computing (HPC) resources. In the past, there was a certain separation in the domain of ab-initio (AI), shell model (SM), and mean-field (MF) approaches, mostly due to the difficulties for AI methods to reliably compute properties of nuclei of sufficiently large mass and to provide a significant benchmarking for SM and MF applications. Because of algorithmic development and the increasing availability of HPC, it is now possible to develop a research program that covers the nuclear chart using theoretical methods like the self-consistent Green's function (SCGF) [Mi1], and quantum Monte Carlo (QMC) along with DFT [Mi2, Mi3] and advanced SM. Different problems can be attacked by designing a coherent path leading from the connection of nuclear forces to lattice-QCD results for few-baryon systems up to the assessment of the effects of pairing in rare ions or the determination of the extent of collective phenomena from the spectroscopy of heavy nuclei.

The community of theoretical nuclear physicists within the INFN enjoys a large variety of expertise and a wide spectrum of applications. The main objective of this Research Project is to attack some of the most significant problems concerning the structure of atomic nuclei, nuclear reactions, and strongly interacting matter exploiting all these capabilities and combining them into a synergistic effort. The proposed research will be closely connected to the ongoing experimental activities, both within INFN and in the more general, international context. The members of this research group have a long tradition of collaboration among them (partly in the context of similar INFN projects, partly based in independent interactions), and the sustained scientific production, testified by the good publication rate and by the numerosity and quality of the international collaborations, will be a sound basis for a successful implementation of this agenda.

Within the articulated structure of the research team, we can identify a number of work packages that will be carried out in collaboration between the various local subgroups, as specified in detail in the next section.

- **WP1: (NS) Modern Approaches to Nuclear Structure**

  One of the most important questions that remain open in nuclear physics is the extent and characterization of three-body forces throughout the nuclear chart, including hypernuclei. While the advent of nuclear-EFT, sided by the analysis of lattice-QCD results, has shed light on this issue, many aspects are yet to be fully addressed, such as those concerning their short-range behavior and isospin-dependence, both crucial in modeling infinite matter. Existing theoretical tools will be revisited and expanded in a constant benchmarking effort. Within this context, the role of short- and long-range correlations in the formulation of increasingly accurate MF approaches will be thoroughly explored. This WP will also include a study of isospin-breaking effects and the extension to hypernuclei. Hyperon physics has a particular relevance for the static and dynamic properties of Neutron Stars.

- **WP2: (NR) Collective phenomena and nuclear correlations**

  The understanding of collective phenomena remains a fundamental topic in nuclear physics, as also testified by the very strong experimental activity. In this WP the quantitative description of excitation modes in the spin-isospin channel, and the connections between collective modes and the EoS beyond magic nuclei will be explored in great detail. A second important line concerns the refinement of the Optical Potential (OP) technique. OPs will be calculated by ab initio methods and related to EFT interactions. Finally, four body structures and clustering effects will be investigated.

- **WP3: (RI) Physics of exotic nuclei**

  The intense development of radioactive beam facilities – with the opening, among others, of the INFN facility SPES and of FRIB at MSU in the near future - has led to an enormous progress in the experimental knowledge of nuclei far from the valley of stability. This subject is of primary interest for our collaboration, especially in view of the many applications in astrophysics. Several challenges arise for theory, such as investigating the role of the three-body force on the evolution of shell structure when going towards a large N/Z ratio. The study of unbound resonant states must involve an accurate treatment of the continuum, as well as a delicate matching between the study of structure and reactions. Specific investigations will concern the role of pairing correlations in halo nuclei, the calculation of absolute cross sections of transfer reactions, the population of nucleon unbound states, the mechanism of breakup reactions, the determination of accurate optical potentials for exotic nuclei, and the study of new excitation modes.

- **WP4: (EW) Electroweak probes**

  The collaboration will employ state of the art many-body techniques to compute nuclear matrix elements relevant for experiments with electromagnetic probes, including electron scattering, neutrino oscillations, radiative capture, single and double-beta decay. Extensive benchmarking will be carried out, in order to validate and discuss theoretical estimates, aiming at a clearer interpretation of experiments.

- **WP5: (HE) Nuclei at high energy and temperature, and nuclear matter**

  The study of heavy-ion collisions (HIC) is of extraordinary interest to understand the properties of nuclear matter. Together with the spectroscopy of rare ions, it provides the only direct access to matter in conditions close to those found in compact stars. Research relative to this WP will be devoted to further develop theoretical tools aimed at interpreting HIC experimental data and derive information useful for inferring the properties of nuclear matter in different density conditions.

