Book of Abstracts

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New Aspects and Perspectives in Nuclear Physics
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National and Kapodistrian University of Athens
and
The University of Ioannina

HINPw6 - 14-16 May 2021

Invited Speakers

Luis Acosta (Mexico)
Nicolas Alamanos (France)
Aldo Bonasera (USA)
Francesco Cappuzzello (Italy)
Jésus Casal (Spain)
Manuela Cavallaro (Italy)
James Kolata (USA)
Walter Loveland (USA)
Ismael Martel (Spain)
Nikolay Minkov (Bulgaria)
Agatino Musumarra (Italy)
Joe Natovitz (USA)
Patrick O’Malley (USA)
Nils Paar (Croatia)
George Perdikakis (USA)
Costel Petrache (France)
Peter Ring (Germany)
Manuela Rodríguez-Gallardo (Spain)
Marcia Rodrigues (USA)
Angel Sanchez-Benitez (Spain)
Ivan Stekl (Czech Rep.)
Martin Veselsky (Czech Rep.)
Sherry Yennello (USA)
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- **Interdisciplinary studies and societal applications**

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The societal impact of nuclear physics

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One of the main beneficiaries in the area of Nuclear physics applications is medicine. From Magnetic Resonance Imaging (MRI) to the different types of radiation used in hospitals, nuclear physics is omnipresent. The development of new radioisotope production techniques, therapy of certain cancers with ions and hadron therapy are among the subjects undergoing rapid development [1]. Moreover, many other fields benefit from the techniques of nuclear physics: archaeometry, the nondestructive investigation of packages or containers at customs, the study of the pollution of our environment and others. Into this concept, I will revise Nuclear physics applications, underling the societal impact of Nuclear Physics.

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Relativistic Brueckner-Hartree-Fock Theory in Nuclear Matter and Finite Nuclear Systems

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Ab initio calculations of the structure of nuclei are of fundamental interest in nuclear physics, and in the past, considerable progress has been made with non-relativistic many-body methods. Dirac-Brueckner-Hartree-Fock theory provides a relativistic *ab intio* approach, which, in the past, has been used mostly to study nuclear matter. It has been found that relativistic effects play an essential role. In contrast to all the non-relativistic ab-initio calculations, which need three-body forces and further input from finite systems, the relativistic Brueckner method is based on two-body scattering data only. However, there are still several open problems. We present an overview about recent progress in this field, in particular on the first solution of the Brueckner equations for nuclear matter in the full Dirac space and on applications in finite nuclei and neutron droplets.

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Nuclear magnetic transitions in the relativistic energy density functional approach

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Magnetic dipole (M1) transitions contribute not only to a fundamental mode of excitation in atomic nuclei, but they are also relevant in nuclear astrophysics. Recently a theory framework has been established for the description of M1 transitions, based on the relativistic nuclear energy density functional [1-4]. The relativistic quasiparticle random phase approximation (RQRPA) has been formulated using density dependent point coupling interactions, supplemented with the isovector-pseudovector interaction channel for studies of unnatural parity transitions. Model calculations have been validated by comparing with the M1 sum rules. The analysis of M1 properties have been performed, including the spin, orbital, isoscalar and isovector M1 transition strengths, that relate to the electromagnetic probe, in magic nuclei ^{48}Ca and ^{208}Pb, and open shell nuclei ^{42}Ca and ^{50}Ti [1,2]. It is shown that pairing correlations have a significant impact on M1 transition strength distributions[1,4]. Due to their relation to the spin-orbit splittings of single-particle states, the M1 excitations could provide an additional constraint to improve nuclear energy density functionals.

Recent measurement of inelastic proton scattering on even-even $^{112\text{-}124}$Sn isotopes provides a novel insight into the isotopic dependence of E1 and M1 strength distributions[5]. Therefore, we have investigated M1 transitions in even-even $^{100\text{-}140}$Sn isotopes from a theoretical perspective, based on relativistic nuclear energy density functional [3]. The calculated M1 transition strength distribution is characterized by an interplay between single and double-peak structures, that can be understood from the evolution of single-particle states, their occupations governed by the pairing correlations, and two-quasiparticle transitions involved. It is shown that discrepancy between model calculations and experiments for the M1 transition strength is considerably reduced than previously known, and the quenching of the g factors for the free nucleons needed to reproduce the experimental data on M1 transition strength amounts g_{eff}/g_{free}=0.80-0.93. Considering that part of the M1 strength above the neutron threshold may be missing in the inelastic proton scattering measurement, we conclude that further experimental studies are required to confirm the reduced quenching of the bare g factors when applied in finite nuclei [3].

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Chirality and wobbling in nuclei: new achievements and perspectives

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The breaking of symmetries in quantum systems is one of the key issues in nuclear physics. In particular, the spontaneous symmetry breaking in rotating nuclei leads to exotic collective modes, like the chiral and wobbling motions, which have been intensively studied in recent years. Chiral bands in even-even nuclei, which were taught to be unfavored energetically, unstable against 3D rotation and difficult to observe, have been instead identified very recently in ^{136}Nd. Multiple chiral bands have been also identified in the neighboring ^{135,137}Nd nuclei, and pseudospin-chiral quartet bands in the presence of octupole correlations have been identified in ^{131}Ba. These new experimental results triggered many theoretical developments and extensions of the previous models, which are now able to describe complex band structures resulting from chirality-parity violation in triaxial nuclei with reflection asymmetry. An overview of the latest experimental results and theoretical developments will be presented.

The wobbling motion is another topic related to triaxial nuclei, with new results and theoretical developments under intense current debate. The first evidence of wobbling bands built on two-quasiparticle configurations has been recently found in ^{130}Ba. Several low-spin bands in odd-even nuclei have been interpreted as wobbling bands with transverse or longitudinal coupling between the odd nucleon and the triaxial core, but the experimental evidence on the collective transitions connecting the wobbling partners is often contradictory. Recent theoretical works revealed the inadequacy of the wobbling interpretation of these low-spin bands, which in reality are tilted precession (TiP) bands. The recently published results and their interpretation will be discussed.

Shape and electromagnetic properties of the ^{229m}Th isomer

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We examine the physical conditions, and specifically the role of the quadrupole-octupole deformation, for the emergence of the 8 eV "clock" isomer ^{229m}Th [1]. Our nuclear structure model suggests that such an extremely low-energy state can be the result of a very fine interplay between the shape and single-particle (s.p.) dynamics in the nucleus. We find that the isomer can only appear in a rather limited region of quadrupole-octupole deformation space close to a line along which the ground-state and isomer s.p. orbitals 5/2[633] and 3/2[631], respectively, cross each other providing the isomer-formation quasi-degeneracy condition. The crucial role of the octupole deformation in the formation mechanism is pointed out. Our calculations within the outlined deformation region show a smooth behaviour of the ^{229}Th electromagnetic properties, including the isomer decay rate, allowing for their more precise theoretical determination. The study suggests that the same dynamical mechanism may govern also in other nuclei excitations close to the border of atomic physics energy scale, thus paving the way for the systematic search for similar low-energy isomers in adjacent and remote nuclear regions.

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Connecting the proxy-SU(3) symmetry to the shell model

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Proxy-SU(3) symmetry is an approximation scheme extending the Elliott SU(3) algebra of the sd shell to heavier shells. When introduced [1] in 2017, the approximation had been justified by calculations carried out within the Nilsson model. Recently our group managed [2] to map the cartesian basis of the Elliott SU(3) model onto the spherical shell model basis, proving that the proxy-SU(3) approximation corresponds to the replacement of the intruder orbitals by their de Shalit-Goldhaber partners, paving the way for using the proxy-SU(3) approximation in shell model calculations. The connection between the proxy-SU(3) scheme and the spherical shell model has also been worked out [3] in the original framework of the Nilsson model, with identical results.

