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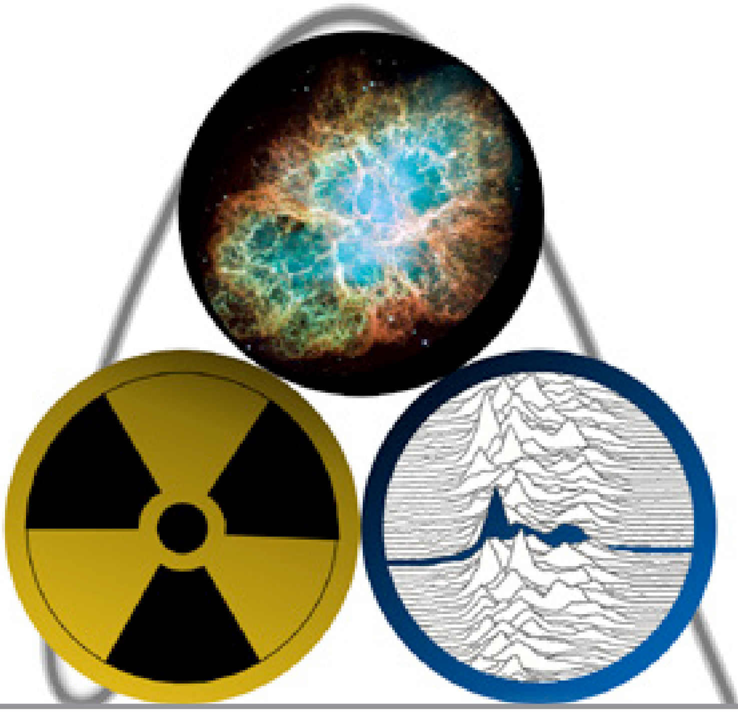
An interdisciplinary workshop

Neutron Stars: Nuclear Physics, Gravitational Waves and Astronomy

29 - 30 July 2013



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UNIVERSITY OF SURREY

Department of Physics

Welcome

Dear colleague,

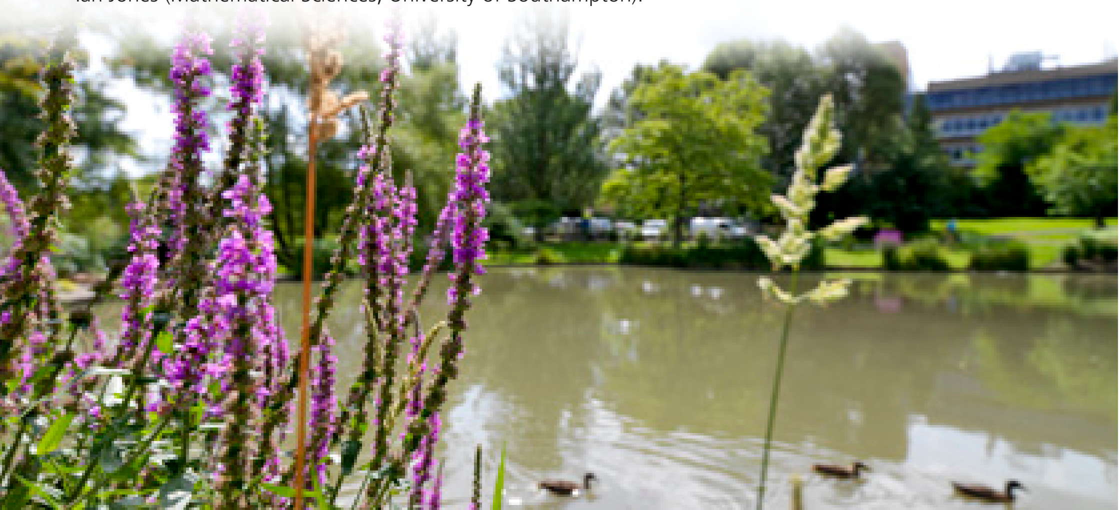
It is with great pleasure that we welcome you to this two-day workshop on "Neutron stars: Nuclear Physics, Gravitational Waves and Astronomy". As is made clear by our title, and underlined by our somewhat tounge-in-cheek logo, our aim is for this to be a genuinely inter-disciplinary affair. Indeed, the participant list consists of experts in several different fields. There are a number of speakers from the equation-of-state community, themselves spanning a wide range of expertise, from the analysis of real laboratory data to the calculation of EoS parameters for input into astrophysical simulations. The field of gravitational wave astronomy is represented, with everyone looking forward to when the new advanced detectors start taking data, probably sometime in 2015 or so, with the first detections hopefully following not too long after. Finally, the "traditional" astrophysical community is well represented too, a reminder that there are many electromagnetically-derived neutron star observations that still, after nearly half a century of study, remain to be properly explained. We hope you all manage to learn something from this meeting, and we remind you that this is a small affair, where a healthy and frank exchange of views and ideas is the aim - so please prepare to speak your minds!

