Neutron stars: the equation of state, superconductivity/superfluidity and transport coefficients (PHAROS WG1+WG2 meeting)

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PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

Book of Abstracts

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Light and heavy clusters in warm stellar matter

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At densities below the nuclear saturation density and not too high temperatures (T<20 MeV), core-collapse supernova matter is unstable with respect to density fluctuations such that inhomogeneous structures develop and clusters can appear. Light (deuterons, tritons, helions, α-particles), and heavy (pasta phases) nuclei can be expected. Their appearance can modify the neutrino transport, which will have consequences in the dynamical evolution of supernovae and the cooling of proto-neutron stars. In this talk, light and heavy clusters are calculated for warm stellar matter in the framework of relativistic mean-field models, in the single-nucleus approximation. The clusters abundances are determined from the minimization of the free energy. In-medium effects of light cluster properties are included by introducing an explicit binding energy shift analytically calculated in the Thomas-Fermi approximation, and the coupling constants are fixed by imposing that the virial limit at low density is recovered. The resulting light cluster abundances come out to be in reasonable agreement with constraints at higher density coming from heavy ion collision data. Some comparisons with microscopic calculations are also shown.

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The effect of dissipation on radial pulsations of neutron stars

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The recent discovery of neutron stars (NSs) with current gravitational-wave experiments gives us an unprecedented opportunity to probe the dynamical behaviour of compact stars. The viscous (and thermal) dissipation plays a fundamental role in the dynamical equations of motion of NSs. It has a damping influence on the oscillation modes and directly determines the minimum period of pulsars that is expected to be observed. We have studied radial pulsations of plausible NS models with various families of EoS in the presence of viscosity (and thermal conductivity) in the neutron matter. We have shown that the stellar pulsation equations can be cast in a nearly Sturm–Liouville form (just like the non-dissipative systems) and converted to a system of finite difference equations for numerical evaluation. We chose a second-order accurate differencing scheme so the resulting system of equations emerges as a tridiagonal matrix eigenvalue problem. Since radial oscillations do not couple to gravitational radiation, it is relatively easy to numerically solve the eigenvalue problem that leads to a discrete set of oscillation frequencies. In the absence of any dissipative process, the oscillation spectrum of a stable stellar model forms a complete set. It is therefore possible to describe any arbitrary periodic radial motion of a NS as a superposition of its various eigenmodes.

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The hydrodynamics of superfluid vortex avalances in neutron stars

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Neutron Stars offer a unique opportunity to study the fundamental physics in extreme conditions. Physical properties of Neutron Stars are believed to be affected by the presence of superfluid matter inside that is connected with pulsar glitches. To study the latter the dynamics of quantized vorticity is used in the most models. However, the problem of establishing connection between the properties on the micro and macro scales still remains unsolved.

We took a first step towards developing a mean field prescription to include the dynamics of vortices in large scale hydrodynamical simulations of superfluid neutron stars. It is shown that allowing for vortices to accumulate and induce differential rotation in the neutron superfluid leads to propagating waves, or 'avalanches', as solution for the equations of motion for the superfluid velocities. The additional variable, namely fraction of free vortices, is introduced. It's found that the new terms contribute linearly to the rise of a glitch, and that, in specific setups, they can give rise to glitch precursors and even to decreases in frequency, or anti-glitches.

We have applied our model to the glitches in the Vela and Crab pulsars, considering two separate cases in which glitch originates either in the crust or in the core, and obtained constraints on the values of the mutual friction parameter, that governs the coupling between the superfluid and the normal fluid.

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Probing the neutron stars interior within the realistic equation of state with induced surface tension

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We apply the novel equation of state, which includes the surface tension contribution induced by the interparticle interaction and the asymmetry between neutrons and protons, to the study of neutron star properties. This high-quality equation of state is obtained from the virial expansion for the multicomponent particle mixtures that takes into account the hard-core repulsion between them. The considered model is in full concordance with all the known properties of normal nuclear matter, provides a high quality description of the proton flow constraints, hadron multiplicities created during the nuclear-nuclear collision experiments and equally is consistent with astrophysical data coming from neutron star observations. The analysis suggests that the best model parametrisation gives the incompressibility factor K0, symmetry energy J and symmetry energy slope L at normal nuclear density equal to 200 MeV, 30 MeV, and 113.28–114.91 MeV, respectively. The found mass-radius relation for neutron stars computed with this equation of state is consistent with astrophysical observations.

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From quantum theory of nuclear matter to hydrodynamics of neutron stars.