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The islands of shape coexistence within the Elliott and the proxy-SU(3) models.

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A novel dual-shell mechanism for the phenomenon of shape coexistence in nuclei within the Elliott SU(3) and the proxy-SU(3) symmetry is proposed for all mass regions. It is supposed, that shape coexistence is activated by large quadrupole-quadrupole interaction and involves the interchange among the spin-orbit (SO) like shells within nucleon numbers 6-14, 14-28, 28-50, 50-82, 82-126, 126-184, which are being described by the proxy-SU(3) symmetry, and the harmonic oscillator (HO) shells within nucleon numbers 2-8, 8-20, 20-40, 40-70, 70-112, 112-168 of the Elliott SU(3) symmetry. The outcome is, that shape coexistence may occur in certain islands on the nuclear map. The dual-shell mechanism predicts without any free parameters, that nuclei with proton number (Z) or neutron number (N) between 7-8, 17-20, 34-40, 59-70, 96-112, 146-168 are possible candidates for shape coexistence. In the light nuclei the nucleons flip from the HO shell to the neighboring SO-like shell, which means, that particle excitations occur. For this mass region, the predicted islands of shape coexistence coincide with the islands of inversion. But in medium mass and heavy nuclei, in which the nucleons inhabit the SO-like shells, shape coexistence is accompanied by a merging of the SO-like shell with the open HO shell. The shell merging can be accomplished by the outer product of the SU(3) irreps of the two shells and represents the unification of the HO shell with the SO-like shell.

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Highest weight irreducible representations favored by nuclear forces within SU(3)-symmetric fermionic systems

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The consequences of the attractive, short--range nucleon--nucleon (NN) interaction on the wave functions of the Elliott SU(3) and the proxy-SU(3) symmetry are discussed [1]. The NN interaction favors the most symmetric spatial SU(3) irreducible representation (irrep), which corresponds to the maximal spatial overlap among the fermions. The percentage of the symmetric components out of the total in an SU(3) wave function is introduced, through which it is found, that no SU(3) irrep is more symmetric than the highest weight irrep for a certain number of valence particles in a three dimensional, isotropic, harmonic oscillator shell. The consideration of the highest weight irreps in nuclei and in alkali metal clusters, leads to the prediction of a prolate to oblate shape transition beyond the mid--shell region [1,2]. Similar effects are seen within the pseudo-SU(3) symmetry scheme, if the highest weight SU(3) irreps are employed [3].

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Shape evolution of Hg isotopes within the covariant density functional theory

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The shape evolution in the neutron-deficient Hg region is investigated within the covariant density functional framework. We study in detail a long chain of even - even mercury isotopes $^{172-202}$Hg using the relativistic point-coupling model. The low-energy excitation spectrum and the B(E2) transitions rates of even-even nuclei are obtained as solutions of a five-dimensional collective Hamiltonian (5DCH) model [1], with parameters determined by constrained self-consistent mean-field calculations based on the relativistic energy density functional DD-PC1 [2], and a finite-range pairing interaction [3,4].

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Weak Interaction Physics at *TwinSol*

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A program to investigate the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix by studying super-allowed mixed mirror β decays has been initiated at the *TwinSol* facility at Notre Dame. These mixed Fermi/Gamow-Teller (F-GT) decays, occurring between T=1/2 isospin doublets in mirror nuclei, provide a complimentary check on the data from super-allowed pure Fermi decays from 0^+ - 0^+ states. The first part of the program, involving the measurement of the lifetimes of the relevant nuclei to the required accuracy of one part in 10^3 or better, has nearly been completed. However, the additional complication introduced by F-GT mixing requires the use of an ion trap to measure this parameter with similar accuracy. In this talk, I will discuss the lifetime measurements and the progress in installing an ion trap at *TwinSol*.

In addition, since the ion trap will require a dedicated beam line for its operation, an opportunity presented itself to greatly improve the performance of the *TwinSol* facility for reaction studies with exotic nuclei. This took the form of an added dipole switching magnet coupled to a third solenoid to form the new *TriSol* facility currently under construction. The expected properties of *TriSol*, and its application to reaction studies of interest for nuclear astrophysics, will also be discussed.

Advancing Research in Texas through Experiments in Medical Isotope Science

Sherry J. Yennello[1,2], Jonathan D. Burns[2], Lauren A. McIntosh[1], Gabriel C. Tabacaru[1], Evgeny E. Tereshatov[1], Laura A. McCann[1,2], Steven J. Schultz[1,2], Amy VonderHaar and Kylie N. Lofton[1,2]

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Alpha emitting radionuclides with medically relevant half-lives are interesting for treatment of tumors and other diseases because they deposit large amounts of energy close to the location of the radioisotope. A program is being developed to explore production of alpha emitters with medically relevant half-lives. The properties of astatine-211 make it a great candidate for targeted alpha therapy for cancer due to its short half-life (7.2 h). Astatine-211 has now been produced multiple times, reliability of this process is being improved. Future directions for isotope production at Texas A&M will be discussed.

Neutrino physics and dark matter at IEAP CTU Prague

Ivan Stekl (IEAP CTU Prague)

Talk is focused on selected issues concerning of neutrino physics, detection of dark matter (DM) and selected technologies of background suppression.

Various experiments with solar, atmospheric, reactor and accelerator neutrinos have provided convincing evidences of oscillations of three active neutrinos caused by their nonzero masses and mixing. Among the most fundamental open question in the theory of neutrinos is that of their nature: are the massive neutrinos Dirac or Majorana particles? Unfortunately, the absolute neutrino mass scale and the nature of neutrinos are inaccessible for oscillation experiments. The latter case would allow for 0νββ decay, arguably the most promising candidate process to address this question. The stronger cousin of the 0νββ decay - the 2νββ decay - provides strong background making the search for 0νββ decay extremely difficult. It is therefore essential to understand them both in a great detail. The 2νββ decay has already been observed in agreement with Standard Model and lepton number conservation for several isotopes, with half-lives $T_{1/2}$ typically ranging from 10^{19} y to 10^{24} y. From precise measurements of the half-lives and detailed calculations of phase-space factors various approaches to the highly non-trivial calculation of the nuclear matrix elements (NMEs) can be tested. Two experimental efforts in double beta decay will be mentioned, LEGEND (0νββ of ^{76}Ge) and SuperNEMO (7 kg of ^{82}Se, with a sensitivity to a half-life of 6.5 x 10^{24} years).

Identifying the particle nature of the cosmological dark matter is also a central challenge in modern physics. Experiments attempting to directly detect weakly interacting massive particles (WIMPs) in the laboratory must be sensitive to the very small recoil energies (1–100 keV) that WIMPs would deposit through elastic scattering on detector target nuclei of comparable mass. The coupling between WIMPs and standard model particles is typically characterized in terms of spin-independent (SI) and spin-dependent (SD) cross sections. As the underlying mechanism for this interaction is unknown, a thorough WIMP-search program must probe both SI and SD couplings. The superheated liquid detector technology (60 l C3F8 bubble chamber installed in SNOLAB) used by the PICO Collaboration affords excellent intrinsic rejection of electron recoils from gamma and beta particles.

