Conference on Quantum-Many-Body Correlations in memory of Peter Schuck (QMBC 2023)

mardi 21 mars 2023 - jeudi 23 mars 2023

IJCLab, Orsay, France

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Auteur: Michael Urban[1]

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Relativistic Brueckner-Hartree-Fock Theory: an ab initio Approach for Finite Nuclei

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Most investigations of collective vibrations in medium-heavy and heavy nuclei are based on nuclear density functional theory. Very successful relativistic and non-relativistic functionals are available nowadays. However, most of them are phenomenological functionals. Therefore it is important to study the connection of such functionals to ab-initio nucleon-nucleon forces. Non-relativistic Brueckner-Hartree-Fock theory was a starting point of ab-initio investigations in nuclear structure in the fifties and sixties. However, it failed because three-body forces were not included at that time. Later it was found that relativistic Brueckner-Hartree-Fock (RBHF) theory can reproduce the saturation properties of nuclear matter. In this contribution, we discuss recent developments of RBHF theory for infinite nuclear matter finite nuclei, particularly applications for neutron stars.

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Studies of odd-A nuclei and high-K isomeric states with the BCPM functional

Auteur: Luis Robledo[1]

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The BCPM (Barcelona-Catania-Paris-Madrid) is a nuclear energy density functional with a central term obtained by using the density of finite nuclei in a polynomial fit to nuclear matter equation of state (both symmetric and neutron matter). As formulated, the BCPM functional does not contain time-odd densities and therefore it should not be used to describe odd-A nuclei and/or multiquasiparticle excitations like the ones making high-K isomeric states. However, the equal filling approximation to full blocking has proved to be very accurate in describing the above mentioned systems, with the advantage of not requiring time odd fields. We have implemented the EFA along with the BCPM

functional to obtain properties of odd-A nuclei like ground state spin and parity and the excitation energy spectrum. The idea can easily be generalized to describe high-K isomeric states.

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Relativistic equation of motion framework for nuclear physics

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Superfluidity in nuclear systems

Auteur: Enrico Vigezzi[1]

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Peter Schuck devoted much attention to the study of nuclear superfluidity and to many-body effects that renormalize the pairing interaction in nuclear systems, going from his works with the Catania group to his recent papers with E. Litvinova.
I will resume the research done on this topic by the Milano group, starting from a paper we wrote together with him [1]. Such research deals not only with atomic nuclei but also with superfluidity in the inner crust of neutron stars and with the structure of vortices.

[1] F. Barranco, P.F.Bortignon, R.A. Broglia, G. Colò, P. Schuck, E. Vigezzi and X. Vinas, Pairing matrix elements and pairing gaps with bare, effective and induced interactions, Phys. Rev. C 73 (2005) 054314

Tuesday 11:15-12:45 / 194

Anti-Screening Effects in the Nuclear Pairing

Auteur: Umberto Lombardo[1]

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Tuesday 11:15-12:45 / 171

Suppression of superfluidity in neutron-star crusts

Auteur: Nicolas Chamel[None]

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Formed in the aftermath of gravitational core-collapse supernova explosions, neutron stars contain matter crushed at densities exceeding that found inside the heaviest atomic nuclei under conditions so extreme that they cannot be reproduced on Earth. Neutron stars are therefore unique laboratories for exploring phases of matter not observed in any other celestial bodies. As early as 1959, the inner crust and the outer core of a neutron star were predicted by Arkhady Migdal to exhibit neutron superfluidity at temperatures below $\sim 10^{10}$ K. Since then, neutron superfluidity has found strong support from radio-timing observations of pulsar frequency glitches, and more recently from the rapid decline of luminosity of the youngest known neutron star in the supernova remnant of Cassiopeia A [1].

In a similar way to laboratory superfluidity of atomic gases in optical lattices, neutron superfluidity in the inner crust of neutron stars is partially suppressed due to the presence of neutron-proton clusters [2]. The reduction of the neutron superfluid density implies that the neutron superfluid cannot flow completely freely despite the absence of viscous drag. Due to this entrainment effect, clusters move with an effective mass and collective excitations of the superfluid are mixed with those of the crust. The extent to which neutron superfluidity is suppressed depends on whether the crust is crystalline or disordered [3]. Recent fully 3D neutron band-structure calculations taking BCS pairing into account will be presented. Astrophysical implications will be discussed.

[1] N. Chamel, J. Astrophys. Astr. 38, 43 (2017).
[2] N. Chamel, J. Low Temp. Phys. 189, 328 (2017).
[3] J. A. Sauls, N. Chamel, M. A. Alpar, eprint arXiv:2001.09959

Tuesday 14:00-15:30 / 183

Probing the BCS-BEC crossover with persistent currents

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Tuesday 14:00-15:30 / 188

Vortices in ultracold Fermi gases: peculiarity of their structure and impact on dynamics

Auteur: Piotr Magierski[1]

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It will be shown that spin polarized vortices in Fermi superfluid acquire a peculiar structure with a reversed circulation inside the core. Their structure admits the vanishing minigap with a characteristic pattern of single-quasiparticle level crossings at the Fermi surface. It is also predicted that the dynamics along the vortex line of spatially localized polarization inside the core will be suppressed. The impact of the vortex core structure on dynamics will be analyzed in the context of recent experiment involving colliding vortex dipoles [Nature (London) 600, 64 (2021)] which revealed nonuniversal dissipative dynamics. Moreover consequences for neutron star crust and the decay of turbulent state will be discussed.
References

[1] Piotr Magierski, Gabriel Wlazłowski, Andrzej Makowski, Konrad Kobuszewski, Phys. Rev. A

