Advances in the investigation of weak and strong interactions

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Book of Abstracts

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Low-energy kaon-nuclei interaction studies at the DAFNE collider: a strangeness Odyssey

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The low-energy QCD, the theory within the Standard Model describing the strong interaction, is still missing fundamental experimental results to achieve a breakthrough in its understanding. Among these, the low-energy kaon-nucleon/nuclei interaction studies are playing a key-role.
Combining the excellent quality of the low-energy kaon beam delivered by the DA⊠NE collider of INFN-LNF with new experimental techniques, like high-precision spectroscopic Silicon Drift Detectors, we performed unprecedented measurements in the low-energy strangeness sector in the framework of the SIDDHARTA Collaboration and are presently running the SIDDHARTA-2 experiment for very challenging kaonic atoms measurements, such as kaonic deuterium first measurement.
I shall introduce the physics of kaonic atoms, the experiment, the first exciting results, and discuss future plans. I shall also present AMADEUS collaboration results on studies of low-energy kaons interacting with various nuclei.
The experiments at DA⊠NE represent a unique opportunity to unlock QCD secrets in the strangeness sector and contribute to better understand the role of strangeness in the Universe, from nuclei to the stars.

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NEutrino Properties Through Use of Nuclei (NEPTUN)

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In my talk I will highlight the background and achievements, as also some prospects, of the NEPTUN (NEutrino Properties Through Use of Nuclei) project's first year. NEPTUN is a 3-year neutrino-related nuclear-physics project funded by the EU through the Romanian Ministry of Research, Innovation and Digitzation. I will discuss the problem of the effective value of the weak axial-vector coupling g_{A} and ways to determine its value through β spectral shapes and the nuclear muon capture. I will also address the studies of total β spectral shapes related to quantification of natural radioactive backgrounds in rare-events and dark-matter experiments, as also the sterile neutrinos in the light of reactor antineutrino anomalies.

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Atomic corrections for the β decay of neutrino mass measurement candidates

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We reexamine one of the most promising candidates for determining the neutrino mass scale: the unique first forbidden β transition from $^{187}\text{Re}(5/2^+)$ to $^{187}\text{Os}(1/2^-)$. With the lowest-known ground-state to ground-state Q-value for a β transition at 2.4709 keV, rhenium's β decay can offer insights into the neutrino mass scale puzzle. However, understanding its electron spectrum is a complex task. Besides involving a mixture of $s_{1/2}$-state and $p_{3/2}$-state electrons, various atomic corrections could strongly influence the rhenium β spectrum. We have incorporated finite nuclear size, diffuse nuclear surface, screening, and exchange corrections into the rhenium β decay model. The last two are accounted for within the Dirac-Hartree-Fock-Slater self-consistent method. We have discovered that both screening and exchange effects significantly alter the partial decay rates for the $s_{1/2}$- and $p_{3/2}$-state emission channels while still maintaining the experimentally confirmed dominance of the $p_{3/2}$-state emission. The ratio between the respective decay rates has been found to be approximately 10^4. Compared to the other corrections, the exchange effect stands out due to the modification it induces in the spectrum shape. We demonstrate that calculations with and without the exchange effect lead to entirely different shape factors for the decay spectrum. Finally, we illustrate that to preserve the linearity of the Kurie plot, it is essential to include the exchange correction in its definition. We conclude that atomic effects, especially the exchange effect, should be considered in current and future investigations of the neutrino mass scale from β decays.

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Advances in atomic electron capture as a tool for neutrino mass determination

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We present the normalized distributions of released energy in electron capture (EC) decay as a method for determining the neutrino mass. Our calculations account for exchange and overlap corrections, shake-up and shake-off atomic effects, electron screening effects, and the intrinsic line-widths of Breit-Wigner resonances.

The wave functions of the electrons were computed using the Dirac-Hartree-Fock-Slater self-consistent method, validated in prior studies for similar calculations. Our analysis focuses on two transitions of 95Tc to two excited states of 95Mo, utilizing the first direct measurement of the ground state to ground state EC Q-value of 95Tc performed with the JYFLTRAP Penning trap mass spectrometer.

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Feasibility measurement of X-ray transitions in kaonic lead with HPGe detector at DAΦNE

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The state-of-the-art value of the charged kaon mass is still less precise than the charged pion mass. Its value is important in the non-perturbative QCD, and it also important in a determination of systematic uncertainty of the D0-meson mass. Since there is a need and a possibility to improve the precision of this value, we will present ongoing analysis of feasibility measurement of X-rays from kaonic transitions in a lead target at the DAΦNE e+e− collider at the LNF-INFN. The X-rays have been detected by HPGe detector and readout based on a CAEN DT5781 fast pulse digitizer [1].