Detection of neutrinos or candidates for DM is extremely rare process (e.g. the neutrinos do not experience any other than the weak interactions). Excellent background controls are required to both operate such a detector and establish confidence that all detector backgrounds are well understood. To mitigate large rates from cosmic-induced backgrounds, these detectors are operated deep underground. Remaining sources of background, including neutrons and alpha particles, come from natural radioactivity. There are different ways how to suppress all types of radioactivity (selection of material using ultra-low background HPGe spectrometry, removing radon by anti-radon facility under 10 mBq/m^3 or construction of detectors in clean room, ISO5, with a radon-free environment). Examples of such techniques will be also presented.

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Upgrade of the MAGNEX spectrometer toward the high-intensity phase of NUMEN

Manuela Cavallaro[1] on behalf of the NUMEN collaboration

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The presentation aims at describing an updated overview of the Research & Development activities related with the NUMEN project at INFN – LNS (Catania, Italy). NUMEN proposes an innovative technique to access the nuclear matrix elements entering the expression of the lifetime of the double beta decay by cross section measurements of heavy-ion induced Double Charge Exchange (DCE) reactions. The main experimental tools for this project are the K800 Superconducting Cyclotron and MAGNEX large acceptance magnetic spectrometer. First experimental results have given an encouraging indication on the capability of the proposed technique to access relevant quantitative information. However, the tiny values of the measured cross sections and the resolution requirements demand beam intensities much larger than those manageable with the present facility. The physics case of NUMEN has given the scientific motivation for an upgrade of the cyclotron accelerator and of the MAGNEX spectrometer to work with high intensity heavy-ion beams (up to 10^{13} pps at the target). The on-going upgrade of the INFN-LNS facilities in this perspective will be discussed at the Workshop.

Current scientific efforts at the Nuclear Science Laboratory

Patrick O'Malley for the Nuclear Science Laboratory

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For more than 80 years there has been an active research program in low energy nuclear physics at the University of Notre Dame Nuclear Science Laboratory (NSL). The NSL has the capacity to produce both stable and unstable beams at low and high intensities to accommodate its broad science program. The basic science research includes, but is not limited to subjects such as low energy nuclear astrophysics, nuclear structure, and fundamental symmetries . In addition there is a growing effort in applied physics studies like proton induced x-ray emission and atomic mass spectroscopy. This talk aims to give an overview of the current scientific studies underway at the NSL, as well as discuss the future prospects for the facility.

Heavy-ion induced quasi-elastic reactions in view of the NUMEN project

F. Cappuzzello[1,2] for the NUMEN collaboration

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In order to get quantitative information on neutrino absolute mass scale from the possible measurement of the 0νββ decay half-lives, the knowledge of the Nuclear Matrix Elements (NME) involved in such transitions is mandatory. Recently the use of heavy-ion induced double charge exchange (DCE) reactions as tools towards the determination of information on the NME has been proposed in Italy [1] and Japan [2]. The basic point is that there are a number of similarities between the two processes, mainly that the initial and final state wave functions are the same and the transition operators are similar, including in both cases a superposition of Fermi, Gamow-Teller and rank-two tensor components [3].

The NUMEN project at INFN-LNS laboratory in Italy proposes to explore the whole network of nuclear reactions connecting the initial and final nuclear states of the ββ-decay. This includes DCE, Single Charge Exchange (SCE), multinucleon transfer reactions, elastic and inelastic scattering, with the purpose to fully characterize the properties of the nuclear wave functions entering in the 0νββ decay NMEs.

Experimental campaigns have been performed at INFN-LNS in order to explore medium-heavy ion induced reactions on target of interest for 0νββ decay. These studies are complemented by a strong activity on the theoretical side, especially tailored to give a detailed description of the challenging DCE reaction mechanisms [4].

An overview of recent activity performed in Catania in this field will be presented at the Conference.

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Study of the one-proton transfer reaction in the $^{18}O+^{48}Ti$ collision at 275 MeV

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The $^{18}O+^{48}Ti$ reaction was studied at the energy of 275 MeV for the first time under the NUMEN [1] and NURE [2] experimental campaigns with aim of investigating the complete net of reaction channels potentially involved in the $^{48}Ti\rightarrow^{48}Ca$ double charge exchange (DCE) transition. Such a DCE transition is of interest because of its relevance to the extraction of $^{48}Ca\rightarrow^{48}Ti$ double beta decay nuclear matrix element (NME). The experiment was visualized at the MAGNEX facility of INFN-LNS in Catania. Angular distribution measurements for the reaction ejectiles were performed by using the MAGNEX large acceptance spectrometer [3]. The present contribution will be focused on the analysis of the one-proton transfer channel. The angular distribution data were analyzed within the Distorted-Wave Born Approximation framework, while the coupling influence of inelastic scattering to the transfer cross-sections was investigated adopting the Coupled-Channels Born Approximation formalism. In the present analysis, the double-folding São Paulo potential was employed for the description of the initial and final state interactions. The spectroscopic amplitudes for the projectile and target overlaps were derived from shell-model calculations using the p-sd-mod and sdpf-mu effective interactions, respectively. The theoretical angular distributions cross-sections were compared to the experimental data and were found to be in excellent agreement suggesting the validity of the adopted Optical Potential and confirming the shell-model description of the involved nuclei.

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Low energy reactions of halo nuclei

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Halo nuclei are extreme nuclear states consisting of one or more weakly-bound valence nucleons spatially decoupled from a tightly bound core [1]. The reduced binding favours barrier tunnelling and extended density distribution, the so called "nuclear halo. Some examples of neutron haloes are ^{6}He, ^{11}Li, ^{11}Be or ^{15}C [2]. For proton rich systems the Coulomb repulsion prevents halo formation and only the cases of ^{8}B and ^{17}Ne have been confirmed [3–5]. In this talk experimental results on low energy reactions with halo nuclei will be reviewed. The weakly bound nature of the halo dominates the reaction probability, but the specific reaction mechanisms depend on the halo, core and target structure [6]. Despite of the inherent complexity of the reaction process, simple two-body cluster models and direct reaction theories can be used to extract useful information of the structure of the halo nucleus and its dynamics [7-9].

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Reaction dynamics of exotic and stable weakly-bound nuclei using a four-body continuum-discretized coupled-channels formalism

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The continuum-discretized coupled-channels (CDCC) method was extended to four-body systems [1-5] in order to study reactions induced by the two-neutron halo Borromean nuclei ^{6}He(^{4}He+n+n) and ^{11}Li(^{9}Li+n+n). Two different approaches were used to build the states of the three-body projectile: Pseudo-State (PS) methods [1,2,6,7] and the binning procedure [3].

Later, the four-body CDCC formalism was applied to reactions induced by the stable Borromean nucleus ^{9}Be(alpha+alpha+n) [6,8,9,10]. This nucleus, although stable, has a small binding energy of 1.5736 MeV below the alpha+alpha+n threshold. The results show that continuum couplings are important in describing the elastic cross section, especially at low energies and on heavy targets. The agreement with the available experimental data supports the reliability of the method in describing reactions induced by three-body projectiles which include more than one charged particle.

Most recently, we have studied the reaction induced by the Brunnian nucleus ^{10}C on ^{208}Pb [11]. The nucleus ^{10}C (alpha+alpha+p+p) is a four-body system in which no binary system is bound. It is stable but has only a couple of states below the alpha+alpha+p+p threshold, with binding energies of 3.82 MeV and 0.47 MeV. We have adopted for ^{10}C a three-body model (^{8}Be+p+p) assuming ^{8}Be is in its ground state, a very narrow resonance only 92 keV over the alpha-alpha threshold. The results show, in this case, that the coupling to the continuum does not have a crucial effect on the elastic scattering.

A comparison between methods to build the projectile states will be shown. The reaction dynamics, as the binding energy of the projectile increases, will be discussed.