106, 033322 (2022)
[2] Andrea Barresi, Antoine Boulet, Piotr Magierski, Gabriel Wlazłowski, Phys. Rev. Lett. 130, 043001 (2023)
[3] Khalid Hossain, Konrad Kobuszewski, Michael McNeil Forbes, Piotr Magierski, Kazuyuki Sekizawa, Gabriel Wlazłowski, Phys. Rev. A 105, 013304 (2022)
[4] Gabriel Wlazłowski, Klejdja Xhani, Marek Tylutki, Nikolaos P. Proukakis, Piotr Magierski, Phys. Rev. Lett. 130, 023003 (2023)
[5] Daniel Pęcak, Nicolas Chamel, Piotr Magierski, Gabriel Wlazłowski, Phys. Rev. C 104, 055801 (2021)

Tuesday 14:00-15:30 / 184

Space-time correlations in turbulence

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The problem of solving a strongly-coupled many-body system arises in classical fluid dynamics when turbulence fully develops. The statistical properties of the turbulent fluid are encoded in an infinite hierachy of coupled equations which leads to what is called the "closure problem" of turbulence. The functional renormalisation group offers an efficient method to tackle this problem and achieve a controlled closure in the limit of large wavenumbers. I will present the principles of this approach and illustrate the results through comparisons with data from both direct numerical simulations and experiments.

Ref: L. Canet, Journal of Fluid Mechanics, Perspectives, 950, 1 (2022)

Tuesday 16:00-17:30 / 160

Neutron star properties from semiclassical methods in nuclear physics

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Semiclassical methods in nuclear physics are a very good tool to study the behavior and composition of neutron stars. Using the Vlasov equation, the neutron star crust-core transition will be discussed, also in the presence of a strong magnetic field as expected inside magnetars. The description of the inner crust within a Thomas Fermi approach will be presented.

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An attempt at semiclassical methods for electronic-structure theory

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Tuesday 16:00-17:30 / **180**

In memory of Peter Schuck: "Semiclassical approximation to pairing in the weak coupling regime: nuclei, cold atoms, and neutron stars"

Auteur: Xavier Viñas[1]

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A novel Thomas-Fermi (TF) approach to inhomogeneous superfluid Fermi-systems is presented and shown that it works well also in cases where the Local Density Approximation (LDA) breaks down. The novelty lies in the fact that the semiclassical approximation is applied to the pairing matrix elements not implying a local version of the chemical potential as with LDA. Applications will be given to the generic fact that if a fermionic superfluid in the BCS regime overflows from a narrow container into a much wider one, pairing is substantially reduced at the overflow point. Two examples pertinent to the physics of the outer crust of neutron stars and superfluid fermionic atoms in traps will be presented. The TF results will be compared to quantal and LDA ones.
[1] P. Schuck and X. Viñas, Phys. Rev. Lett. **107**, 205301 (2011).
[2] X. Viñas, P. Schuck and M. Farine, J. Phys. Conf. Ser. **321**, 012024 (2011); J. Phys. Conf. Ser. **338**, 012016 (2012).
[3] *Fifty years of Nuclear BCS: Pairing and Finite Systems*, 212, Ed. R. Broglia, World Scientific, 2013.

Cocktail & Poster session / **243**

Core level chemical shift by ab initio mehods: from mean-field to many-body theory

Auteurs: Iskander Mukatayev[1]; Florient Moevus[2]; Benoît Sklénard[3]; Valerio Olevano[4]; Jing Li[3]

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The binding energy of core electrons may not only provide information on the chemical composition, but also some additional information such as the type of bonding, which could be inferred from the shift of the binding energy, (also known as chemical shift). We present the study of the chemical shift using different theories, from Hartree-Fock and density-functional theory to many-body perturbation theory (COHSEX, *GW*). We benchmarked the accuracy of the chemical shift of the carbon 1s electron in a set of molecules against experiments. Besides, our study reveals the physical origin of the chemical shift.

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Equation of state of superfluid neutron matter with low-momentum interactions

Auteurs: Viswanathan Palaniappan[1]; Sunethra Ramanan[2]; Michael Urban[1]

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[2] *IIT Madras*

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In this work, we calculate the ground state energy of pure neutron matter using the renormalization group based low-momentum effective interaction $V_{\text{low-}k}$ in Bogoliubov many-body perturbation theory (BMBPT), which is a perturbative expansion around the Hartree-Fock-Bogoliubov (HFB) ground state. In order to capture the low-density behavior of neutron matter, it turns out to be better to use a density dependent cutoff in the $V_{\text{low-}k}$ interaction. Perturbative corrections to the HFB energy up to third order are included. We find that at low densities corresponding to the inner crust of neutron stars, the HFB state that includes pairing is a better starting point for perturbation expansion. It is observed that including the higher order perturbative corrections, the cutoff dependence of the ground state energy is reduced.

Reference: V. Palaniappan, S. Ramanan, M. Urban, Phys. Rev. C 107, 025804 (2023)

Cocktail & Poster session / 242

Electron removal energies in noble gas atoms up to 100 keV: ab initio GW vs XPS

Auteurs: Iskander Mukatayev[1]; Benoît Sklénard[2]; Valerio Olevano[3]; Jing Li[2]

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X-ray photoelectron spectroscopy (XPS) measures electron removal (quasiparticle) energies, providing direct access to core and valence electron binding energies, hence probing the electronic structure. We present the benchmark of the *ab initio* many-body *GW* approximation on the complete electron binding energies of noble gas atoms (He-Rn), which spans 100 keV. Our results demonstrate that *GW* achieves an accuracy within 1.2% in XPS binding energies, by systematically restoring the underestimation from density-functional theory (DFT, error of 14%) or the overestimation from Hartree-Fock (HF, error of 4.7%). Such results also imply the correlations of *d* electrons are very well described by *GW*.