We would like to thank the Institute of Advanced Studies and the Department of Physics of the University of Surrey for sponsoring and hosting this meeting. We would also like top thank you all for taking the trouble to come, and very much hope that you enjoy your time here in the University of Surrey.

Best wishes,

The Organisers

Arnau Rios and Paul Stevenson (Department of Physics, University of Surrey)
Ian Jones (Mathematical Sciences, University of Southampton).



Programme

Venue: School of Management, 32 MS 01
Monday (29 July)

08:45	**Registration and Coffee** (MS Foyer)
09:15	**Welcome - N Gilbert (IAS Director)**
09:30	**N. Andersson (Southampton)** *Neutron star superfluidity: from cooling to glitches*
10:20	**S. Lander (Tuebingen)** *The magnetic field in a superconducting neutron star*
10:40	**S. Clowes (Surrey)** *Spectroscopy of magnetic compact objects*
11:10	**Coffee** (MS Foyer)
11:30	**N. Chamel (Bruxelles)** *Vela pulsar glitches and nuclear superfluidity*
12:00	**A. van Eysden (NORDITA)** *Pulsar glitch recovery and properties of bulk nuclear matter*
12:20	**B. Haskell (AEI Potsdam)** *Modelling glitches in radio pulsars and magnetars*
12:40	**W. Ho (Southampton)** *Mass and radius of the Cassiopeia A neutron star and tests of superfluid and superconducting gaps*
13:00	**Lunch** (81 MS 02)
14:00	**N. Stergioulas (Thessalonika)** *Binary neutron star mergers and constraints on the EOS*
14:50	**M. Hempel (Basel)** *Equation of state effects in core-collapse supernova simulations*
15:10	**A. Bauswein (Garching)** *Equation of state dependence of gravitational waves, nucleosynthesis and optical transients from neutron-star mergers*
15:40	**Coffee** (MS Foyer)
16:00	**K. Glampedakis (Murcia)** *A new r-mode saturation mechanism*
16:30	**H.-T. Janka (Garching)** *Gravitational waves from core-collapse supernovae*
16:50	**P. Sutton (Cardiff)** *Searches for gravitational-wave bursts from neutron stars*
17:40	**Poster session and reception** (MS Foyer)
18:40	**Depart for dinner, Shere Village (transport organised)**

Venue: School of Management, 32 MS 01

Tuesday (30 July)

09:00	**Coffee** (MS Foyer)
09:30	**P. Danielewicz (Michigan State)** *Symmetry energy: from nuclei to neutron stars*
10:20	**Phil Goddard (Surrey)** *Why is lead so kinky?*
10:40	**L. Zana (Edinburgh)** *Measurement of the neutron radius of ^{208}Pb through parity violation in e^- scattering*
11:10	**Coffee** (MS Foyer)
11:30	**S. Zane (UCL)** *LOFT - Large Observatory for X-ray Timing*
12:00	**Anna Watts (Amsterdam)** *LOFT and the neutron star equation of state*
12:20	**A. Maselli (la Sapienza)** *I Love Q forever*
12:40	**D. Siegel (AEI Potsdam)** *The magnetorotational instability in relativistic hypermassive neutron stars*
13:00	**Lunch** (81 MS 02)
14:00	**B. Stappers (Manchester)** *Using pulsars to test gravity*
14:50	**A. Carbone (Barcelona)** *Nuclear and neutron matter with chiral forces*
15:10	**E. Kolomeitsev (Matej Bel)** *Excitation modes in superfluid nuclear matter and neutron star cooling*
15:40	**Coffee** (MS Foyer)
16:00	**J. Pons (Alicante)** *Too much pasta for pulsars to spin down*
16:30	**D. Watts (Edinburgh)** *Neutron skins from coherent pion photoproduction*
16:50	**M. Alford (St. Louis)** *Quark matter in neutron stars*
17:40	**Short discussion and close: A. Rios (Surrey)**
18:00	**Conclusion**