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Linking structure and dynamics with two-neutron halos

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Recent advances in RIB physics have triggered the exploration of the exotic properties and decay modes of light nuclear systems at the limit of stability and beyond the driplines [1]. Of particular interest is the case of two-neutron halo nuclei, such as ^{6}He, ^{11}Li or ^{14}Be. These are Borromean systems, or three-body nuclei with no bound binary subsystems. While the correlations between the valence neutrons are known to play a fundamental role in shaping the properties of two-neutron halo nuclei [2], it is well known that a proper understanding of their structure requires also solid constraints on the unbound subsystems ^{5}He, ^{10}Li or ^{13}Be [3]. Here, the delicate interplay between pairing and tensor correlations [4], as well as the effect of Pauli blocking and the possible coupling to the core collective excitations [5], may be of crucial relevance to understand exotic phenomena such as parity inversion or shell gap quenching.

Recently, the properties of two-neutron halo nuclei and their binary core+n subsystems have been studied in intermediate-energy (p,pn) reactions in inverse kinematics [3]. A theoretical description of these processes, using structure overlaps within a full three-body model and the Transfer to the Continuum (TC) formalism [6], will be presented. The method will be applied to the ^{11}Li(p,pn)^{10}Li [6] and ^{14}Be(p,pn)^{13}Be [7] reactions to compute relative-energy spectra and momentum distributions, showing a good agreement with the available experimental data. The computed structure overlaps will also be used to describe the neutron-neutron correlations in momentum space [2,8], confirming that the mixing between different-parity states in the binary subsystems is key in developing dineutron correlations in two-neutron halo nuclei, and also in overall agreement with the most recent data [9,10].

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Searching for “treasures” at deep sub-barrier energies: The ^{8}Be and ^{7}Be case

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According to our phenomenologica[1] predictions, reported for the first time in Ref. [1], strong direct channels appear at sub-barrier energies. These for heavy targets become dominant even at deep sub-barrier energies where the ratio of direct to total saturates to one. Into this concept, we will review in this workshop our recent breakup results of ^{8}Be+^{208}Pb at 30MeV corresponding to 58% of the Coulomb barrier, reported in Ref. [2]. Further on, we will present new experimental results for ^{7}Be+^{208}Pb $^{(4}$He and ^{3}He production) at 22.4 MeV corresponding to 54% of the Coulomb barrier.

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Study of $^4He(^4He,^4He)^4He^*$ inelastic scattering at the MAGNEX facility

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A recent ab-initio calculation of the monopole transition form factor of ^4He [1] pointed to a strong dependence on the different realistic potentials used. The inconsistencies met between the recent ab-initio form factor calculation and the existing data from $^4He(e,e')^4He^*$ call for further investigation [1]. In order to shed some light on this challenging subject, the (^4He,^4He) reaction was invoked and the advantages of using this probe compared to the (e,e') one will be presented. An exclusive measurement of the $^4He + ^4He \rightarrow ^4He + ^4He^* \rightarrow ^4He + ^3H + ^1H$ reaction in the region of the first 0^+ excited state of ^4He was performed at the MAGNEX facility [2] of INFN – Laboratori Nazionali del Sud (Italy). The ^4He ions were momentum analyzed at the MAGNEX spectrometer [2-4], while the ^3H ions were detected by the OSCAR telescope [5]. The $^4He + ^4He \rightarrow ^4He + ^4He^* \rightarrow ^4He + ^3He + n$ reaction was also measured simultaneously thanks to the large momentum acceptance of the MAGNEX spectrometer [2]. The reduction of the data, including the relevant Monte Carlo simulations [6], will be presented and discussed.

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Chasing the X17 Boson – Theory and Experiments

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Abstract

Theoretical prediction for the distribution of the angle between electrons and positrons originating in internal pair creations is a monotonic featureless decrease with the opening angle. Recent studies on excited states of ^{8}Be and ^{4}He nuclei, made in ATOMKI, Hungary, however, revealed deviations from this expectation. If true, such a result may have a fundamental impact. The anomaly can be explained by introducing a new short-lived neutral boson - called X17 - that can still fit into known experimental and theoretical constraints. Although serious work has been done on the theoretical side, an independent laboratory has not yet verified these results yet, although related experiments are being prepared worldwide. In this talk, we will present the current theoretical interpretations together with our theoretical model (VPL model) [1,2] and also some implication of it to the neutron stars structure. In addition, we will present the experimental effort which operates at the Institute of Experimental and Applied Physics (IEAP) Van-de-Graaff accelerator facility, in order to confirm or refute the above-mentioned anomaly.

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Precise branching ratio measurement for the superallowed β^+ decay of ^{34}Ar

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Superallowed $0^+ \rightarrow 0^+$ nuclear β decays provide the most precise value for V_{ud}, the up-down quark mixing element in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, a pillar of the standard model. This allows for the most demanding test of the unitarity of the CKM matrix. Precise *ft* values gain more weight if they are able to disentangle between models used to calculate the isospin symmetry correction. In this context, pairs of mirror superallowed transitions allow for a very sensitive test of the isospin-symmetry-breaking correction [1]. The reported branching ratio for the superallowed β^+ decay of ^{34}Ar [2] completes the $T_Z = -1$ part of the mirror pair: $34Ar \rightarrow 34Cl$ and $34Cl \rightarrow 34S$. The talk will focus on the experimental challenges required to obtain in the case of the $T_Z = -1$ parent ^{34}Ar an *ft*-value accurate to better than 0.1%

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"Employing ternary fission as a probe of low density nuclear matter"

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Yields of equatorially emitted light isotopes, observed in ternary fission in the reaction ^{241}Pu (n_{th}, f) have been employed to determine chemical reaction quotients for cluster formation in low-temperature and low-density nuclear matter. The degree of equilibration and the role of medium modifications have been probed using two different techniques. In the first, the experimentally derived reaction quotients have been compared to theoretical equilibrium constants calculated using a relativistic mean-field model that employs a universal medium modification correction for the attractive σ meson coupling. and taking contributions of excited states into account. In the second, the non-equilibrium statistical operator method was employed to construct a generalized Gibbs distribution and determine yields taking excited states and continuum correlations into account, in accordance with the virial expansion of the equation of state. The results of these comparisons indicate that near equilibrium is achieved for the lighter ternary fission isotopes. For the heavier isotopes experimental reaction quotients are well below calculated equilibrium constants. This is attributed to a dynamical limitation reflecting insufficient time for full equilibrium to develop.

Calculation of the $^{12}C+^{12}C$ sub-barrier fusion cross section in an imaginary time-dependent mean field theory

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ABSTRACT

The $^{12}C+^{12}C$ sub-barrier fusion cross section is calculated within the framework of a Time Dependent Hartree-Fock (TDHF) based classical model using the Feynman Path Integral Method. The modified astrophysical S-factor is compared to direct and indirect experimental results. A good agreement with the direct data is found. In the lower energy region, where recent analyses of experimental data obtained with the Trojan Horse Method (THM) lead to contrasting results, the model predicts a non resonant S* factor half way between those results. Low energy resonances revealed in the THM data are added to the calculation and the relative reaction rate in the Gamow region is calculated. In particular including 0^+ resonances result in some agreement to the THM data. The role of different resonances is discussed in detail and their influence on the reaction rate at temperatures relevant to stellar evolution is investigated.*

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From Nuclear Astrophysics to Fundamental Nuclear Physics: challenging experimental approaches at n_TOF (CERN)

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The n_TOF installation at CERN [1] is one of the leading neutron facilities worldwide undergoing now a major update of the neutron spallation source. The update will provide higher *n*-flux in the experimental areas and the combined possibility to perform neutron cross section measurements at very high neutron flux (NEAR-Station). The renewed capabilities of the facility must be supported by smart and non-conventional experimental approaches. In this framework two examples will be reported. The first one concerns the measurement of a key reaction channel involved in Primordial Nucleosynthesis: the $^{7}Be(n,a)$, by using a radioactive ^{7}Be target [2]. The second one provides a state-of-the-art scenario for the *n-n* scattering length measurement. This will be performed by neutron-deuteron (*nd*) breakup measurement. In this case, the envisaged experimental setup will provide a complete three-body kinematic reconstruction [3]. By these important physics cases we are crossing the technological frontiers for charged particle and neutron detection.