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Neutrino Scattering Rates of Neutron-star and Supernova Matter within Skyrme RPA

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Supernova explosions, which will leave behind a neutron star, are the most powerful neutrino sources. The neutrino emission is also the dominating cooling mechanism for a (proto-)neutron star, whose interior is mainly composed of extremely dense and hot nuclear matter. Neutrinos can be scattered frequently inside stars before they escape. We study the neutrino scattering rates of neutron-star and supernova matter within Skyrme RPA response functions. The neutrino scattering rates in neutron-star matter depend sensitively on the adopted interaction. The minimum scattering angle is different for different interactions because it depends on the Fermi velocity. We also find that many Skyrme interactions present the unphysical feature that the Fermi velocity of neutrons in neutron-star matter exceeds the speed of light at a density below the maximum central density of the neutron star predicted by the Skyrme interactions.

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Static self energy and effecive mass of the homogeneous electron gas from Quantum Monte Carlo calculations

Auteur: Markus Holzmann[1]

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Landau's Fermi liquid theory has provided a paradigmatic frame for the phenomenological description of equilibrium and transport properties of degenerate fermions in terms of very few characteristic parameters. Silin has set out the path to generalize for long-range forces, such to extend it for normal metals in condensed matter. Although the formal structure of the underlying microscopic theory is known for a long time, most explicit calculations of the Fermi liquid parameters basically rely on approximative, perturbative schemes. As diagrammatic perturbation theory is not expected to converge for typical electronic densities, basic Fermi liquid parameters of the homogeneous electron gas (jellium), like the effective mass m^* and the renormalization factor Z, considerably vary according to the underlying approximation. Recently, diagrammatic Monte Carlo calculations (DiaQMC) [1] have been performed to include and control higher order terms of the perturbation series. Those calculations found an overall agreement for Z with previous quantum Monte Carlo calculations (QMC) [2]. However, DiaQMC results on m^* have been strongly questioned by QMC calculations yielding substantial different values [3]. Here, we rewise the methodology of zero temperature QMC calculations of the effective mass, in order to resolve the discrepancy between QMC and perturbative/DiaQMC results.

[1] K. Haule and K. Chen, Scientific Reports 12, 2294 (2022).
[2] M. Holzmann, B. Bernu, C. Pierleoni, J. McMinis, D. M. Ceperley, V. Olevano, and L. Delle Site, Phys. Rev. Lett.
107, 110402 (2011).
[3] S. Azadi, N.D. Drummond, and W.M.C. Foulkes, Phys. Rev. Lett. 127, 086401 (2021).

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Neutron stars within the Bogoliubov quark-meson coupling model

Auteur: Aziz Rabhi[1]

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A quark-meson coupling model based on the quark model proposed by Bogoliubov for the description of the quark dynamics is developed and applied to the description of neutron stars. Starting from a SU(3) symmetry approach, it is shown that this symmetry has to be broken in order to satisfy the constraints set by the hypernuclei and by neutron stars. The model is able to describe observations such as two-solar-mass stars or the radius of canonical neutron stars within the uncertainties presently accepted. If the optical potentials for Λ and Ξ hyperons in symmetric nuclear matter at saturation obtained from laboratory measurements of hypernuclei properties are imposed, the model predicts no strangeness inside neutron stars.

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Thermal phase transitions and giant resonances in atomic nuclei with chiral effective interactions

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Ab initio approaches to the nuclear many-body problem have seen their reach considerably extended over the last decade. However, collective excitations have seldom been addressed in that context, due to the prohibitive cost of solving the corresponding equations of motion.

We adapt a novel method originally proposed in the framework of the nuclear energy density functional method, and derive its extension to non-zero temperatures.
We thus obtain the first fully self-consistent ab initio study of multipolar responses of atomic nuclei using two- and three-body chiral interactions, at zero and finite temperature.

The method is applied to the mid-mass nucleus ^{56}Fe, which is challenging for ab initio interactions due to its mid-mass, deformed and superfluid character. After reproducing the temperature-induced shape transition at the mean-field level, we analyse the evolution of the isovector dipole strength function within a temperature range $k_B T \in [0; 4]$ MeV. A strong dependence is observed, characterised by a downwards shift of the resonance centroid when the system is heated up.

[1] T. Nakatsukasa, T. Inakura, and K. Yabana. Finite amplitude method for the solution of the random-phase approximation. Phys. Rev. C, 76:024318, Aug 2007. doi: 10.1103/PhysRevC.76.024318.
[2] Y. Beaujeault-Taudière. Study of the multipolar excitations in cold and hot, deformed and superfluid systems with the method of finite amplitudes. Theses, Université Paris-Saclay, Oct 2021.
[3] Y. Beaujeault-Taudière et al. Ab initio description of multipolar responses in superfluid and deformed nuclei at finite temperature: application to dipole modes in 56Fe. Mar 2022. doi: 10.48550/arXiv.2203.13513.
[4] A. C. Larsen, N. Blasi, A. Bracco, F. Camera, T. K. Eriksen, A. Görgen, M. Guttormsen, T. W. Hagen, S. Leoni, B. Million, H. T. Nyhus, T. Renstrøm, S. J. Rose, I. E. Ruud, S. Siem, T. Tornyi, G. M. Tveten,
A. V. Voinov, and M. Wiedeking. Evidence for the dipole nature of the low-energy ⊠ enhancement in 56Fe. Phys. Rev. Lett., 111:242504, Dec 2013. doi: 10.1103/PhysRevLett.111.242504.