Keynotes

Quark matter in neutron stars

Mark Alford, Washington University in St Louis (USA)

The densest predicted state of matter is color-superconducting quark matter. This form of matter may well exist in the core of neutron stars, and the search for signatures of its presence is currently proceeding. I will discuss the features of color-superconducting quark matter, and discuss some ideas for finding it in nature.

Neutron star superfluidity: from cooling to glitches

Nils Andersson, University of Southampton (UK)

In this talk, I will summarise our understanding of how observations can teach us about nucleon superfluidity at the extreme densities present in a neutron star's core. I will discuss the theory behind these systems, introducing the main ideas from nuclear physics and laboratory superfluids, and show how observations are beginning to constrain the theory in a useful way. The examples will involve the observed real-time cooling of the young neutron star in Cassiopeia A and the enigmatic glitches seen in many young radio pulsars. I will conclude by describing other settings where superfluidity is likely to play an important role.

Symmetry energy: from nuclei to neutron stars

Pawel Danielewicz, Michigan State University & NSCL (USA)

The symmetry energy impacts the structure of neutron stars and of nuclei. Narrow constraints on the symmetry energy in the subnormal density region, following from the systematic of nuclear isobaric analogue states and from asymmetry skins are discussed. Plans for the determination of the symmetry energy at supranormal densities in heavy-ion collisions, using charged pion yields, are outlined. Implications for neutron-star structure of the current constraints are explored.

Using pulsars to test gravity

Benjamin Stappers, Jodrell Bank & University of Manchester (UK)

The extremely stable rotation rates of pulsars means that they can be used as precision instruments to study the extremes of physics. Amongst other things, they provided us with the first indirect evidence for gravitational wave emission. I will present some recent advances in the precision and types of gravity tests that have been possible with high precision pulsar timing of pulsars in binary systems. I will also discuss the use of an array of pulsars distributed across the sky to directly detect gravitational waves associated with a stochastic background of events in the early universe and also to try and detect burst events more locally. I will also discuss briefly the future prospects for these areas of research through the discovery of more extreme systems and the improvements in technology and telescopes like the Square Kilometre Array.

Binary neutron star mergers and constraints on the EOS

Nikolaos Stergioulas, University of Thessalonika (Greece)

There is a strong potential for constraining the high-density EOS of compact stars through gravitational-wave observations of binary neutron star mergers. In the talk we will give an overview of what can be learned on the structure of compact stars from the inspiral signal and from the post-merger signal, with emphasis on nonlinear post-merger oscillations. The detection of at least a single oscillation frequeny seems plausible with second-generation detectors. Third-generation detectors will enable the detection of additional nonlinear combination frequencies, opening the way for applying techniques of asteroseismology.

Searches for gravitational-wave bursts from neutron stars

Patrick Sutton, Cardiff University (UK)

Transient "bursts" of gravitational waves are expected to be produced by a variety of phenomena involving compact objects, such as core-collapse supernovae, pulsar glitches, and hypermassive neutron-star formation in binary mergers. Gravitational waves could provide a probe of these systems, which are typically difficult to model, and yield insights into the physics of matter at very high densities and in strong gravitational fields. However, the scientific exploitation of bursts presents a significant challenge: separating and characterising rare weak signals of unknown waveform from non-Gaussian, non-stationary background noise. I will introduce some of the techniques developed to search for gravitational-wave bursts, review highlights of results from LIGO, Virgo, and GEO, and summarise prospects for gravitational-wave burst science with the advanced detector network.