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Experimental constraints on reaction rates relevant to the radiogenic heating of planets

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The quantity of radioactive isotopes in a planet's mantle and the evolution of its heating due to the isotopes' radioactive decay determines the capability of that planet to develop geological features associated with a habitable environment such as surface crust and plate tectonics. One of the major isotopes responsible for the radiogenic heating of our planet and Earth-like exoplanets is 40K. Predicting the amount of 40K enrichment in the solar system of a given exoplanet is key for a reliable calculation of the planet's heating evolution. From a nucleosynthesis point of view, the uncertainty in the abundance of 40K is associated with the reactions that create and destroy 40K in stellar nucleosynthesis processes and the corresponding reaction rates. Our research aims to experimentally constrain the two reaction rates responsible for the destruction of ^{40}K in stars, namely the ^{40}K(n,p) and ^{40}K(n,a). The objective of the research was to deduce both reaction rates through the ^{40}Ar(p,n)^{40}K and ^{37}Cl(a,n)^{40}K reaction cross-section measurements at the Edwards accelerator of Ohio university. The measurements were performed using the swinger facility of Ohio University, the LENDA neutron detector and a setup of two $LaBr_3$ detectors to obtain angular distributions of neutrons and gamma rays. In my talk, I will present details of the measurements so far and will discuss published and preliminary results from our experimental campaign.

Spectroscopy of key nuclei in astrophysics by beta-delayed proton emission

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Thermonuclear reaction rates are basic inputs in the nuclear reaction networks presently used for modeling the explosive nucleosynthesis that occurs in the late stages in the life of the stars. Whether the nucleosynthesis is thought to proceed via one path or another depends upon the stellar scenario (temperature, density, proton-rich or neutron-rich environment, etc) and subsequently the type of reactions ((p,gamma), (n,gamma), etc). As a general statement, it is extremely difficult (if not technically impossible) to perform a direct measurement of the corresponding cross section for a given thermonuclear reaction in the available laboratories worldwide. It is in this context where indirect methods reveals its potentialities, specially when the reaction rate is dominated by a narrow isolated resonance. Beta-delayed proton emission is a powerful technique which allows for the experimental investigation of (p,gamma) reactions involving low and medium mass proton-rich radioactive nuclei, where such resonances are likely to occur.

The fate of a star of initial mass bigger than 8 Solar masses is to end its life starting by a mechanism so-called "core collapse supernova" (CCSN) explosion in a time lapse of the order of seconds [1]. Nucleosynthesis of ^{44}Ti in CCSN and its subsequent decay chain makes of this nucleus a good tracer for Gamma Astronomy as it serves to detect supernovae events [2]. But the importance of ^{44}Ti spans as the comparison between the observation of its yield in CCSN and CCSN computational models gives severe constrains to the later [3].

Nucleosynthesis of ^{44}Ti occurring in CCSN explosions is thought to be quite sensitive to the ^{45}V(p,gamma)^{46}Cr reaction [4]. This reaction has not been experimentally studied so far due to the radioactive nuclei taking part on it. In this talk we present preliminary results on the spectroscopy of ^{46}Cr around the proton emission threshold seeking for resonant contributions to the ^{45}V(p,gamma)^{46}Cr reaction. It will be shown the analysis made so far of data taken in a experiment performed in the LISE fragment separator at GANIL (Caen, France) [5]. The beta decay of the progenitor ^{46}Mn and excited states of his daughter nucleus ^{46}Cr were studied after selecting ^{46}Mn among other species in the cocktail beam delivered by LISE.

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The AMS technique as an important tool for the measurement of astrophysical cross sections.

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Accelerator Mass Spectrometry is a technique commonly used to approach low concentrations of certain long half-life radioisotopes. The most important contribution of the technique is the accurate measure of organic sample ages, by separating masses 12,13 and 14 in the case of carbon allocated in such a samples. However, the reach of AMS could cover many other scientific scopes, due to it can give us a precise measure of a very small concentration of a radioisotope. On this direction, AMS can be used to approach reactions of interest for astrophysics, if we spot an specific radioisotope which concentration can be measure with AMS. Starting with this, we have selected specific reactions involving ^{14}C, ^{10}Be and ^{26}Al, produced with low neutrons at a reactor and positive ions at an accelerator. All of this reactions are important in astrophysics processes, and most of their cross sections are not well experimentally defined. The main idea is to produce a particular reaction and later to measure the radioisotopic concentration using AMS. In this study our first results for ^{14}C and ^{10}B nuclei produced with neutrons, and the preliminary results for ^{26}Al nuclei produced with deuterium are shown.

Thermal properties of hot and dense matter: Influence of rapid rotation on protoneutron stars, hot neutron stars, and neutron star merger remnants

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The knowledge of the equation of state is a key ingredient for many dynamical phenomena that depend sensitively on the hot and dense nuclear matter, such as the formation of protoneutron stars and hot neutron stars. In order to accurately describe them, we construct equations of state at finite temperature and entropy per baryon for matter with varying proton fractions. This procedure is based on the momentum dependent interaction model and state-of-the-art microscopic data. In addition, we investigate the role of thermal and rotation effects on microscopic and macroscopic properties of neutron stars, including the mass and radius, the frequency, the kerr parameter, the central baryon density, etc. The latter is also connected to the hot and rapidly rotating remnant after neutron star merger. The interplay between these quantities and data from late observations of neutron stars, both isolated and in matter of merging, could provide useful insight and robust constraints on the equation of state of nuclear matter.

Constraints on the speed of sound of dense nuclear matter through the tidal deformability of neutron stars

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One of the greatest interest and open problems in nuclear physics is the upper limit of sound speed in dense nuclear matter. Neutron stars, both in isolated and binary system cases, constitute a very promising natural laboratory for studying this kind of problem. This present work is based on one of our recent study, regarding the speed of sound and possible constraints that we can obtain from neutron stars [1]. To be more specific, in the core of our study lies the examination of the speed of sound through the measured tidal deformability of a binary neutron star system (during the inspiral phase). The relation between the maximum neutron star mass scenario and the possible upper bound on the speed of sound is investigated. The approach that we used follows the contradiction between the recent observations of binary neutron star systems, in which the effective tidal deformability favors softer equations of state, while the high measured masses of isolated neutron stars favor stiffer equations of state. In our approach, we parametrized the stiffness of the equation of state by using the speed of sound. Moreover, we used the two recent observations of binary neutron star mergers from LIGO/VIRGO, so that we can impose robust constraints on the speed of sound. Furthermore, we postulate the kind of future measurements that could be helpful by imposing more stringent constraints on the equation of state.