- **WP6: (AP) Connection to Evolving Technologies and Applications**

  A relevant growing aspect of our research in nuclear physics is the development of quantum computing techniques and nuclear physics, for instance for the direct simulation of nuclear reactions with realistic potentials. This will be carried out in strict connection to the general effort that INFN is making in this direction, and in collaboration with experimental groups in Italy and abroad. Another important set of applications concerns studies in medical physics, as for instance those related to cancer-therapy based on irradiation of protons or heavier ions.

The time span of the project is sufficient to envision the production of at least five focused papers for each WP. The networking structure of the group is already well established, at least for the most part, and this will guarantee a prompt starting of operation. Particular care will be devoted to the organization of regular meetings, both within each single WP and general, in order to favor the continuous exchange of ideas and good practices and to foster novel collaborations, that might also go beyond the scopes of each single WP.

Proposed activities and role of the various Research Units

In this section, we present the articulation of the activity referred to the Work Packages previously introduced.

- **WP1: (MONSTRE-NS)** *Catania, Lecce, LNS, Milano, Napoli, Padova, TIFPA*

As mentioned in the general description of WP1, one of the most impacting open questions in nuclear structure is the difficulty in generating a consistent scheme for the three-nucleon forces applicable throughout the nuclear chart and to nuclear matter.
The researchers within the collaboration have a long tradition in both ab-initio methods (SCGF, QMC) and SM calculations [Mi1, Na1, Tn1]. An important role is played by chiral-EFT, which exploits the broken symmetry pattern of QCD to derive consistent two- and three-nucleon interactions. Our plan is to extend systematic calculations from light nuclei to heavier systems by making use of our extensive toolbox. SCGF calculations with chiral forces will be extended to non-harmonic-oscillator bases such as Discrete Variable Representation (DVR) (to improve continuum) and to include Particle-Vibration Coupling (PVC) in open shells (*Milano*). Recently, also Auxiliary Field QMC codes have been improved and now provide reliable results for medium-mass nuclei. We will continue exploring other nuclear EFT schemes. The latter include pion-less EFT, which allows for a systematic connection to LQCD results, and, on the other extreme, a pion-full EFT scheme, where pions are treated as explicit degrees of freedom [Tn2] (*TIFPA, Milano*).
Since 2002, SM calculations have been extended to the study of this modern class of nuclear forces, also including three-body force effects, by deriving the shell-model Hamiltonian from chiral potentials including three-body terms [Na2, Na3]. SM results will be further refined and benchmarked against ab-initio calculations. This is particularly important in view of other applications of the SM method pertaining to WP2, WP3, and WP4 (*Napoli, TIFPA, Milano*)
An important, needed step to reach out to the heaviest nuclei is to find a way for improving current energy density functionals (EDFs), along different avenues: building functionals based on state-of-the-art ab initio calculations [Mi2], or with new constraints coming from experimental data [Mi3, LNS1], or using reverse engineering [Mi2] (inverse DFT problem: deducing functionals from densities) (*Catania, Lecce, LNS, Milano, TIFPA*). We have a unique collection of computational tools, like self-consistent HF+RPA calculations in spherical and deformed nuclei with Skyrme and Gogny density functionals; Auxiliary Field DMC and CBF techniques for explicitly correlated states, and BcDor for SC Green's function for the ab initio method [Mi1], that will give us the opportunity of effectively explore this route. In this context, we also want to improve our understanding of isospin-breaking effects (*Padova, Milano*) through the evaluation of Coulomb energy differences and mirror energy differences and the role played by the tensor forces [Mi3, Pd1]. Within the shell-model framework we also intend to study the role of halo orbits in the difference of analogue excited states in mirror nuclei and in the evolution of charge radii along isotopic chains (*Padova*) [Pd2]. Finally, we want in general to extend our calculations to systems with strangeness, where the nuclear Hamiltonian is still mostly unconstrained, implementing a strategy making use of both EFT- and phenomenology-based interactions, as a further playground for the application of our many-body theory toolbox (*Lecce, Milano, TIFPA*).