Papers

Equation-of-state dependence of gravitational waves, nucleosynthesis and optical transients from neutron-star mergers

Andreas Bauswein, Max Planck Institute for Astrophysics (Garching, Germany)

By a representative set of hydrodynamical simulations we investigate the influence of the high-density equation of state on observable features of neutron-star mergers. The dependence of the gravitational-wave emission on the equation of state of neutron-star matter is addressed. On the basis of our survey, we point out a novel possibility to determine neutron-star radii from gravitational-wave detections of the postmerger phase of a neutron-star coalescence. This idea is based on the observation that the dominant oscillation frequency of the merger remnant correlates with the radii of neutron stars. The analysis also reveals constraints on other properties of neutron stars and the equation of state. The likelihood of a corresponding gravitational-wave observation is estimated. Moreover, nucleosynthesis calculations are presented showing a robust rapid neutron-capture process in the matter becoming gravitationally unbound by neutron-star collisions. The properties of optical transients which are powered by the radioactive decay of the freshly synthesized elements, are discussed as well. Also from these possibly observable signals information on the equation of state may be inferred.

Nuclear and neutron matter with chiral forces

Arianna Carbone, University of Barcelona (Spain)

The microscopic description of infinite nuclear systems is an open window onto the study of astrophysical compact objects. A basic aim of nuclear many-body theory is the full description of the microscopic and bulk properties of nuclear matter from a microscopic quantum-mechanical point of view. I will present advances in the Self-Consistent Green's Functions approach and discuss how this theory has been consistently expanded to include three-body nuclear forces. We will see how the inclusion of these forces helps symmetric nuclear matter approach its empirical saturation properties, and furthermore how the equation of state of pure neutron matter stiffens. This opens the way for an improved calculation of the density dependence of the symmetry energy, a crucial ingredient needed to understand many important properties of nuclei and neutron stars. I will conclude remarking the importance of continuously improving nuclear many-body physics, as a discipline strongly bonded to advances in astrophysics.

Vela pulsar glitches and nuclear superfluidity

Nicolas Chamel, Université Libre de Bruxelles (Belgium)

At the endpoint of stellar evolution, pulsars are spinning extremely rapidly with periods ranging from milliseconds to seconds and delays of a few milliseconds per year at most, thus providing the most accurate clocks in the universe. Nevertheless, some pulsars exhibit sudden decreases of their spin period. Because it was the first observed pulsar to exhibit such "glitches", Vela has become the testing ground for glitch theories. Sudden pulsar spin-ups have long been thought to be the manifestation of a neutron superfluid permeating the crustal layers of these dead stars [1]. However, recent calculations indicate that this scenario is unrealistic [2, 3] because neutrons are very strongly coupled to the crust due to non-dissipative entrainment effects [4]. These effects, which were previously ignored, not only challenge the interpretation of Vela pulsar glitches but also suggest that a revision of the interpretation of other observed neutron-star phenomena might be necessary.

[1] P. W. Anderson and N. Itoh, *Nature* 256, 25 (1975).
[2] N. Andersson, K. Glampedakis, W. Ho and C. M. Espinoza, *Phys. Rev. Lett.* 109, 241103 (2012).
[3] N. Chamel, *Phys. Rev. Lett*. 110, 011101 (2013).
[4] N. Chamel, *Phys. Rev. C* 85, 035801 (2012).

A new r-mode saturation mechanism

Kostas Glampedakis, University of Murcia (Spain)

This talk describes how the interaction between neutron vortices and proton fluxtubes in a superfluid neutron star core may act as a natural non-linear saturation mechanism for the r-mode instability. The talk also includes a discussion of the astrophysical implications of this new effect on systems like rapidly rotating accreting neutron stars.

Pygmy dipole resonances and the symmetry energy

Philip Goddard, University of Surrey (UK)

The kink in the charge radius shift of even-even nuclei near the N=126 shell closure has been difficult to explain theoretically for several decades. Most non-relativistic mean-field models struggle to reproduce the kink [1]. We present a new explanation, advocating the influence of the $1i_{11/2}$ neutron orbital upon tightly bound n=1 proton orbitals [2]. The connection with the symmetry energy and the equation of state of neutron-rich matter will be discussed, with special emphasis on how radii can constrain bulk nuclear properties.

[1] P.-G. Reinhard and H. Flocard, Nucl. Phys. A584, 467 (1995).
[2] P.M. Goddard, P.D. Stevenson and A. Rios, Phys. Rev. Lett. 110, 032503 (2013).