Cocktail & Poster session / 246

Spin-polarized droplets in ultracold Fermi gas

Auteurs: Bugra Tuzemen[1]; Gabriel Wlazłowski[1]; Piotr Magierski[1]

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We demonstrate the existence of a new type of spatially localized excitations in the unitary Fermi gas: spin polarized droplets with a peculiar internal structure involving the abrupt change of the pairing phase at the surface of the droplet. It resembles the structure of the Josephson-π junction occurring when a slice of a ferromagnet is sandwiched between two superconductors. The stability of the impurity is enhanced by the mutual interplay between the polarization effects and the pairing field, resulting in an exceptionally long-lived state. We show that the motion of spin-polarized impurity (ferron) in ultracold atomic gas is characterized by a certain critical velocity which can be traced back to the amount of spin imbalance inside the impurity. We have calculated the effective mass of ferron in two dimensions. We show that the effective mass scales with the surface of the ferron. We discuss the impact of these findings; in particular, we demonstrate that ferrons become unstable in the vicinity of a vortex.

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Disordered structures in ultracold spin-imbalanced Fermi gas

Auteurs: Bugra Tuzemen[1]; Gabriel Wlazłowski[1]; Piotr Magierski[1]; Tomasz Zawiślak[1]

[1] *Warsaw University of Technology*

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We investigate the properties of spin-imbalanced ultracold Fermi gas in a large range of spin polarizations at low temperatures. We present the results of microscopic calculations based on mean-field and density functional theory approaches, with no symmetry constraints. At low polarization values we predict the structure of the system as consisting of several spin-polarized droplets. As the polarization increases, the system self-organizes into a disordered structure similar to liquid crystals, and energetically they can compete with ordered structures such as grid-like domain walls. At higher polarizations the system starts to develop regularities that, in principle, can be called supersolid, where periodic density modulation and pairing correlations coexist. The robustness of the results has been checked with respect to temperature effects, dimensionality, and the presence of a trapping potential. Dynamical stability has also been investigated.

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Simulation of the time evolution for one-dimensional wave-functions with quantum computation

Auteur: Jing Zhang[1]

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Quantum computation is a relatively new field that seeks to harness the power of quantum mechanics to perform calculations that would be impossible with classical computers. The Schrödinger equation lies at the heart of quantum physics. In this poster, we present how to address the one-dimensional time evolution of wave-functions, as governed by the Schrödinger equation, on quantum computation devices. The potential of quantum computation to achieve reliable simulation of the process is demonstrated. In the end, we highlight the challenges of implementing non-unitary boundary conditions.

Wednesday 09:15-10:45 / **173**

Causes and consequences of the emergence of clusters in nuclei

Auteur: Jean-Paul EBRAN[1]

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Nuclear clustering refers to the appearance of multi-nucleon localized structures, predominately under the form of α particles, within the interior of a nucleus. The detailed understanding of how quantum correlations among nucleons give rise to nuclear clustering is still lacking, the main difficulty being the need to a priori include four-nucleon correlations.
Using the Energy Density Functional framework, conditions for the emergence of clusters are analyzed and spectroscopic signatures of these structures are discussed.

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Study of alpha condensate and beyond

Auteur: Yasuro Funaki[1]

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After the proposal of the so-called THSR wave function in 2001, it has been developed for 20 years and applied to many nuclear systems. We discuss the achievement in the study of the alpha condensation physics and related issues with the THSR ansatz, which has been done in collaboration with Prof. Peter Schuck.

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Temperature and Density Conditions for Alpha Clustering in Alpha-Conjugate Nuclei

Auteur: Bernard Borderie[1]

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Wednesday 11:15-12:45 / 178

Pairing in systems with imbalance and BCS-BEC crossover

Auteur: Armen Sedrakian[1]

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I will discuss the work initiated in collaboration with Peter Schuck and others on the imbalance of superfluid on the isospin asymmetric nuclear matter. The current understanding of the phase diagram of dilute nuclear matter which includes the phases with broken space symmetries will be discussed covering the temperature-density regime across the BCS-BEC crossover.

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FFLO correlations in polarized ultracold Fermi gases

Auteur: Pierbiagio Pieri[1]

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Quite generally, an imbalance between the densities of spin-up and spin-down fermions hinders pairing and superfluidity in two-component attractive Fermi gases. The Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase, in which pairs condense at a finite value of center-of-mass momentum to compensate for the mismatch of the two Fermi surfaces, was proposed many years ago as a possible superfluid phase compatible with a finite polarization. In this talk, I will discuss how significant precursor FFLO fluctuation effects appear already in the normal phase of polarized Fermi gases at finite temperature [1], and how they could be observed experimentally. At zero temperature [2], I will discuss how the quasi-particle parameters of the normal Fermi gas are changed when approaching an FFLO quantum critical point. Within a fully self-consistent t-matrix approach we find that the quasi-particle residues vanish, and the effective masses diverge at the FFLO quantum critical point, with a complete breakdown of the quasi-particle picture that is similar to what is found in heavy-fermion materials at an antiferromagnetic quantum critical point.

References

[1] M. Pini, P. Pieri, and G. Calvanese Strinati, Phys. Rev. Res. **3**, 043068 (2021).
[2] M. Pini, P. Pieri, and G. Calvanese Strinati, arXiv:2211.15529.