- **WP2: (MONSTRE-NR)** *Bologna, Catania, LNS, Milano, Padova*

Collective excitations will be studied, in parallel with the intense ongoing experimental activity, improving both the effective interactions and the many-body methods adopted.
Particular attention will be given to an accurate description of spin and isospin excitations, constraining the density functionals with results from ab initio theory and from charge exchange reactions [Mi2, LNS2] (*Milano, LNS*). Collective excitations provide valuable information concerning the nuclear EoS, for instance regarding the incompressibility and the symmetry energy [Mi3]. This connection will be thoroughly studied in the case of open shell and deformed nuclei. Also, the excitation mechanism and the properties of pygmy dipole states [Ct3] will be investigated in deformed nuclei (*Catania, Padova*). The properties of collective excitations will be studied by Second RPA making use of recent theoretical developments to overcome double counting and stability issues [LNS1] (*LNS*).
The study of the fine structure of collective excitation spectra and low-lying spectral properties is based on the single-particle and core excitations coupling [Particle Vibration Coupling (PVC)]. PVC stems in a natural way from the perturbative solution of the Dyson

equation and will be studied within the SCGF ab initio method as well as within self-consistent schemes based on the Nuclear Field Theory. An important aspect of the SCGF formalism is its suitability to determine OPs, by taking into account the coupling of the projectile with a large number of virtual excitations of the target [Mi4], and efforts will be made to extend the class of included multiple particle-hole states (*Milano*). OPs will also be obtained from realistic NN potentials to study nucleon elastic scattering processes in spin unsaturated nuclei, and inelastic channels, both for protons and antiprotons as probes (*Bologna*). The fragmentation of the single-particle strength revealed by one-nucleon transfer reactions [Mi5], and the interplay of long-range and short-range correlations will be investigated, also in relation with systematic experimental investigations (*Padova, Milano*).

The effect of core excitation in direct transfer reactions in weakly bound nuclei populating collective states in the continuum will be investigated (*LNS, Milano, Padova*).

We also intend to pursue a detailed study of four-body structures and of their impact on low-energy spectra. Nuclear quarteting has long been claimed to represent a crucial aspect of nuclear structure. The difficulty in handling alpha-like correlated structures has been recently overcome by a microscopic formalism [Ct4, Ct5] which will be employed for the analysis of self-conjugate nuclei. The emergence of clustering and the formation of nuclear molecules and collective rotations and vibrations at low energy will be investigated in approaches making use of discrete symmetry and point-groups [Pd3] (*Catania, Padova*).

- **WP3: (MONSTRE-RI)** *Bologna, Catania, Lecce, LNS, Milano, Napoli, Padova*

SM calculations will be used to investigate the relevance of chiral potentials, with particular focus on the 3-body component, to phenomena connected with exotic nuclei and the location of nuclear drip lines (*Milano, Napoli*). Starting from free nuclear potentials, we construct microscopic shell-model Hamiltonian derived by means of many-body perturbation theory or semi-realistic Hamiltonians, in which some two-body matrix elements are readjusted by applying mainly monopole corrections.

We plan to investigate the structure of exotic nuclei in different mass regions, as for instance the neutron-rich Ca isotopes, nuclei in the $_{78}$Ni region or beyond $_{132}$Sn, explaining and/or predicting specific phenomena as the origin of the islands of inversion, the disappearance of magic numbers and the onset of quadrupole collectivity (*Napoli, Padova*). To gain more understanding from a complementary viewpoint, mean field methods will be used to study nuclear deformation (*Bologna, Catania, Lecce, LNS, Milano, Napoli*). This WP implies a strict synergy between structure and reaction theory developments. Concerning the latter, we plan to benchmark quantum mechanical and semi-classical inclusive breakup models [Pd5], within the surface approximation, and to consider numerical implementations of quantum mechanical elastic breakup. Special attention will be devoted to the derivation of microscopic optical potentials for exotic nuclei (*Bologna, LNS, Milano, Padova*). The proper theoretical description of two-neutron transfer reactions involving weakly-bound nuclei will be investigated [Pd4]. These reactions are a key to understanding several properties of the pairing interaction, which underpins the emergence of nuclear superfluidity and determines the stability of two-nucleon halos. The study of resonances in unbound nuclei populated via knockout or transfer reactions will also be pursued [Mi5, LNS3]. The analysis of NN and core-N correlations in the decay of these systems is of timely relevance for the current experimental developments (*Catania, LNS, Milano, Padova*). We also plan to investigate, within DWBA and/or coupled channel calculations, the impact of clustering effects in light nuclei on fusion/transfer cross sections of astrophysical interest, which show an unexpected enhancement close to the Gamow peak, usually attributed to “electron screening” effects (*LNS, Milano, Padova*).

- **WP4: (MONSTRE-EW)** *Lecce, LNS, Milano, Napoli, TIFPA*

The main focus within this WP is the calculation of nuclear matrix elements (NME) relevant for electroweak processes utilizing state of the art nuclear many-body approaches.