[1] D. Bosnar et al., 2024, arXiv:2405.12942

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High precision X-ray spectroscopy at the DAΦNE collider: with SIDDHARTA-2 experiment

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High-precision X-ray spectroscopy of light kaonic atoms serves as a crucial method for exploring into low-energy QCD within the strangeness sector, allowing the determination of the antikaon-nucleon interaction at threshold without the need of extrapolation to zero energy The SIDDHARTA-2 collaboration is currently engaged in the complex task of measuring kaonic deuterium transitions to its fundamental level at the DAΦNE collider of the INFN-LNF, with the measurement underway. In pursuit of this goal, the collaboration has designed and built an experimental setup, taking advantage of the optimized veto systems for the background rejection and a new Silicon Drift Detectors system able to operate in the high background environment of the DAΦNE collider. The contribution presents the experimental apparatus and the results obtained during the preparation phase for the kaonic deuterium run.

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Kaonic Atom Properties and Cascade Models: Exploring Strong Interactions through First-Principles Calculations

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Kaonic atom experiments at SIDDHARTA2 provide a unique platform to explore the effects of strong interactions at low momenta. Specifically, during the de-excitation process of the highly excited kaonic atom, known as cascade, the emitted X-rays may be significantly influenced by the strong nuclear interaction between the nucleus and the kaon. Here, I present a detailed description of the method to calculate kaonic atom properties completely from first principles. Using the Multi-Configurational Dirac Fock approach, I will present applications from transition energy calculations with the inclusion of electronic screening effects, up to the setting bounds on the kaon mass value. Furthermore, I will describe how to model the cascade process with the Monte Carlo approach to predict and explain the experimentally observed X-ray transition yields. This work aims to deliver precise theoretical insights that can guide future experimental investigations in the field of strong nuclear interaction.

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The KAMEO proposal: investigating the strong kaon-nucleus interaction through the E2 nuclear resosnance effect in kaonic atoms

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Kaonic atoms are atomic systems in which a negatively charged kaon is captured in the atomic shell, replacing an electron. The capture occurs at a highly excited atomic level, then the kaon starts an electromagnetic cascade to the innermost atomic levels, where the strong kaon-nucleus interaction becomes detectable with X-ray spectroscopy. Kaonic atoms allow the study of strong interaction in the strangeness sector, at low energies. The E2 nuclear resonance occurs when atomic de-excitation energy is closely matched by nuclear excitation energy. It mixes the atomic and nuclear states due to the electrical quadrupole excitation of the nucleus. In the specific, the mixing occurs among $(n, l, 0^+)$ and $(n', l-2, 2^+)$ states. As a consequence, the E2 nuclear resonance produces an attenuation of some of the atomic x-ray lines from resonant versus normal isotope target and, in kaonic atoms, it allows the negatively charged kaon to reach inner levels of the atom not easily accessible through the electromagnetic cascade, because of the nuclear absorption. The investigation of the nuclear E2 resonance effect in kaonic ticklish atoms could provide important information about strong kaon nucleus interaction. The E2 nuclear resonance effect is expected to occur in four kaonic Molybdenum isotopes ($^{94}_{42}$Mo, $^{96}_{42}$Mo, $^{98}_{42}$Mo, and $^{100}_{42}$Mo) with similar energy values. The KAMEO (Kaonic Atoms Measuring Nuclear Resonance Effects Observables) proposal plans to measure this effect in kaonic Mo isotopes at the DAΦNE e^+e^- collider, in Frascati (LNF-INFN). The KAMEO apparatus will equip four solid strip targets of enriched Mo isotope each, exposed to negatively charged kaons produced by DAΦNE. A high-purity germanium detector, placed just behind the target strips, will be used for the x-ray spectroscopy. An additional solid strip target of non-resonant $^{92}_{42}$Mo isotope will be exposed to be used as a reference for standard non-resonant transitions. This experiment would provide a conclusive measurement of the E2 nuclear resonance effects in 4 isotopes of kaonic molybdenum, investigating strong kaon-nucleus properties, at low energies, in heavy kaonic atoms.