Wednesday 11:15-12:45 / **193**

Ferromagnetism in coherently coupled atomic mixtures

Auteur: Alessio Recati[1]

[1] *Pitaevskii BEC Center, CNR-INO and Dipartimento di Fisica, Trento, Italy*

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In the present talk we review the properties of a spin-1/2 Bose-Einstein condensate (BEC) in presence of both longitudinal and transverse external fields. The system has very peculiar properties not only with respect to the single component BEC, but also with respect to BEC mixtures (where the atom number of each species is conserved). In particular the system can exhibit a para- to ferromagnetic transition, has a gapped spin spectrum, and can sustain peculiar magnetic defects. Most of the peculiar properties are due to the system being an analog of a (non-dissipative) ferromagnetic material well described by the so-called Landau-Lifshitz equation. We then present some of the system's properties that have very recently been tested experimentally in our lab using ^{23}Na atomic gases. In particular we measured the excitation spectrum by modulating the trapping potential and generating Faraday patterns, we started characterising the ferromagnetic transition and obtain the first results on magnetic bubble generation from out-of-equilibrium initial states.

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Cooperation with Peter Schuck on many-body correlations in nuclei

Auteur: Doru Delion[1]

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The first topic describes the Selfconsitent Random Phase Approximation (SCRPA) [1]. The nonlinear SCRPA system of equations is numerically solved for the three level Lipkin model [2]. Goldstone mode and mass parameter in the deformed region are analyzed.
The second topic analyzes simultaneous description of alpha and electromagnetic transitions in ^{212}Po in terms of the surface alpha clustering [3]. Large dipole electromagnetic transitions from recently discovered unnatural parity states are explained.
[1] P. Schuck, D.S. Delion, J. Dukelsky, M. Jemai, E. Litvinova, G. Ropke, and M. Tohyama, Equation of Motion Method for strongly correlated Fermi systems and Extended RPA approaches, Physics Reports 929 (2021) 1.
[2] D.S. Delion, P.Schuck, and J. Dukelsky, Self Consistent Random Phase Approximation and the restoration of symmetries within the three level Lipkin model, Physical Review C 72 (2005) 064305.
[3] D.S. Delion, R.J. Liotta, P. Schuck. A. Astier, and M.-G. Porquet, Shell model plus cluster description of negative parity states in ^{212}Po, Physical Review C 85 (2012) 064306.

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dRPA, RPAx, SRPA, SCRPA, rRPA, …: tell me who you are and I will tell your RPA

Auteur: Valerio Olevano[1]

Co-auteur: Peter SCHUCK [2]

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[2] *Institut de Physique Nucleaire*

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The many-body problem, *i.e.* the solution of the Schrödinger equation in interacting many-body systems, is a formidable problem in condensed matter and nuclear physics, as well as in quantum chemistry, so far insolute despite considerable efforts of a whole generation of physicists and chemists. Every community has attacked the problem from a different point of view; has along the years elaborated varied theories, from wave-function to density-functional, up to Green function based approaches; and has achieved sometimes common findings, but also, and more often, different insights and complementary comprehension. Merging these insights and comprehension was the intuition of Peter Schuck's "RPA multidisciplinary conference" series, which was very stimulating and led to fruitful work in collaboration. Taking inspiration from this work, I will try to present here the largest landscape available, within my comprehension limits, about RPA flavors and many-body approaches encompassing quantum chemistry, condensed-matter and nuclear physics, speaking in a common, as much as possible, Esperanto language.

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Neutrino-nucleon interactions in dense and hot matter

Auteur: Micaela Oertel[1]

Co-auteurs: Aurélien Pascal [2]; Jérôme Novak [3]; Lami Suleiman [4]; Marco Mancini [5]

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Neutrinos play an important role in compact star astrophysics: neutrino-heating is one of the main ingredients in core-collapse supernovae, neutrino-matter interactions determine the composition of matter in binary neutron star mergers and have among others a strong impact on conditions for heavy element nucleosynthesis and neutron star cooling is dominated by neutrino emission except for very old stars. Many works in the last decades have shown that in dense matter medium effects considerably change the neutrino-matter interaction rates, whereas many astrophysical simulations use analytic approximations which are often far from reproducing more complete calculations. In this talk I will present a scheme which allows to incorporate improved rates into simulations and show as an example some results for core-collapse supernovae and proto-neutron star cooling.

Wednesday 16:00-18:00 / 168

Nuclear pastas in neutron stars: uncertainties of ETFSI approach

Auteurs: Nikolai Shchechilin[1]; Nicolas Chamel[1]; John Michael Pearson[2]; Mikhail Gusakov[3]; Andrei Chugunov[3]

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The region between the crust and the core of a neutron star (NS) may consist of a mantle of so-called nuclear pastas. If they exist, these exotic nuclear structures could significantly affect the transport and mechanical properties of dense matter, leaving their imprints on such NS observables as continuous gravitational-wave emission, NS oscillations and their damping, the spin period of x-ray pulsars, and NS cooling.

Such an extremely dense, neutron-rich and inhomogeneous environment represents unique conditions inaccessible to laboratory experiments and challenging for a fully microscopic treatment. Although nuclear pastas have been extensively studied within (semi-) classical methods, limited self-consistent mean-field calculations have been carried out so far due to high computational cost. For this reason, we follow an alternative approach adding proton shell corrections perturbatively via the Strutinsky integral theorem on top of the energy calculated within the 4th-order Extended Thomas-Fermi method [1]. We evaluate the uncertainties of this ETFSI approach using the generalized Skyrme effective interaction BSk24 [2].