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Momentum dependent mean-fields of hyperons & antihyperons

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The in-medium properties of hyperons and antihyperons are studied with the Non-Linear Derivative (NLD) model and focus is made on the momentum dependence of strangeness optical potentials. The NLD model is based on the Relativistic Mean Field (RMF) approximation to Relativistic Hadrodynamics (RHD) approach of nuclear systems, but it incorporates an explicit momentum dependence of mean-fields. The extension of the NLD model to the baryon and antibaryon octet is based on SU(6) and G-parity arguments. It is demonstrated that with a proper choice of momentum cut-offs, the Λ and Σ optical potentials are consistent with recent studies of the chiral effective field theory and Ξ optical potentials are consistent with Lattice-QCD calculations, over a wide momentum region. We also present NLD predictions for the in-medium momentum dependence of $\acute{\Lambda}$ -, $\acute{\Sigma}$ - and $\acute{\Xi}$ - hyperons. This work is important for future experimental studies, like CBM, PANDA at FAIR and is relevant to nuclear astrophysics as well.

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Constraining the neutron star equation of state via gamma ray burst remnants and gravitational wave radiation

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The focus of this project is constraining the Equation of State (EoS) of neutron stars, via Gamma Ray Burst (GRB) light curves and Gravitational Wave Radiation. We assume a favored progenitor model for short duration GRBs, being the coalescence of two neutron stars. A possible outcome of their merger is a highly magnetized rotating neutron star, called magnetar. This newly born magnetar, loses its rotational energy via magnetic dipole radiation and gravitational waves in the form: of mass quadrupole deformation (ellipticity with amplitude ε) and r-mode fluid oscillations (with amplitude a). The observed GRB light curves, carry an internal X-ray plateau, followed by a rapid decay. The form of the curve can be attributed to the magnetar, acting as an internal engine for the GRB, causing the plateau and later on collapsing into a black hole, due to loss of energy, forming the rapid decay phase. This collapse time depends on the initial period of the magnetar, its magnetic field, the mass of the protomagnetar and also the parameters of the neutron star EoS. We use observational data from two GRBs, GRB 101219A and GRB 160821B, to pin down the initial period, magnetic field and collapse time. By calculating the collapse time for several EoSs, we compare our findings with the observations and therefore constrain the possible EoS scenarios.

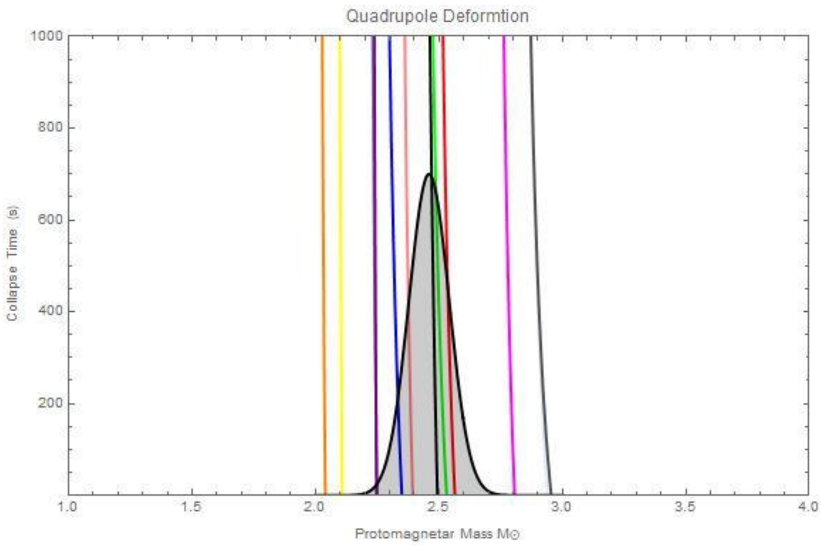

Figure 1: Collapse time as a function of the protomagnetar mass. The data is taken from the GRB 160821, for an r-mode amplitude of α=0.1.

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Twin neutron stars: probe of phase transition from hadronic to quark matter

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In agreement with the gravitational-wave events which are constantly increasing, new aspects of the internal structure of compact stars have come to light. A scenario in which a first order transition takes place inside these stars is of particular interest as it can lead, under conditions, to a third gravitationally stable branch (besides white dwarfs and neutron stars). This is known as the twin star scenario. The new branch yields stars with the same mass as normal compact stars but quite different radii. In my presentation, I will focus on hybrid stars undergone a hadron to quark phase transition near their core and how this new stable configuration arises. Emphasis is to be given especially in the aspects of the phase transition and its parameterization in two different ways, namely Maxwell Construction and Gibbs Construction. Qualitative findings of mass-radius relations of the team I am a member of considering these stars will also be presented.

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Low energy proton induced reactions for application purposes

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Proton induced charge exchange reactions have been suggested as the tool for producing neutron beams for low energy Compact Accelerator – driven Neutron Sources (CANS). In view of our recent measurements on proton induced reactions at low energies [1-4], and a re-new interest for building CANS [5-6], we reviewed critically cross sections of all reaction products in p+^{7}Li and p+^{9}Be systems at 3 and 5 MeV. The present analysis suggested the breakup mechanism on a ^{9}Be target as a substantial source of neutron production and the breakup of ^{7}Li as a substantial source of triton production, the last to be considered for radioprotection purposes. These results highlight the societal impact of Nuclear Physics [7,8].

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Study of the neutron induced radiation background at the MAGNEX facility via FLUKA simulations

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The upgrade of the K800 Superconducting Cyclotron at the Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud (INFN-LNS) is in progress. This requirement was driven by the NUMEN (Nuclear Matrix Elements for Neutrinoless double beta decay) project [1] which aims to study Double Charge Exchange (DCE) reactions, characterized by low cross-sections, as a mean to obtain information about the Nuclear Matrix Elements (NMEs) of the $0\nu\beta\beta$ decay. Once the Cyclotron upgrade is completed, in the case of NUMEN experiments, the usage of ^{18}O and ^{20}Ne ion beams with an intensity of (1-10) kW is foreseen. The interaction of such high intensity beams with the target materials may lead to a substantial increase in the radiation level inside the MAGNEX experimental hall. This is an important aspect to take into consideration during the R&D of the electronic devices as well as of the detectors in the new Focal Plane Detector (FPD) of the MAGNEX spectrometer [2,3]. To this extend, Monte Carlo simulations for the neutron-induced radiation background at the MAGNEX facility were performed using the FLUKA code [4-6]. The results of the simulations will be presented and discussed.

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Connecting the NEoS to the interplay between fusion and quasi-fission processes in low-energy nuclear reactions

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Within the time-dependent Hartree-Fock (TDHF) approach, we investigate the impact of several ingredients of the nuclear effective interaction, such as incompressibility, symmetry energy, effective mass, derivative of the Lane potential, and surface terms on the exit channel (fusion vs quasifission) observed in the reaction $^{238}U + ^{40}Ca$, close to the Coulomb barrier. Our results show that all the ingredients listed above contribute to the competition between fusion and quasifission processes; however, the leading role in determining the outcome of the reaction is played by incompressibility, symmetry energy, and the isoscalar coefficient of the surface term. This study unravels the complexity of the fusion and quasifission reaction dynamics and helps us to understand the microscopic processes responsible for the final outcome of low-energy heavy-ion collisions in terms of relevant features of the nuclear effective interaction and associated equation of state (EOS).