Modelling glitches in radio pulsars and magnetars

Brynmor Haskell, Max Planck Institute for Gravitational Physics, AEI (Potsdam, Germany)

I will review recent progress in modelling pulsar glitches in the superfluid vortex pinning scenario. I will discuss how issues such as crustal entrainment and vortex/flux tube pinning in the outer core can affect these models and what constraints on the equation of state can be inferred from observations.

In particular, I will not only focus on radio pulsars, but also discuss how particular features of magnetar glitches can be explained in this scenario and what we can learn from these phenomena.

Equation of state effects in core-collapse supernova simulations

Matthias Hempel, Basel University (Switzerland)

In this talk, characteristic properties of available supernova equations of state (EOS) are discussed, with focus on the behavior of the symmetry energy and mass-radius relations. The EOSs are confronted with available experimental and observational constraints. In the second part, I discuss the role of the EOS in core-collapse supernovae by use of spherical simulations with detailed neutrino transport. Only a moderate impact of the symmetry energy on the evolution of the electron fraction and shock radii could be identified for the early phase of standard core-collapse supernovae. EOS effects are more pronounced in the late evolution, in the so-called neutrino-driven wind phase, or if one goes to extremely massive progenitors which lead to black hole formation.

Mass and radius of the Cassiopeia A neutron star and tests of superfluid and superconducting gaps

Wynn Ho, University of Southampton (UK)

The observed rapid cooling of the Cassiopeia A neutron star can be interpreted as being caused by neutron and proton transitions from normal to superfluid/superconducting states in the stellar core. Here we present measurements of the neutron star mass and radius found from consistent fitting of both the Chandra X-ray spectra and cooling behavior. This comparison is only possible for individual nuclear equations of state. We also test phenomenological superfluid and superconducting gap models, that mimic most of the known theoretical models, against the cooling behavior and obtain constraints on the gaps.

Gravitational waves from core-collapse supernovae

Hans-Thomas Janka, Max Planck Institute for Astrophysics (Garching, Germany)

Core-collapse supernovae are the birth sites of neutron stars and one of the most promising sources of strong gravitational-wave emission. In this talk, I will report the latest progress in modelling stellar core collapse and explosion in two and three dimensions, and in predicting the gravitational-wave emission during such events. Although the signals cannot be expected to possess template character, they exhibit interesting systematic dependencies of their characteristic properties, e.g. of their dominant frequency and its evolution and of the radiated energy, on progenitor-dependent variations of the post-bounce accretion phase and the explosion dynamics, as well as on the properties (mass, radius) of the newly formed neutron star. In the case of a Galactic supernova, a gravitational-wave measurement could therefore provide extremely valuable, unique diagnostic access to the core conditions of the dying star and to the processes associated with the still disputed mechanism of the explosion, especially when the wave measurement is complemented by the likely detection of the neutrino burst from the supernova.

Excitation modes in superfluid nuclear matter and neutron star cooling

Evgeni Kolomeitsev, Matej Bel University (Slovakia)

Neutrino emission in the processes of breaking and formation of nucleon Cooper pairs is studied in the framework of the Larkin-Migdal and Leggett approaches of superfluid Fermi liquids at finite temperatures. The conserving properties of the Fermi-liquid approach are discussed in the context of the Ward identities for axial and vector baryon currents. A systematic expansion of the neutrino emissivities for small temperatures and nucleon Fermi velocity is performed.

The magnetic field in a superconducting neutron star

Samuel Lander, University of Tuebingen (Germany)

The bulk of a neutron star is believed to be a multifluid core, composed of superfluid neutrons, superconducting protons and normal electrons. Such a system is expected from the terrestrial theory of superconductivity but also has persuasive observational evidence in its favour: the rapid cooling of the young neutron star Cas A, and the occasional spin-up events seen in a number of pulsars. Proton superconductivity is expected to cause a quantisation of the star's magnetic field into an array of thin fluxtubes surrounded by unmagnetised matter. This, in turn, changes the macroscopic magnetic force from the familiar Lorentz force to a fluxtube tension force. We wish to study what kind of magnetic field configuration is likely to exist in a neutron star. To this end, we solve the equilibrium equations for a neutron star, modelled as the multifluid core described above, matched to a relaxed crust. This involves reformulating the original equations for the magnetic field in terms of a single equation in the stream function, then solving this numerically with an iterative scheme. We present solutions for different field configurations, calculating the magnetically-induced distortion to the star and the corresponding gravitational-wave emission. We discuss the implications of these field configurations for neutron star evolution and dynamics.