First, we show within the ETF approach that the range of densities for which pasta phases are present and the types of pastas can depend on the parameterization of the nucleon profiles employed to speed up the calculations. To improve them, we introduce two new parametrizations for which we have found lower ETF energy solutions, therefore, more accurate nucleon profiles than previously obtained. In the second stage, when adding the SI corrections, we find that the differences in energies corresponding to the adopted parametrizations are (partially) compensated, such that the ETFSI

results for the two new profiles are in good agreement. In contrast to the purely ETF calculations, the spaghetti phase is now replaced by spherical clusters, which can also intersperse the lasagna phase and thus shrink the NS mantle. However, results at high densities become sensitive to the imposed boundary conditions to calculate the SI correction. In summary, quantum effects are shown to play an important role for pasta phases, however, fully self-consistent mean-field calculations are still required to identify the configurations that are present near the crust-core boundary.

[1] J. M. Pearson and N. Chamel, Phys. Rev. C 105, 015803 (2022)
[2] S. Goriely, N. Chamel, and J. M. Pearson, Phys. Rev. C 88, 024308 (2013)

Wednesday 16:00-18:00 / 192

Cluster structures in light nuclei

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Wednesday 16:00-18:00 / 191

Thermodynamics of quark matter with multi-quark clusters in an effective Beth-Uhlenbeck type approach*

Auteur: David Blaschke[1]

Co-auteurs: Mateusz Cierniak ; Gerd Röpke [2]

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We describe multi-quark clusters in quark matter within a generalized Beth-Uhlenbeck approach in a background gluon field that is coupled to the underlying chiral quark dynamics using the Polyakov-gauge and an effective potential for the traced Polyakov-loop. A higher multi-quark cluster of size n is described as a binary composite of smaller subclusters n1 and n2 (n1+n2=n) with a bound state and scattering state spectrum. For the corresponding cluster-cluster phase shifts we use two simple ansätze that capture the Mott dissociation of clusters as a function of temperature and chemical potential. We compare the simple "step-up-step-down" model that ignores continuum correlations with an improved model contains them in a generic form. In order to explain the model, we restrict ourselves here to the cases where n= 1, 2, ⋯, 6.
A striking result is the suppression of the abundance of colored multi-quark clusters at low temperatures by the coupling to the Polyakov loop. This is understood in close analogy to the suppression of quark distributions by the same mechanism and we derive here the corresponding Polyakov-loop generalized distribution functions of n-quark clusters. With the input of the temperature (T) and chemical potential (μ) dependence of the chiral condensate from lattice QCD, we construct the QCD thermodynamics in good agreement with the data. Special emphasis is on the density and entropy density and their ratio in the T- μ plane that show the effect of multi-quark cluster formation and dissociation.

*) This work was initiated by Peter Schuck at the ECT Trento Workshop on "Light Clusters in Nuclei and Nuclear Matter: Nuclear Structure and Decay, Heavy Ion Collisions, and Astrophysics "(2019)

Wednesday 16:00-18:00 / 174

The neutron star crust in the liquid phase

Auteur: Francesca Gulminelli[1]

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The crust and mantle of neutron stars are exceptional laboratories for the theoretical study of clustering in nuclear matter, and their specific transport properties are known to play an important role in many different observable phenomena, such as the thermal emission of X-ray pulsars, quasi-periodic oscillations, giant flares, pulsar glitches, just to cite a few.
Thanks to density functional theory, the composition and properties of crustal matter is relatively well known at zero temperature. The finite temperature problem has been much less addressed in the literature ; still, neutron stars are born hot, and the crustal ions as well as the non-spherical « pasta » nuclear clusters are in the liquid phase at all temperatures beyond about 10^10 K. In such a configuration, the ions are put into collective motion, the simplifying one-component Wigner-Seitz approximation is not valid, and the collective entropy contributions can strongly affect the thermodynamic and transport properties, as well as the composition of matter. This finite temperature modelling might also have some relevance in the late cooling stage of the neutron stars. Indeed, if the cooling is sufficiently fast, the crust composition might be frozen before the catalyzed configuration is reached. Notably, the cooling history of a neutron star is imprinted in the presence of impurities in the crustal lattice, that are at the origin of the highly resistive behavior of the crustal mantle.

In this contribution, I will present our latest results concerning the thermodynamic and transport properties of the neutron star crust in the liquid phase [1-5]. Concerning static properties, I will discuss the effect of going beyond the one-component plasma approximation and including a renormalization of the ion mass calculated in the hydrodynamic limit. Concerning transport, I will present analytical expressions for the anisotropic collision frequencies in the pasta phase using the Boltzmann equation in the relaxation time approximation, and numerical results for the associated electrical and thermal conductivities.

1. S.Mallik and F.Gulminelli, Statistical treatment of nuclear clusters in the continuum, PRC 103 (2021) 015803

2. T.Carreau, A.F.Fantina and F.Gulminelli, Inner crust of a neutron star at the point of crystallization in a multicomponent approach, A&A 640, A77 (2020).

3. M.R.Pelicer, D.P.Menezes, C.C.Barros Jr., F.Gulminelli, Fluctuations in the nuclear pasta phase, PRC 104 (2021) L022801

4. H.Dinh Thi, A.F.Fantina, F.Gulminelli, The proto-neutron star inner crust in the liquid phase, A&A, submitted

5. M.R.Pelicer, M.Antonelli, D.P.Menezes, F.Gulminelli, Anisotropic electron transport in the nuclear pasta phase, MNRAS, submitted

Thursday 09:15-10:45 / 169

Josephson effect at finite temperature throughout the BCS-BEC crossover with the inclusion of pairing fluctuations

Auteurs: Giancarlo Calvanese Strinati[1]; Leonardo Pisani[1]; Verdiana Piselli[2]