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The role of dust in the star-formation and galaxy evolution, and its characteristic scaling relations

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Interstellar dust, a processor of stellar radiation, a gas coolant and a good interstellar medium (ISM) tracer, is formed out of elements mostly forged in stars. Its precise composition, grain size and distribution are essential for the galaxy attenuation curves, for the stellar or dust evolution models. Likewise, dust and star formation scaling relations are essential in studies of ISM evolution, in star formation and galaxy evolution studies, and in studies related to the duty cycle of dust and gas in galaxies. I will show this through recent results from a detailed study of these relations done on a representative sample of galaxies from the nearby Universe.

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Description of particle-antiparticle bound systems via numerical solutions of the Dirac-Coulomb equation

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In this talk we discuss binary particle-antiparticle atomic systems starting from the formulation (in 16×16 matrix form) of the relevant 2-body Dirac-Coulomb Hamiltonian. Then, we apply the separation of the radial dependence from the angular-spin dependence of the Dirac-spinor components based on the conservation laws that must be full filled as: the well-defined charge-conjugation, the particle-exchange symmetries and the existence of Dirac-spinor components with positive and negative energy that must respect the positive and negative particle/antiparticle) rest masses. The radial wave functions are obtained: (i) through the reduction of the above eigenfunction problem to equivalent ordinary differential equations of (two-body) Klein-Gordon- and Schr\"oedinger type, and (ii) by solving these differential equations by utilizing the recently developed algorithms (in Python language) which are based on neural network techniques and use modern activation functions. We specifically focus on the calculations of the wave functions and energies of the low-lying states of lepton-antilepton (of equal masses $m_1 = m_2$) atoms. Such prominent binary systems with are the Positronium (e^-, e^+), the true Muonium $(\mu^- \mu^+)$ and the true Tauonium $(\tau^- \tau^+)$) purely leptonic atoms. Our goal is to make theoretical predictions for the low-lying energy spectra of these systems by assuming that the lepton and antilepton interact via a static Coulomb potential plus the Gaunt (magnetic) part of the known Breit interaction.

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Introducing SPADES

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SPADES (Spectra and Phase spAce factors in Double bEta decayS), a software package for theoretical double beta decay analysis, integrates RADIAL package and the DHFS method to compute electron wave functions accurately in complex atomic systems. Its user-friendly interface facilitates input of parameters for seamless computations. Researchers can compare spectra and phase space factors across various approximations, exploring diverse theoretical frameworks and assessing nuclear structure uncertainties. SPADES offers the important capability to generate double beta decay events in HEPMC3 format, with additional formats available on request. This feature enhances its utility for Monte Carlo simulations and compatibility with different analysis tools. With its emphasis on precision, versatility, and ease of use, SPADES emerges as a valuable tool for unraveling the complexities of double beta decay processes and advancing our understanding of fundamental particle physics.

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Neutrinoless double-beta decay investigations of 82Se using three shell model Hamiltonians

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Recent studies of neutrinoless double-beta decay matrix elements have employed statistical approaches based on modified shell model effective Hamiltonians for 48Ca (Phys. Rev. C 106, 054302 (2022)) and 136Xe (Phys. Rev. C 107, 045501 (2023)). The analyses rely on inducing perturbations in the starting effective Hamiltonians to observe the behavior of a wide range of observables, besides the $0\nu\beta\beta$) NME, that are compared with experimental data. Following a Bayesian Model Averaging approach, the range of probable values for the neutrinoless double-beta decay matrix elements is presented. In this paper, we present a similar study for 82Se, which is described in the same model space as 76Ge that is under experimental observation. Due to its faster calculation time compared to 76Ge, 82Se can be used as an appropriate substitute in our complex statistical study. Using the calculations performed for the statistical analysis of the neutrinoless double-beta decay matrix elements we also search for the correlations between the observables that we can compare to experimental data.

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Exploring the quark-gluon plasma with ALICE

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Measurements of two- and multi-particle azimuthal correlations provide valuable information on the properties of the system created in collisions of hadrons and nuclei at high energy. In this talk, the ALICE results for inclusive and identified particle azimuthal correlations are reported in different collision systems after a brief introduction of the concepts of a heavy-ion collision.

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Double-beta decay: a window to physics beyond the SM

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Double beta decay (DBD) is a currently hot research topic as it can offer a wide range of physics investigations beyond the Standard Model (BSM). These refer to fundamental neutrino properties, yet unknown (neutrino nature –is it a Dirac or a Majorana particle, the neutrino absolute mass and mass hierarchy, number of neutrino flavors, etc.), conservation of the lepton number and validity of Lorentz and CP symmetries, as well as to different BSM mechanisms that can contribute to the neutrinoless double-beta decay.
In my talk, I will first summarize the current theoretical challenges facing the DBD study and then briefly present the latest results in the field obtained by our group in Bucharest.