I Love Q forever

Andrea Maselli, la Sapienza, University of Rome (Italy)

Coalescing binaries are among the most promising sources of gravitational waves for the new generation of terrestrial and space interferometers. Moreover, they have been suggested as a possible explanation of short gamma-ray bursts. Tidal interactions occurring in the last phases of these systems can cause the disruption of a neutron star and are equation-of-state dependent. Detection of the emitted gravitational signal may provide useful information on the stellar internal structure.

In this talk, we present a new semi-analytical approach to describe tidal interactions in black hole-neutron star or neutron star-neutron star binaries, based on the post-Newtonian expansion and the Affine approximation. We show how this model allows to derive the neutron star deformation properties. In particular, we study the evolution of the neutron star tidal deformability during the inspiral, evaluating the impact of its change for a future gravitational wave detection. Moreover, we determine the range of validity of the I-Love relation between the tidal Love number and the star momentum of inertia, up to the merging phase. We also discuss the possibility of using a new relation, involving the Love number and the star compactness, to measure the neutron star radius with an accuracy ~10 % from gravitational-wave observations.

Spectroscopy of magnetic compact objects

Benedict Murdin (presented by Steven Clowes), University of Surrey (UK)

The spectrum of white dwarfs includes absorption lines for hydrogen gas that is in the atmosphere above the star. Many white dwarfs have enormous magnetic field because the magnetic flux from the precursor star gets trapped during the collapse and concentrated in a much smaller surface area. Neutron stars can be even more extreme. The highest reported field on a WD is 1 gigagauss (10^5 T). The hydrogen spectrum in extreme field is very different from the ordinary Lyman and Balmer series. In terrestrially reproducible fields, which are far weaker, the field can be treated as a small perturbation and the energy levels shift linearly according to the Zeeman effect. At high field the field provides a cylindrical symmetry potential that competes with the spherical symmetry of the Coulomb potential and causes very strong mixing of states and a complex splitting of the absorption lines (the quadratic Zeeman effect). Coincidentally, the electric energy equals the cyclotron energy at 10^5 T. At higher field, appropriate for neutron stars, the Coulomb potential is the small perturbation.

We have performed laboratory experiments to measure the absorption spectrum in an analogue of hydrogen, the phosphorus impurity in a silicon crystal [1]. These impurities ("shallow donors") have a single outer electron orbiting a singly positively charged core and exhibit spectra closely resembling hydrogen, but with the Rydberg energy shifted from the UV to the far-infrared. The greatly reduced Coulomb energy is much easier to approach with the cyclotron energy, and equivalence is reached at only 32 T. Our results show excellent agreement with the theory for the quadratic Zeeman effect up to the equivalence point. Other impurities which can be used to examine higher fields appropriate to neutron-stars will be discussed.

[1] Murdin *et al., Nature Communications* 4, 1469 (2013).

Too much pasta for pulsars to spin down

José Pons, University of Alicante (Spain)

The lack of X-ray pulsars with spin periods larger than 12 s raises the question of where the population of evolved high magnetic field neutron stars has gone. Unlike canonical radio pulsars, X-ray pulsars are not subject to physical limits to the emission mechanism nor observational biases against the detection of sources with longer periods. Here we show that a highly resistive layer in the innermost part of the crust of neutron stars naturally limits the spin period to a maximum value of about 10-20 s. This highly resistive layer is expected if the inner crust is amorphous and heterogeneous in nuclear charge, possibly due to the existence of a nuclear pasta phase. Our findings suggest that the maximum period of isolated X-ray pulsars can be the first observational evidence of an amorphous inner crust, whose properties can be further constrained by future X-ray timing missions combined with more detailed models.