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Neutron stars are the biggest objects in the universe that are thought to contain superfluid matter. However, almost fifty years after the first observation of pulsar, detailed theory of dynamics of the stellar interior still remains open to debate.
The reason for that is a large discrepancy of length scales - quantum theory operates at distances of fm and have to provide input to relativistic hydrodynamics describing motion of matter at ranges of km. In my talk I will propose a consistent connection between microscopic and macroscopic theory with an intermediate step –mesoscopic model. This model is validated by underlying quantum approach and can be utilized to construct hydrodynamic equations.
To illustrate the procedure I will concentrate on a case of neutron star crust, where nuclei immersed in neutron superfluid are expected to coexist with quantum vortices. After presentation of preliminary vortex-nuclei scattering simulations in quantum regime, I will demonstrate how obtained results can be used to legitimize semi-classical treatment of vortex moving through the lattice of nuclear impurities.
Due to strict validation, the proposed hierarchy of models can be considered as possibly the most accurate way to investigate the origin of dynamical phenomena like glitches (events of sudden spin-up of a whole neutron star).

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Pion condensation and the QCD phase diagram at finite isospin density

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In this talk I will discuss various aspects of pion condensation at finite temperature and density. At T=0, the phase diagram will be mapped out in the mu_I-mu_B plane, and we will discuss the competition between an inhomogeneous chiral condensate and a pion condensate. At finite T, we map out the phase diagram in the mu_I-T plane focusing on the deconfinement and chiral transitions as well as the onset of pion condensation. Comparison with recent lattice data will be made.

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EOS dependence of the proto-neutron stars evolution

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We explore the Equation Of State (EOS) dependence of the proto-neutron star (PNS) evolution for the first tens of seconds after the core bounce in spherical symmetry.
In particular, we determine the neutrino signal on terrestrial detectors and the frequencies of the gravitational waves due to stellar oscillations.
In our study we consider a nuclear many-body theory EOS, the mean-field GM3 EOS, and the Lattimer-Swesty EOS.
These EOSs are included in a thermodynamical consistent way with a new fitting formula for the interacting free energy at arbitrary temperature and composition.
Moreover, the neutrino mean free paths are determined consistently with the underlying EoS, accounting for the EOS-dependent baryon in-medium effects with the proton and neutron effective masses and single particle potentials.

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Transition and crustal properties in neutron stars

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The modelling of neutron stars requires the determination of the point of the transition between the core and the crust of the star. In this work, the core-crust transition is studied with finite-range nuclear interactions using the dynamical method for detecting the instability of the matter in the core against density perturbations. We analyze the correlation of the transition properties such as the density and pressure with the slope of the symmetry energy associated to the nuclear equation of state. Knowing the core-crust transition point for these finite-range forces, we compute the relation between the neutron star masses and radii, as well as the mass, thickness and moment of inertia of the neutron star crust.

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Constraining the nuclear matter EoS from the GW170817 merger event

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The observation of NS allows us to constrain the equation of state(Eos) of the dense matter well beyond the densities available in earth laboratories. For example, observations of the NS mass-radius relation and the mass–moment-of-inertia relation can be used to infer the NS Eos within a certain uncertainty. However, the mass of several NS are known with good precision but their radii still suffer from large uncertainty which leads to a weaker constraint on Eos. The recent observation of gravitational waves GW170817, and its electromagnetic counterparts allows us to constrain the dense matter Eos in new and complementary ways. The upper limit of the tidal deformability is put on by the merger event and the lower limit by the kilonova AT2017gfo signal. This translates into an allowed window for the radius of the 1.4Mo stellar configuration between~11.5 and 13. 5km. In this case, we calculate neutron star's moment of inertia and tidal deformability using various microscopic Eos which are derived based on two- and three-body realistic nucleon interaction for nuclear and hybrid star configurations. We show that they are fully compatible with constraints imposed by interpretation of the first observed neutron-star merger event.

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Glitches as an indirect probe for the internal physics of pulsars

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Issues involving nuclear superfluidity are thought to play key roles for neutron star phenomenology. Pulsar glitches (sudden jumps in the period of otherwise steadily spinning down pulsars) offer a glimpse into the superfluid interior of a neutron star: within the currently accepted scenario these timing irregularities are explained in terms of an expulsion of the quantized vortex lines that permeate the superfluid region. Vortex pinning to ions in the crust can provide the mechanism for storing the angular momentum which can be eventually released during a glitch. A consistent model for the angular momentum reservoir of pinned vorticity gives a general and quantitative inverse relation between size of the maximum glitch and the pulsar mass, allowing to put some limits on the mass of a pulsar.