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The BCS-BEC crossover is a research topic common to ultra-cold Fermi gases and the nuclear matter [1]. It represents a useful tool for testing fundamental theories such as the connection between superconductivity and fermionic superfluidity. At zero temperature, a reasonable description of this crossover can be obtained by a mean-field approach. In fact, this approximation provides accurate enough results even at finite temperature provided that the Cooper pair size is much larger than the average inter-particle distance (weak inter-particle interaction). However, a mean-field approach fails when the Cooper pair size is comparable or even smaller than the average-interparticle distance (strong-interparticle interaction). In this case it is necessary to include pairing fluctuations beyond mean-field to obtain reliable results [2]. In the present work, we include pairing fluctuations over and above mean-field in the LPDA (Local Phase Density Approximation) equation, which is a coarse-grained version of the Bogoliubov-de Gennes equations. The LPDA equation is a (highly) non-linear differential equation for the gap parameter, which allows one to study inhomogeneous superfluid systems with a considerably reduced computational time and memory space with respect to the original Bogoliubov-de Gennes equations [3]. In particular, in the present work we address the Josephson effect using a modified (mLPDA) version of the LPDA equation which includes pairing fluctuations on top of the original equation. We show that the outcomes of our numerical simulations for the coupling and temperature dependence on the critical current favorably compare to recent experimental results obtained at LENS with ultra-cold Fermi gases [4,5].

[1] Giancarlo Calvanese Strinati, Pierbiagio Pieri, Gerd Röpke, Peter Schuck, and Michael Urban. The BCS-BEC crossover: From ultra-cold Fermi gases to nuclear systems. *Physics Reports*, 738:1-76, April 2018.
[2] P. Pieri, L. Pisani, and G. C. Strinati. Bcs-bec crossover at finite temperature in the broken-symmetry phase. *Phys. Rev. B*, 70:094508, Sep 2004.
[3] S. Simonucci and G. C. Strinati. Equation for the superfluid gap obtained by coarse graining the bogoliubov˘de gennes equations throughout the bcs-bec crossover. *Phys. Rev. B*, 89:054511, Feb 2014.
[4] W. J. Kwon, G. Del Pace, R. Panza, M. Inguscio, W. Zwerger, M. Zaccanti, F. Scazza, and G. Roati. Strongly correlated superfluid order parameters from dc josephson supercurrents. *Science*, 369(6499):84-88, 2020.
[5] G. Del Pace, W. J. Kwon, M. Zaccanti, G. Roati, and F. Scazza. Tunneling transport of unitary fermions across the superfluid transition. *Phys. Rev. Lett.*, 126:055301, Feb 2021.

Thursday 09:15-10:45 / 196

Ultracold fermions: from Nuclear to Atomic Physics

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Thursday 09:15-10:45 / 164

Three-body contact of the resonant Fermi gas

Auteurs: Félix Werner[1]; Xavier Leyronas[2]

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For fermions with two internal states and two-body interactions of large scattering length a, we express the number of nearby fermion triplets in terms of a quantity C_3 , the three-body contact.

We calculate the three-body contact in a high-temperature regime, similar to a virial expansion. First, at the unitary limit, we use a wave-function approach and we find an analytical formula for the three-body contact in this case. Second, we use a diagrammatic approach in the BEC-BCS crossover. In this approach, the non-trivial scaling of the three-body correlation function is recovered, and we are able to calculate the three-body contact by numerically solving the 3-body problem. At unitarity, we numerically recover the result of the wave-function approach. These calculations could be used as benchmarks for comparisons with experiments.

Thursday 11:15-12:45 / 182

Microscopic energy density functional: Success and limitations

Auteur: Marcello Baldo[1]

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Thursday 11:15-12:45 / 167

Constructing nuclear functionals for neutron stars and nucleosynthesis applications

Auteur: Guilherme Grams[1]

Co-auteurs: Wouter Ryssens [2]; Guillaume Scamps [3]; Stephane Goriely [4]; Nicolas Chamel [4]

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Describing all different neutron star layers within a unified framework is a challenge in view of the very wide range of densities encountered. The description of massive pulsars such as J1614-2230 and J0740+662 [1], for example, brings the requirement of a stiff neutron matter equation of state in order to balance the strong gravity field of these compact objects. Additionally, the description of the rapid neutron-capture process (or r-process) nucleosynthesis taking place in neutron-star mergers requires detailed knowledge of nuclear reactions and radioactive decays (hence of the nuclear-structure properties, in particular nuclear masses) for a few thousand exotic neutron-rich nuclei. The challenge for nuclear theory is then the construction of a model that accurately describes: (i) masses of neutron-rich nuclei present in the crust of neutron stars, and (ii) masses of all the neutron-rich potentially produced during the r-process nucleosynthesis, together with (iii) a stiff enough neutron matter equation of state to explain the most massive observed pulsars.
A new family of microscopic nuclear energy density functionals and associated nuclear mass models have been recently proposed [2]. The Brussels-Skyrme-on-a-Grid (BSkG) functionals have the advantage of being based on the concept of utmost symmetry breaking for exotic nuclear configuration, allowing for exotic shapes like for instance triaxial or octupole deformation during the adjustment process. To compensate for the increase in computational cost, machine learning techniques were employed to optimize the parameter adjustment.

We show in this contribution the latest parametrization BSkG3, which greatly improves the infinite nuclear matter properties of BSkG functionals. To do so, we follow the procedure of Ref. [3] and use an extended form of the Skyrme functional to ensure a stiff enough neutron-matter equation of state at high densities. This new functional BSkG3 is consistent with observations of heavy pulsars. Furthermore, we include a pairing interaction designed to match the 1S0 pairing gaps in infinite nuclear matter deduced from ab-initio calculations. The latter is particularly important for a reliable description of superfluids in neutron stars. Both improvements, combined with our state-of-the-art description of atomic nuclei and simultaneous accurate description of many different observables, including in particular nuclear masses for thousands of nuclei, make BSkG3 a tool of choice for applications in nuclear structure and astrophysics.