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Ultra high energy cosmic rays induced air showers: from nuclear interactions of particles in the air to detection techniques on the ground

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Ultra-high energy cosmic rays (UHECRs) are the most energetic, rare and mysterious particles in the Universe. Although they are known to be of extragalactic origin, their actual sources remain a subject of debate yet. Modern large-scale experiments are indirectly observing them on the ground, and are further expanded to increase data statistics with improved mass-sensitive measurements of cosmic rays induced air showers, i.e. when a cosmic ray particle enters the Earth's atmosphere, it develops an extensive air shower of secondary particles through multiple nuclear interactions.
In this talk, I will shortly introduce the physics of cosmic rays air showers, with the detection methods used nowadays, e.g. at the world's largest cosmic rays experiment, the Pierre Auger Observatory, including Monte Carlo simulations, with the focus on radio signals from air showers and

the detector response. Additional emphasis will be put on data analysis and online tools for data visualization.

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Alpha-clustering and related phenomena in medium and heavy nuclei

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Recent theoretical developments in the phenomenology of alpha-clustering are presented. The interplay of clustering with decay phenomena mediated by electromagnetic and weak interactions is outlined, together with its importance for modern nuclear structure and related fields.

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Elastic scattering of alpha particles: going beyond optical potential models

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The elastic scattering of alpha particles on N=Z nuclei exhibits a significant enhancement of the cross section at large scattering angles, a phenomenon known as anomalous large angle scattering (ALAS) [1]. Several studies [2] suggest that ALAS is linked to the alpha-like correlations present in N=Z nuclei. Moreover, this behavior cannot be satisfactorily explained within the standard framework of optical potential models [3]. In this study, the potential describing the interaction between the alpha particle and the target nucleus is obtained using a single folding procedure [4]. This method incorporates an alpha-nucleon potential [5] and the nuclear density of the target nucleus, the latter being evaluated based on microscopic quantum approaches.
[1] G. Gaul et al., Nucl. Phys. A137 (1969) 177.
[2] N. C. Schmeing, Nucl. Phys. A142 (1970) 449.
[3] X.-W. Su, and Y.-L. Han, Int. J. Mod. Phys. E, vol. 24, no. 12 (2015).
[4] G. R. Satchler, and W. G. Love, Phys. Rep. 55 (1979) 183-254.
[5] F. E. Bertrand et al., Phys. Rev. C22 (1980) 1832.

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Recent approaches for assessing the nuclear matrix elements for double beta decays and double electron captures

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In my talk I will present new statistical methods for assessing the values and their uncertainties of the nuclear matrix elements for neutrinoless double beta decays, two neutrino double beta decays, two neutrino double electron capture, and neutrinoless double electron capture. The analyses are made within the traditional shell model approach. Examples for 48Ca, 82Se, 124Xe, and 136Xe will be provided.

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Collectivity of PYGMY dipole resonance and its contribution to nuclear polarizability

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Pygmy Dipole Resonance in nuclear systems, related to the dipole response around neutron separation energy, was under a close scrutiny of several experimental and theoretical investigations during the last decade. Critical questions regard its nature, centroid position and width, the evolution of its features with the number of neutrons in excess, its role in the astrophysical context. We introduce some microscopic approaches able to predict this state and its collective features. We also discuss the role of the symmetry energy on the isoscalar-like nature of this mode.

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Concluding discussions

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Seven Great Mysteries of Modern Physics: From Black Holes to Parallel Universes

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From the theory of relativity to quantum mechanics; from quarks and the Higgs boson to stars and galaxies, modern physics answers many questions and curiosities about how the world and the Universe are structured, while raising many other, increasingly fascinating questions. I will present seven great mysteries of modern physics: the disappearance of antimatter from
the Universe; the mysterious black holes; the hidden face of the Universe: dark matter and dark energy; research in the field of quantum mechanics related to the famous "Schrödinger's cat"; the structure of neutron stars; the possible existence of parallel universes and worlds; and the Fermi paradox: do extraterrestrials exist? I invite you to discover with me the
fascinating world of modern physics and some of its enigmas, towards new horizons and… perhaps new worlds and universes!

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Closing remarks