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CompOSE

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CompOSE (CompStar Online Supernovae Equations of State) is a repository of equation-of-state (EoS) tables for use in astrophysical simulations like core-collapse supernovae or neutron-star mergers. They contain information on thermodynamic properties of compact-star matter, its chemical composition and on microscopic quantities. The data are stored in a simple but flexible format. In addition, programs are available for extracting original and derived data from the EoS tables according to the needs of the user. The service is accessible at compose.obspm.fr with additional information and online features. In this contribution the status of the projects will be presented and possible further developments and extensions will be discussed.

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The role of mass, equation of state and superfluid reservoir in pulsar glitches

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In the interior of a mature neutron star, the differential rotation of the neutron superfluid star with respect to the normal component allows to store angular momentum, which is released during a pulsar glitch. Recent preliminary studies show how it is in principle possible to estimate pulsar masses from observations related to their timing properties. In this talk we will present a generalisation of a previous model for the stratified reservoir of a neutron star when describing glitches, by examining the possibility of different extensions of the S-wave superfluid domain. In particular, we study the dependence of the glitcher's mass inferred within this model on the still uncertain extension of the region in which the $^1S_0$ neutron pairing gap is big enough to allow for superfluity. Hence, we can quantify the general expected trend that to a smaller extension of the $^1S_0$ pairing channel's region should correspond a smaller mass estimate. The employment of different equations of state for the star matter does not affect the general tendency described above: future independent estimates of masses of a couple of objects in our sample has the potential to calibrate our results and put indirect constraints on the microphysics of neutron stars.

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EOS effects on NS mergers

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We study in detail the deconfinement phase transition that takes place in hot/dense nuclear matter in the context of neutron stars and neutron star mergers. For this purpose, the Chiral Mean Field (CMF) model, an effective relativistic model that includes self-consistent chiral symmetry restoration and deconfinement to quark matter, is employed.

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Constraining the equation of state with GW170817

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With the detection of GW170817 we have observed the first multi messenger signal
from two merging neutron stars. This signal carried a multitude of information

about the underlying equation of state of nuclear matter.
I will demonstrate how this observation can be used
to constrain macroscopic properties of neutron stars, in particular the radius and the maximum mass and hence to set limits on the equation of state. I will also comment on the possibility of how we can use future gravitational wave detections in order to set limits on the existence of twin stars. Finally, I will briefly comment on the detectability of a quark-hadron phase transition in a neutron star merger event.

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Non-uniform matter and cluster distribution in core-collapse supernova

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In most core-collapse supernova (SN) simulations, the equation of state (EoS) has been usually modelled within the single-nucleus approximation. In this approach, the ensemble of nuclei expected to be present in the medium is replaced by one (average) nucleus. Although this approximation is adequate to predict thermodynamic properties of the medium in the temperature-density range of interest, a full statistical distribution is required to properly describe microscopic processes where reaction rates on specific nuclei are required (e.g., the electron capture).

In this contribution, a formalism to include a cluster distribution within the Nuclear Statistical Equilibrium (NSE) model in an EoS of hot stellar matter at subsaturation density is presented. A particular case, where this method is applied to an EoS for supernova simulations, will be discussed.

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Non-dissipative fluid couplings in rotating superfluid neutron stars and application to pulsar glitches

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We have computed stationary and axisymmetric configurations of uniformly rotating superfluid neutron stars in a fully general relativistic framework with realistic equations of state. At low rotation rates, the neutron superfluid and the rest of the star are not only coupled by entrainment, but general relativity leads to an additional coupling through frame-dragging effects, which is likely to affect the dynamics of superfluid neutron stars. Using a quasi-stationary approach, we then discuss the role of general relativity on the global dynamics of giant pulsar glitches.

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Cooling of hypernuclear compact stars

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We study the thermal evolution of hypernuclear compact stars constructed from covariant density functional theory of hypernuclear matter and parameterizations which produce sequences of stars containing two-solar-mass objects. For the input in the simulations, we solve the BCS gap equations in the hyperonic sector and obtain the gaps in the spectra of Λ, Ξ^0 and Ξ^- hyperons. For the models with masses $M/M_\odot \geq 1.5$ the neutrino cooling is dominated by hyperonic direct Urca processes in general. In the low-mass stars the (Λp) plus leptons channel is the dominant direct Urca process, whereas for more massive stars the purely hyperonic channels $(\Sigma^-\Lambda)$ and $(\Xi^-\Lambda)$ are dominant. Hyperonic pairing strongly suppresses the processes on Ξ^-s and to a lesser degree on Λs. We find that intermediate-mass $1.5 \leq M/M_\odot \leq 1.8$ models have surface temperatures which lie within the range inferred from thermally emitting neutron stars, if the hyperonic pairing is taken into account. Most massive models with $M/M_\odot \simeq 2$ may cool very fast via the direct Urca process through the (Λp) channel because they develop inner cores where the S-wave pairing of Λs and proton is absent.