A first direction concerns the study of electron- and neutrino-nucleus scattering, which has a twofold impact. On the one hand, it has important implications for the studies of short-range nuclear dynamics carried out at J-Lab, MAMI, and other electron-scattering facilities worldwide. On the other one, our calculations are relevant for the correct interpretation of neutrino-oscillation signals, as measured by current and planned accelerator-neutrino experiments, including DUNE and T2K. The methods that will be employed are Quantum Monte Carlo, and more specifically the Green's Function Monte Carlo (*TIFPA*), combined with integral-transform methods [Tn3, Tn4] and finite-range interactions DFT methods (*Lecce*). Our calculations will be accompanied by robust estimates of the theoretical uncertainties, which will ultimately enter the error budget of neutrino-oscillation parameters.

The collaboration has a long-standing experience in the study of beta decay processes, which has led in the last years to the microscopic calculation of neutrinoless double beta decay NMEs. Following previous work [Na4, Na5] we will attack the calculation of the NMEs for the $_{100}$Mo decay within the nuclear SM both for the $2v$ and $0v$ channels (*Napoli)*. This case - that will be investigated in future next-generation INFN experiments (in particular by the CUPID collaboration) - is of particular interest. Two-body meson-exchange currents that can be derived within the chiral perturbation theory consistently with the starting nuclear Hamiltonian will be employed (*Napoli*). We envisage a fruitful interplay with CBF to better assess the role of nuclear correlations.

New efforts will be devoted to modeling, within quantum scattering theory, heavy ion double CE (DCE) reactions, and to explore the common aspects with double beta-decay [LNS2] (LNS).

Reactions of current experimental interest (NUMEN collaboration), involving nuclei candidates for the $0v\beta\beta$ process (such as $_{76}$Ge-$_{76}$Se), will be investigated, employing RPA (*LNS*) and SM (*Napoli*) inputs for the NMEs. With the advent of ambitious experimental programs at MESA (Germany) and JLab (USA), we also plan to pursue the study of the parameters of the standard model (weak mixing angle) as well as nuclear structure properties such as the weak charge distribution, intimately related to the neutron distribution, via parity violating electron scattering by nuclei (*Lecce, Milano*).

- **WP5: (MONSTRE-HE)** *Catania, LNS, Milano*

The understanding of dissipative heavy ions collisions at the Fermi energies and beyond is a powerful method to extract information on the Nuclear EoS far from the stability, of crucial importance for the physics of core-collapse supernove and neutron stars. The reaction dynamics will be modeled with upgraded transport theories (i.e. extended time-dependent DFT employing the same functionals as in structure studies) incorporating many-body correlations (*LNS*) [LNS4]. In particular, the Constrained Molecular Dynamics (CoMD) model solves the nucleonic wave-packet dynamics in the semi-classical approximation, with constraints related to the Pauli principle [Ct1, Ct2] *(Catania)*. Many-body correlations allow for a spontaneous cluster production in nuclear reactions. A comprehensive analysis of new experiments will be undertaken, characterizing fragment production, low- density clustering and isospin effects, to get insights into the EoS properties. Further modifications of the effective interaction, including also finite range effects, are planned in order to improve the comparison with data as far as details of the final cluster and light particle production are concerned. These phenomenological studies are complementary to microscopic investigations of the nuclear EoS (*Milano).*

- **WP6: (MONSTRE-AP)** *LNS, TIFPA*

Recent progress in the development of quantum computer prototypes has opened the perspective of efficiently attacking problems that are still not accessible with standard computational techniques. In the framework of this collaboration new algorithms that can be implemented on existing quantum testbeds will be developed, in strict cooperation with the experimental groups building and/or maintaining the hardware. The strategy on which we will focus is related to optimal control techniques [Tn5], and the first target will be implementing real time evolution with realistic nuclear interactions to study simple reactions by directly emulating the physical process (*TIFPA*).

An important application of the theoretical tools developed in the collaboration relates to medical physics. Upgraded semi-classical transport theories will be applied to fragmentation studies of interest for medical applications, for light ion reactions at intermediate energies (30-80 MeV/nucleon) (*LNS*). We aim at getting a better description of experimental data, with respect to models existing in GEANT4 [LNS5], as well as reproducing the dispersion of secondary electrons by means of methods based on the Auger spectroscopy (*LNS, TIFPA*).