[1] P. B. Demorest, et. al, Nature 467, 1081 (2010); .M.C. Miller et al., ApJL 918, L28 (2021); T.E. Riley et al., ApJL 918, L27 (2021).
[2] G. Scamps et al., Eur. Phys. J. A 57, 333 (2021); W. Ryssens et al., Eur. Phys. J. A 58, 246 (2022).
[3] N. Chamel, S. Goriely and J. M. Pearson, Phys. Rev. C 80, 065804 (2009).

Thursday 11:15-12:45 / 161

Machine learning light hypernuclei

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We employ a feed-forward artificial neural network to extrapolate at large model spaces the results of ab-initio hypernuclear No-Core Shell Model calculations for the Λ separation energy B_Λ of the lightest hypernuclei, ${}^3_\Lambda$H, ${}^4_\Lambda$H and ${}^4_\Lambda$He, obtained in computationally accessible harmonic oscillator basis spaces using chiral nucleon-nucleon, nucleon-nucleon-nucleon and hyperon-nucleon interactions. The overfitting problem is avoided by enlarging the size of the input dataset and by introducing a Gaussian noise during the training process of the neural network. We find that a network with a single hidden layer of eight neurons is sufficient to extrapolate correctly the value of the Λ separation energy to model spaces of size $N_{max} = 100$. The results obtained are in agreement with the experimental data in the case of ${}^3_\Lambda$H and the 0^+ state of ${}^4_\Lambda$He, although they are off of the experiment by about 0.3 MeV for both the 0^+ and 1^+states of ${}^4_\Lambda$H and the 1^+ state of ${}^4_\Lambda$He. We find that our results are in excellent agreement with those obtained using other extrapolation schemes of the No-Core Shell Model calculations, showing this that an ANN is a reliable method to extrapolate the results of hypernuclear No-Core Shell Model calculations to large model spaces.

Thursday 14:00-16:00 / 195

Pairing dynamics in nuclear collisions

Auteurs: Andrzej Makowski[1]; Piotr Magierski[1]; Kazuyuki Sekizawa[None]; Gabriel Wlazłowski[None]; Matthew C. Barton[None]

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I will present the results of nuclear collisions involving medium mass or heavy nuclei, obtained within time-dependent density functional theory (TDDFT) extended to superfluid systems. I will discuss the possible manifestations of pairing dynamics in nuclear collisions, at the vicinity of the Coulomb barrier. These include the mechanism for the increase of the barrier for capture generated by solitonic excitation appearing as a result of pairing phase distortion. Moreover, I will discuss pairing instability occuring in di-nuclear system formed by merging magic nuclei which lead to significant enhancement of pairing correlations.

Thursday 14:00-16:00 / 176

Fission properties of r-process nuclei predicted with the BCPM energy density functional

Auteur: Samuel Andrea Giuliani[1]

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The rapid neutron capture process, or r process, is responsible for the production of about half of the elements heavier than iron found in nature, including the heaviest uranium and thorium. During the r process, several thousands of neutron-rich nuclei are synthesized in few seconds, powering an electromagnetic transient known as kilonova. Since most of such exotic nuclei have never been experimentally observed due to their exceedingly short half-lives, the estimation of abundances and kilonova light curves must rely upon the theoretical predictions of nuclear properties. During this talk, I will present calculations of nuclear properties obtained with the Barcelona-Catania-Paris-Madrid energy density functional (EDF) and their impact on the r process. In particular, I will focus on the nucleosynthesis of translead elements in the merger of two neutron stars, and the role that nuclear masses, beta decays and fission play in shaping the r-process abundances and kilonova light curves.

Thursday 14:00-16:00 / 170

Superfluid dynamics in neutron stars

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Produced during gravitational-core collapse supernova explosions with initial temperatures as high as ~10^{12} K, neutron stars cool down to temperatures 10^9 K within a few days. The very dense matter in their interior is expected to undergo various quantum phase transitions analogous to those observed in terrestrial laboratories. Similarly to electrons in conventional terrestrial superconductors, free neutrons in the inner crust and the outer core of neutron stars are predicted to form a Bardeen-Cooper-Schrieffer (BCS) condensate of Cooper pairs. Nuclear superfluidity has found support from the rapid decline of luminosity of the Cassiopeia A remnant and has been corroborated by radio-timing observations of frequency glitches in numerous pulsars.

Despite the importance of the superfluid dynamics for interpreting these latter astrophysical phenomena, most microscopic calculations of the nuclear pairing properties have been carried out so far for static situations. We have recently studied the dynamics of hot neutron-proton superfluid mixtures within the self-consistent time-dependent nuclear energy density functional theory [1,2]. In application to neutron stars, we have computed $^1S_0$ neutron and proton pairing gaps in the homogeneous core in the presence of arbitrary currents and we have determined the mutual neutron-proton entrainment coupling coefficients [3].

We have also shown within the same framework that there exists a dynamical "gapless"state in which nuclear superfluidity is not destroyed even though the energy spectrum of quasiparticle excitations exhibits no gap. The absence of an energy gap leads to a nucleon specific heat that is very different

from that in the classical BCS state (in the absence of superflows). The implications for the cooling of neutron stars will be discussed.

[1] N. Chamel & V. Allard, Phys. Rev. C **100**, 065801 (2019).
[2] V. Allard & N. Chamel, Phys. Rev. C **103**, 025804 (2021).
[3] V. Allard & N. Chamel, Universe **7**, 470 (2021).

Thursday 14:00-16:00 / 181

Scalar field, nucleon structure and relativistic chiral theory for nuclear matter

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