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Effects of the tetraneutron condensation in neutron stars

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Based on recent experimental and theoretical hints on possible formation of a resonant four-neutron system we study effects of appearance of such a cluster in neutron rich baryon matter inside NSs. For this purpose we employ a relativistic mean field approach which includes nucleons, Δ-baryons as well as light nuclear clusters. Our analysis demonstrates that tetraneutrons existing as the Bose-Einstein condensate can affect the equation of state of cold baryonic matter and observable characteristics of neutrons stars. Tetraneutron driven suppression of Δ-baryons is another important result of our study. Influence of tetraneutrons on formation of superconducting phase is also discussed.

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Bulk Viscosity in Neutron Star Cores with Modern Hyperonic Equations of State

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Bulk viscosity of neutron star cores is responsible for a number of interesting phenomena, e.g., r-mode stabilization [1] and magnetic inclination-angle evolution [2]. It originated because of non-equilibrium particle mutual transformations in dense stellar plasma, and strongly depends on the actual core composition. It is well-known that account for hyperons in the core dramatically increases

the bulk viscosity comparing to purely nucleonic one [3]. Modern equations of state, calibrated to the up-to-date hypernuclear data (e.g., [4,5]), predict that hyperons are mainly presented in the form of Λ's and Ξ^-'s, while all the existing calculations of the non-equilibrium reaction rates ([3,6,7] and others) have been performed for $\Sigma^-\Lambda$ hyperonic composition.

In the present work we fill this gap by calculating the bulk viscosity for $npe\mu\Lambda\Xi^-$ matter. A number of viscosity-generating nonequilibrium reactions is considered, some of them have never been studied in the neutron-star literature before. The calculated reaction rates and bulk viscosity are approximated, for a number of realistic equations of state, by simple analytic formulas, in order to facilitate their use in applications. Possible consequences of our results for the r-mode physics are briefly discussed.

References
[1] Haskell, B. 2015, IJMPE, 24, 1541007.
[2] Lander, S. K. & Jones, D. I. 2018, arXiv:1807.01289.
[3] Lindblom, L. & Owen, B. J. 2002, PRD, 65, 63006.
[4] Fortin, M., Avancini, S. S., Providência, C., et al. 2017, PRC, 95, 65803.
[5] Jie Li, J., Long, W. H. & Sedrakian, A. 2018, arXiv:1801.07084.
[6] Haensel, P., Levenfish, K. P. & Yakovlev, D. G. 2002, A&A, 381, 1080.
[7] van Dalen, E. N. & Dieperink, A. E. 2004, PRC, 69, 25802.

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Strains and stresses in rotating neutron stars

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The breaking of a neutron star crust is believed to play a fundamental role in some astrophysical phenomena like glitches, flares and the emission of gravitational waves from isolated compact objects. However, there is still lack of systematic (and quantitative) studies of the crustal deformation under different types of loads, which can be induced by rotation, pinning of superfluid vortices into the crustal lattice and magnetic fields. We introduce a simple Newtonian model that allows calculating the displacements, stresses, and strains due to a chosen force on a self-gravitating, compressible neutron star (NS). The object under study is here divided into two layers, an inner fluid core and an elastic crust, but with our approach an arbitrarily large number of layers are possible. As a first case of study we introduce the polytropic relation $n = 1$ as equation of state for the matter inside the NS and, considering rotation as the perturbating force, we study the impact of different adiabatic indexes (simulating different astrophysical scenarios) and mass on the calculated quantities. We obtain that small variation in the adiabatic index cause large variations in the response of the star, both in displacements and strains, and explain what is the physic behind this behaviour. Moreover, we show that the deformation of a NS due to rotation is larger for lighter stars. Finally, we calculate that the strain developed between two glitches is orders of magnitude smaller than the lowest expected breaking strain.

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Temperature-dependent oscillation modes in rotating superfluid neutron stars

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We calculate the spectrum of inertial oscillation modes in a slowly rotating superfluid neutron star, including for the first time both effects of finite temperatures and entrainment between superfluid neutrons and protons. We work in Newtonian limit and assume minimal core composition (neutrons, protons and electrons). We also developed an approximate method that allows to calculate the superfluid r-mode analytically. Lastly, we derive and analyze a dispersion relation for inertial modes in superfluid NS matter in a short wavelength limit.