Section III:

List of the most significant publications of the last five years of each Research Unit related to the proposal

- INFN Unit **Bologna**

[Bo1] M. Vorabbi, P. Finelli, and C. Giusti,
Theoretical optical potential derived from nucleon-nucleon chiral potentials,
Phys. Rev. C **93**, 034619 (2016)

[Bo2] M. Vorabbi, P. Finelli, and C. Giusti,
Optical potentials derived from nucleon-nucleon chiral potentials at N4LO,
Phys. Rev. C **96**, 044001 (2017)

[Bo3] M. Vorabbi, P. Finelli, and C. Giusti,
Proton-Nucleus Elastic Scattering: Comparison between Phenomenological and Microscopic Optical Potentials,
Phys. Rev. C **98**, 064602 (2018)

[Bo4] P. Finelli, M. Vorabbi, and C. Giusti,
Optical Potentials: Microscopic vs. Phenomenological Approaches,
EPJ Web of Conferences **223**, 01015 (2019)

[Bo5] M. Vorabbi, M. Gennari, P. Finelli, C. Giusti, and Petr Navràtil,
Elastic Antiproton-Nucleus Scattering from Chiral Forces,
Phys. Rev. Lett. **124**, 162501 (2020)

- INFN Unit **Catania**

[Ct1] M. Papa,
Many-body correlations in semiclassical molecular dynamics and Skyrme interaction,
Phys Rev C **87**, 014001 (2013)

[Ct2] M. Papa et al.,
Dipolar degrees of freedom and isospin equilibration processes in heavy ion collisions,
Phys. Rev. C **91**, 041601(R) (2015)

[Ct3] A. Bracco, E.G. Lanza and A. Tamii,
Isoscalar and isovector dipole excitations: Nuclear properties from low-lying states and from the isovector giant dipole resonance,
Prog. Part. Nucl. Phys. **106**, 360 (2019)

[Ct4] M. Sambataro and N. Sandulescu,
Four-body correlations in nuclei,
Phys. Rev. Lett. **115**, 112501 (2015)

[Ct5] M. Sambataro and N. Sandulescu,
Quartetting in odd-odd self-conjugate nuclei,
Phys. Lett. B **763**, 151 (2016

- INFN Unit **Lecce**

[Le1] G. Co', M. Anguiano, A. M. Lallena
Nuclear structure uncertainties in coherent elastic neutrino-nucleus scattering
JCAP **04**, 044 (2020)

[Le2] M. Anguiano, A. M. Lallena, R. Bernard, G. Co'
Neutron gas and pairing
Phys. Rev. C **99,** 034302 (2019)

[Le3] G. Co', M. Anguiano, V. De Donno, A. M. Lallena
Matter distribution and spin-orbit force in spherical nuclei
Phys. Rev. C **97**, 034313 (2018)

[Le4] V. De Donno, G. Co', M. Anguiano, A. M. Lallena
Pairing in spherical nuclei: Quasiparticle random-phase approximation calculations with the Gogny interaction
Phys. Rev. C **95** 054329 (2017)

[Le5] M. Anguiano, R. N. Bernard, A. M. Lallena, G. Co', V. De Donno
Interplay between pairing and tensor effects: a study of N=82 even-even isotopes
Nucl.Phys. A **955,** 181 (2016)

- INFN Unit **LNS**

[LNS1] D. Gambacurta, M. Grasso, O. Vasseur,
Electric dipole strength and dipole polarizability in $_{48}$Ca within a fully self-consistent second random–phase approximation,
Phys. Lett. B **777,** 163 (2018) 163-168

[LNS2] H. Lenske, F. Cappuzzello, M. Cavallaro, M. Colonna,
Heavy ion charge exchange reactions as probes for nuclear β-decay,
Prog. Part. Nucl. Phys. **109,** 103716 (2019)

[LNS3] A. Bonaccorso, F. Cappuzzello, D. Carbone, M. Cavallaro,
G.Hupin, P. Navratil, S. Quaglioni,
Application of an ab initio S matrix to data analysis of transfer reactions to the continuum populating $_{11}$Be,
Phys. Rev. C **100**, 024617 (2019)

[LNS4] M.Colonna,
Collision dynamics at medium and relativistic energies,
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List of the main national or international collaborations related to the proposal

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- GAMMA Experiment, INFN, Italy
- CUPID Experiment, INFN, Italy
- NEWCHIM experiment, INFN, Italy
- ASFIN experiment, INFN, Italy
- Asy-EOS international collaboration

- SπRIT international collaboration
- INDRA-FAZIA international collaboration