Two-stage description of ^{56}Fe+p spallation reactions at 0.3-1.5 GeV/A

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Abstract

Spallation reactions of $^{56}Fe + p$ at 0.3-1.5GeV/A are studied in the framework of the two-stage hypothesis [1]. The intra-nuclear cascade (INC) stage of the reaction is simulated with the code ISABEL [2,3] and a Constrained Molecular Dynamics code (CoMD) [4]. The de-excitation of the highly excited pre-fragments is followed with the multi-sequential binary decay code MECO [5], based on a generalized Weisskopf-Ewing formalism. Emission of nucleons, gamma rays and IMFs in their ground, excited bound and unbound states is taken into account. Calculated cross sections are compared with experimental mass, charge and isotopic distributions of $^{56}Fe + p$ spallation reaction products studied at GSI with the fragment separator FRS in the energy-range 0.3-1.5GeV/A [6,7]. A good description of the experimental data is obtained with ISABEL-MECO calculations at all bombarding energies with a global set of parameters. The results of this calculation at 1GeV/A are compared with the ones of CoMD-MECO and discussed. Further comparisons are made with the ISABEL code coupled with the sequential binary decay code GEMINI [8] and the statistical multi-fragmentation code SMM [9,10].

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Recent developments in the study of peripheral collisions below the Fermi energy

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In this talk, we give an overview of our recent experimental and theoretical work on the study of peripheral heavy-ion collisions in the energy range 15-25 MeV/nucleon. The experimental work concerns mass spectrometric measurements of projectile fragments from a) ^{40}Ar and ^{86}Kr projectiles analyzed with the MARS spectrometer at the Cyclotron Institute of Texas A&M University, and b) ^{70}Zn (15 MeV/nucleon) projectiles recently obtained with the MAGNEX spectrometer at LNS Catania, and currently under analysis.

The focus of the work is the production of neutron rich isotopes in multinucleon transfer processes. Special effort is now been devoted in the study of the momentum distributions of the projectile fragments. These distributions are primarily characterized by of two peaks: a narrow quasi-elastic peak and a broader deep-inelastic peak. The experimental data are compared with model calculations based on the phenomenological Deep-Inelastic Transfer Model (DIT) [2], and the microscopic Constrained Molecular Dynamics model (CoMD) [3]. The de-excitation of the hot projectile-like fragments is performed with the Gemini model [4]. The capabilities of the DIT model have been examined, offering a fair overall description of these reactions [5,6]. Presently, we are systematically exploring the parameters of the effective interaction in the CoMD model with the goal of reaching a satisfactory microscopic description of the channels leading to exotic neutron-rich isotopes.

The CoMD work on these reactions goes in parallel with efforts of exploring the properties of nuclear ground states (binding energies, radii, neutron skins) and the dynamics of the GDR (Giant Dipole Resonance) as given by the CoMD. We expect that CoMD may provide a unified description of the low energy nuclear dynamics and offer a reliable framework for further exploration of the production and the dynamics of neutron-rich exotic nuclei.

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Studies of multinucleon transfer in peripheral collisions of ^{86}Kr with ^{124} Sn, ^{112}Sn at 15 MeV/nucleon

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In this talk, after an overview of production methods of neutron rich nuclei, we present our recent efforts to study the mechanism of multinucleon transfer in peripheral collisions of a ^{86}Kr beam (15 MeV/nucleon) with targets of ^{124}Sn and ^{112}Sn. Experimental data on cross sections at two angles (4 and 7 degrees) were employed from the previous work [1] of our group with the MARS spectrometer at the Cyclotron Institute of Texas A&M University.

Special attention is paid to the momentum distributions of the projectile fragments that have recently been extracted from the original experimental data [1]. The momentum distributions are primarily characterized by of two peaks: a narrow quasi-elastic peak and a broader deep inelastic peak (corresponding to large TKEL - total kinetic energy loss). We have employed two-body kinematics to characterize the excitation energies of these regions.

Furthermore, the data are compared with model calculations based on a two-step approach in which the dynamical stage is described with either the phenomenological Deep-Inelastic Transfer Model (DIT) [2], or with the microscopic Constrained Molecular Dynamics model (CoMD) [3]. The de-excitation of the hot projectile-like fragments is performed with the Gemini model [4,5]. While we have exhausted the capabilities of the DIT model in describing the experimental data, we are carefully exploring the parameters of the effective interaction in CoMD, expecting to obtain a satisfactory microscopic description of the channels leading to neutron-rich isotopes.

In conjunction with recent work [6,7], our continued efforts in the study of peripheral reactions in the Fermi energy regime using, combined with the possibilities offered by current low-energy heavy-ion accelerator facilities worldwide, delineate new opportunities to shed light to the reaction mechanism(s) of rare isotope production, and may effectively contribute to the study of unexplored regions of the nuclear chart toward the r-process and the neutron drip line.

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Studies of peripheral heavy-ion reactions with the MAGNEX spectrometer for the production of neutron-rich isotopes

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The present project is focused on our research group's recent efforts to study the production of neutron-rich rare isotopes from peripheral reactions with the MAGNEX spectrometer at beam energies from the Coulomb barrier to the Fermi energy (~20-40 MeV/nucleon) [1,2]. High quality experimental data were obtained from a recent experiment of our group with the MAGNEX mass spectrometer at the INFN-LNS in Catania, Italy. The main goal of this presentation is to describe the adopted identification techniques used to analyze the data from the reaction ^{70}Zn (15 MeV/nucleon) + ^{64}Ni. The particle identification method is based on the approach presented in [3]. This approach is based mainly on the correlation of the position at the focal plane X_{foc} versus residual energy, that results in a separation of particles according to their $\sqrt{m/q}$. This work is of great importance, as it leads to the extraction of important physical observables, such as the mass number, atomic number and velocity of the produced projectile fragments. However, due to the presence of heavy ejectiles, a special effort is devoted to the reconstruction of the atomic number of these heavy ions based on their TOF and velocity. In parallel, the high-resolution energy and angle reconstruction possibility offered by the MAGNEX spectrometer allows a thorough investigation of various multinucleon transfer channels. We expect that the analysis of the data will play a key role in better understanding the complex reaction mechanisms that dominate this energy regime.

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Microscopic dynamics description of multinucleon transfer in peripheral collisions of ^{40}Ar with ^{64}Ni,^{58}Ni at 15 MeV/nucleon

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In this talk, we present a detailed study of projectile fragments from the peripheral reaction of ^{40}Ar + ^{64}Ni and ^{58}Ni at 15 MeV/nucleon [1]. The experimental data presented here were obtained with the MARS spectrometer at the Cyclotron Institute of Texas A&M University [2]. Along with the experimental data, we present detailed calculations with the Deep Inelastic Transfer model (DIT) [3] and the microscopic Constrained Molecular Dynamics model (CoMD) [4]. The de-excitation of the projectile-like fragments is performed by the GEMINI code [5].

Our efforts focus on the description of the experimental yield and momentum distributions. We tried to optimize the parametrization of the effective interaction in the CoMD model in order to achieve a satisfactory description of the experimental data. We examined the effect of the configurations of the projectile and target used in the CoMD calculations. Furthermore, we studied the effect of several key parameters (compressibility, effective mass, nucleon-nucleon scattering cross sections) with most notable the Pauli constraint. Finally, we examined the behaviour of the angular distributions of the elastic channel. From these efforts we expect to gain valuable insight into the multinucleon transfer mechanism that leads to the production of extremely neutron-rich nuclides towards the r-process path and the neutron drip line.