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Superfluid matter and its elementary excitations

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The role of superfluidity for the transport processes in Neutron Stars is briefly discussed. The emphasis will be on the different elementary excitations that can occur in the superfluid matter. A throughout microscopic study of the excitations in different physical conditions inside Neutron Stars is presented and discussed. The results include the overall strength functions of the electron, proton and neutron components, which in particular indicate the rate of damping of the excitations.

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Imprints of a neutron star's history on its magnetic field

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Because a neutron star's magnetic field is likely to evolve very slowly, present-day magnetic fields will bear imprints of the star's early life. In particular, for stronger magnetic fields the star will achieve hydromagnetic equilibrium whilst still in the proto-neutron star phase, meaning that finite-temperature effects should be accounted for. Slightly later, the crust (and pasta regions) begins to form and the core protons condense into a superconducting state, again affecting the magnetic-field distribution of the star. We discuss how better modelling of the (macroscopic) magnetic field of a mature neutron star thus depends on microphysics from shortly after its birth.

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A 2.3 Solar-mass neutron star

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The macroscopic properties of neutron stars depend on how sub-atomic particles interact in their interiors. These interactions, encoded in the equation of state, are specially uncertain in the central regions, where densities exceed that of an atomic nucleus. The maximum mass of a neutron star can discriminate between proposed equations of state. New millisecond pulsars in compact binaries provide a good opportunity to search for the most massive neutron stars. We present observations and detailed modeling of an extremely irradiated companion to a millisecond pulsar, using the largest optical telescope on Earth. We develop and apply a new method to measure the velocity of both sides of the companion star, and find that the binary hosts one of the most massive neutron stars known to date, with a mass of 2.27[+0.17-0.15] MSun. A 2.3 Solar-mass neutron star would rule out most currently proposed equations of state, casting doubt on the existence of exotic forms of matter in the core.

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Asymmetry of the neutrino mean free path in hot neutron matter under strong magnetic fields

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The neutrino mean free path in neutron matter under a strong magnetic field is evaluated for the inelastic scattering reaction and studied as a function of the neutron matter density in the range $0.05 \leq \rho \leq 0.4$ fm^{-3} for several temperatures up to 30 MeV and magnetic field strengths B=0 G, 10^{18} G and 2.5×10^{18} G.
Polarized neutron matter is described within the non−relativistic Brueckner−Hartree−Fock (BHF) approach using the Argonne V18 nucleon-nucleon potential supplemented with the Urbana IX three-nucleon force. Explicit expressions of the cross section per unit volume for the scattering of a neutrino with a spin up or spin down neutron are derived from the Fermi Golden rule. Our results show that the mean free path depends strongly on the angle of the incoming neutrino, leading to an asymmetry in this quantity. This asymmetry depends on the magnetic field intensity and on the density, but it is rather independent of the temperature. For a density of 0.16 fm^{-3} at a temperature T= 30MeV, the asymmetry in the mean free path is found to be of $\sim 15\%$ for B=10^{18}G and $\sim 38\%$ for B=2.5×10^{18}G.

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Transport in neutron stars

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I will give a review of transport properties of matter inside neutron stars and point out their significance for astrophysical observables. This will include various phases of the star, from the outer layers to the densest possible phases, such as deconfined quark matter. I will try to focus on general methods and principles, but also touch on specific open questions for future research.

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Depletion of the superfluid reservoir in neutron-star crust

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The breaking of translational symmetry leads to the depletion of the neutron superfluid reservoir in the inner crust of a neutron star, similarly to superfluid helium in porous media or cold atomic gases in optical lattices. During this talk, calculations of the neutron superfluid fraction will be reviewed, and some astrophysical implications will be briefly discussed.

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An overview of equation of state constraints from electromagnetic observations of neutron stars

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While the study of gravitational waves from merging neutron stars rises as a new tool for physics and astrophysics, observing the electromagnetic neutron stars still provides crucial information necessary to understand their interior composition, and therefore to place constraints on the equation of state of matter at extreme density. A few independent methods permit measurements of the neutron star radius, but the existence of potential systematic uncertainties have been pointed out for these methods. It is therefore necessary to pursue all these in parallel to permit inter-comparison their results. This talk will present an overview these methods to measure the neutron star properties, their recent results, and I will discuss the various observational ways to address the potential systematic uncertainties that may affect the measurements.