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Constrained Fermionic Dynamics of Nuclear Systems: Near Ground State Properties and the Isospin Symmetry

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The nuclear interaction is one of the most fascinating and complicated forces responsible for stuctures in nature, while its understanding is the key for a broad range of applications. The nuclear interaction manifests itself in the nuclear N-body problem. In the present work, we employed the CoMD (Constrained Molecular Dynamics) model that provides an approximate solution of this problem through the Time Dependent Variational Principle leading to Hamiltonian equations of motion [1]. The total nuclear wavefunction is taken as the product of one-body nucleonic wavefunctions, parametrised as Gaussian wavepackets. For the solution of the equations of motion, the initial configuration of nucleons is needed. This is obtained via a Simulated-Annealing algorithm. The characteristics of the configuration space depend strongly on the parameters of the effective interaction. We studied the effects of these parameters and developed a process for global optimisation of a configuration based upon its binding energy, rms radius, average density and average phase space occupation fraction.

In parallel, we studied the Giant Dipole Resonance (GDR) which is one of the most interesting phenomena of low energy nuclear dynamics. This resonance mode consists of an off-phase oscillation of neutrons against the protons. In our study, we developed a theoretical treatment of GDR based on the CoMD formalism. The effect of the parameters of the effective interaction to the GDR characteristics were studied. Finally, we calculated the GDR spectra for the optimised configurations of several nuclei. We plan to systematically study the characteristic energy and the width of the GDR peak across the nuclear chart with the goal of obtaining stringent constraints of the nuclear equation of state [2,3].

Finally we study the Isospin Symmetry Breaking (ISB) in the near ground state properties. The total nucleonic wavefunction is eigenfuction of the Isospin operators (square norm and third projection) and the corresponding eigenvalues characterise the type of the nucleon. A neutron has +1/2 third projection eigenvalue, while a proton has a -1/2. The strong nuclear force has an approximate isospin symmetry and shows a breaking of this symmetry when the electroweak force is accounted for. The mirror nuclear pairs are nuclei connected via the transformation N→Z and are central to the research of the ISB phenomenon [4]. In this work we also studied the approximate isospin symmetry and the corresponding breaking modes for various isobaric and isotopic chains of mirror nuclei. We have developed a theoretical treatment of ISB based on the CoMD formalism and we present computational results for the binding energies, neutron skins and GDR centroid energies and widths of the nuclei we studied.

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Total kinetic energy release in the fast neutron induced fission of actinide nuclei

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The total kinetic energy (TKE) release in the fast neutron-induced fission of various actinide nuclei was measured for neutron energies from En =2.6 –100 MeV at the Weapons Neutron Research facility of the Los Alamos National Laboratory. Analysis of the fragment mass distributions indicates that the decrease in TKE with increasing En is a consequence of the fading out of shell effects at high excitation energies (resulting in an increase of symmetric fission) and the decrease of the total kinetic energy associated with asymmetric fission with increasing En . The data are compared to various models of the fission process.

Texas A&M US Nuclear DATA Program

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Nuclear data evaluation is an independent century-long expert activity accompanying the development of the nuclear physics science. Its goal is to produce professional periodic surveys of the world literature in order to recommend and maintain the set of the best nuclear data parameters of common use in all basic and applied sciences. After WWII the effort extended and while it become more international it continued to be supported mainly by the US for the benefit of the whole world. The Evaluated Nuclear Structure Data File (ENSDF) is the most comprehensive nuclear structure database worldwide maintained by the United States National Nuclear Data Center at Brookhaven National Laboratory and echoed by the IAEA Vienna's Nuclear Data Services. Part of the US Nuclear DATA Program since 2005 the Cyclotron Institute is one of the important contributors to ENSDF. Since 2018 we became an international evaluation center working in a consortium of peers hosted traditionally by prestigious national institutes as well as universities. In this presentation the main stages of the evaluation work are presented in order to facilitate a basic understanding of the process as a guide for our potential users. Our goals are to maintain a good productivity vs. quality performance assuring the currency of the data and participating in the effort of modernizing the structure of ENSDF databases in order to make them compatible with the "data-centric" paradigms of the future.

A novel approach to medical radioisotope production using inverse kinematics

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A novel approach to produce medically important radionuclide using inverse kinematics has been developed at the Cyclotron Institute at Texas A&M University. The methodology consists in directing a heavy-ion beam of appropriate energy on a light gas target (e.g., H, d, He) and collecting the isotope of interest, typically focused along with the beam direction, on an appropriate foil catcher after the target. In addition, there are the possibilities to use the secondary emitted particles such as neutrons from the primary nuclear reaction to irradiate other targets for further radionuclide production. As the quantity of the material required to prepare heavy-ion beam is ~1,000 times less than that used in the standard solid target approach, material costs are expected to be considerably reduced through this methodology.

As a proof-of-principle study, the production of the theranostic radionuclide ^{67}Cu ($T_{1/2}$ = 62 h) through the reaction of a ^{70}Zn beam at 15 MeV/nucleon with a hydrogen gas target [1] were performed. The experimental set up for the irradiation is schematically represented in Figure 1. The ^{67}Cu radionuclide alongside other coproduced isotopes, was collected after the gas target on an aluminum catcher foil and their radioactivity was measured by off-line γ-ray analysis. After 36 h post irradiation, apart from the product of interest ^{67}Cu, the main radioimpurity coming from the ^{70}Zn + p reaction was ^{69m}Zn ($T_{1/2}$ = 13.8 h), which can be reduced by further radio-cooling. In addition, the forward-focused neutrons from the primary reaction were used to irradiated 20 blocks of ^{nat}Zn in order to produce more ^{67}Cu. The main requirement to obtain activities appropriate for preclinical studies is the development of high-intensity heavy-ion primary beams.

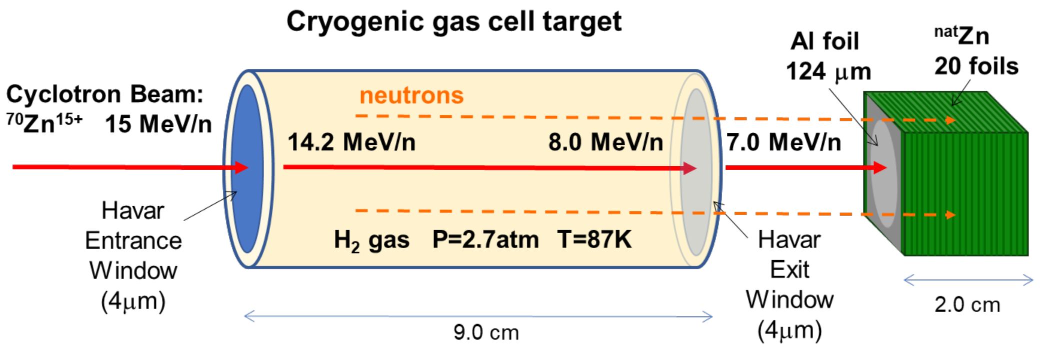

Figure 1: Schematic diagram of the irradiation set up.

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Enhanced production of ^{99}Mo in inverse kinematics heavy ion reactions

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Today, radioisotopes are commonly used in medicine, both in diagnosis and therapy. A novel method for the production of important medical radioisotopes has been developed at the Cyclotron Institute at Texas A&M University. After a successful test of the production of the theranostic radionuclide ^{67}Cu ($T_{1/2}$ = 62 h) through the reaction of a ^{70}Zn beam at 15 MeV/nucleon with a hydrogen gas target [1], the production routes were studied for the formation of medically interesting ^{99}Mo with the use of cyclotrons. The reaction of a ^{100}Mo beam at 12 MeV/nucleon impinging on a ^{4}He gas cell target was performed. The ^{99}Mo alongside other co-produced isotopes were collected after the gas target on an aluminum catcher foil and their respective radio-activities were measured by off-line γ-ray analysis. Results of Thick Target Yield, TTY(E), which is used to discuss the possibility of optimal large-scale production conditions of the produced radioisotopes, have been extracted.

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