The magnetorotational instability in relativistic hypermassive neutron stars

Daniel Siegel, Max Planck Institute for Gravitational Physics, AEI (Potsdam, Germany)

A differentially rotating hypermassive neutron star (HMNS) is a metastable object which can be formed in the merger of neutron-star binaries. The eventual collapse of the HMNS into a black hole is a key element in generating the physical conditions expected to accompany the launch of a short gamma-ray burst. We investigate the influence of magnetic fields on HMNSs by performing three-dimensional simulations in general-relativistic magnetohydrodynamics. In particular, we provide direct evidence for the occurrence of the magnetorotational instability (MRI) in HMNS interiors. For the first time in simulations of these systems, rapidly-growing and spatially-periodic structures are observed to form with features like those of the channel flows produced by the MRI in other systems. Moreover, the growth time and wavelength of the fastest-growing mode are extracted and compared successfully with analytical predictions. The MRI emerges as an important mechanism to amplify magnetic fields over the lifetime of the HMNS, whose collapse to a black hole is accelerated. The evidence provided here that the MRI can actually develop in HMNSs could have a profound impact on the outcome of the merger of neutron-star binaries and on its connection to short gamma-ray bursts.

Pulsar glitch recovery and properties of bulk nuclear matter

Anthony van Eysden, NORDITA (Sweden)

Pulsar glitches are believed to arise from a massive transfer of angular momentum from the superfluid interior of a neutron star to its crust via an avalanche-unpinning event in the superfluid vortex array. This impulsive spin-up event is followed by a quasi-exponential recovery phase, as the interior components of the star and the crust attempt to establish rotational equilibrium. The recovery is strongly affected by the interior, where the thermal creep of vortices, magnetic fields, turbulence, compositional variations and exotic phases of the strong nuclear force may play a role. Using hydrodynamic models for the neutron star interior, we explore how these effects manifest themselves during glitch recovery and discuss the possibility of using radio timing and gravitational wave observations to constrain the properties of bulk nuclear matter, for example, transport coefficients like the viscosity and mutual friction parameters as well as the equation of state.

LOFT and the neutron star equation of state

Anna Watts, University of Amsterdam (Netherlands)

LOFT, the Large Observatory for X-ray Timing, is one of five candidates currently being considered for ESA's M3 class mission, competing for a launch window in the 2020s. One of LOFT's primary science goals is to constrain the neutron star equation of state by measuring mass and radius to within a few percent. LOFT will employ three main techniques to achieve this goal. The first involves pulse profile modelling of burst oscillations (brightness asymmetries that develop during thermonuclear bursts on the surfaces of accreting neutron stars). As photons propagate out of the deep potential well, relativistic effects encode information about mass and radius in the shape of the resulting pulsations. Using oscillations from known bursters we expect to be able to use this technique to obtain tight constraints on mass and radius for several neutron stars. The second technique is to search for extremely rapidly rotating neutron stars, to exploit constraints resulting from break-up limits. Accreting neutron stars are prime candidates for rapid rotation due to accretion-induced spin-up, but such stars may only be weak or intermittent accretion-powered pulsars due to fluctuations in the magnetic channeling process. The large collecting area of LOFT will enable highly sensitive searches for pulsations (and hence spin rates) from the many accreting neutron stars whose spin rates are not yet known. The third technique is to search for quasi-periodic oscillations associated with global seismic vibrations triggered by magnetic explosions on magnetars. Oscillations detected in giant flares from these sources have opened up the field of neutron star seismology, but these large events are extremely rare, and attempts to use the vibrational frequencies to constrain the dense matter equation of state have been hampered by the limited dataset. LOFT will be sensitive to oscillations in the much more frequent intermediate flares. In this talk I will illustrate how X-ray timing techniques can be used to constrain the dense matter equation of state and discuss the results expected from LOFT over its mission lifetime. I will also illustrate how LOFT would complement both laboratory-based experiments and other astronomical investigations of the neutron star equation of state.

Neutron skins from coherent pion photoproduction

Daniel Watts, University of Edinburgh (UK)

New measurements of coherent pion photoproduction from nuclei will provide data to accurately constrain the properties of the neutron skin. The photon is an ideal probe of nuclear matter as its interaction is well understood and it can probe the entire nuclear volume without the complications of initial state interactions. For low momenta near the reaction threshold pion-nucleus interactions in the exit channel are small. A major programme of measurements of coherent pion photoproduction is underway at the MAMI facility in Germany using the Crystal Ball detector. Recent determination of the skin thickness and skin diffuseness for ^{208}Pb will be presented. Preliminary analyses of the neutron skin evolution in tin isotopes will also be discussed.

Measurement of the neutron radius of ^{208}Pb through parity-violation in electron scattering

Lorenzo Zana, University of Edinburgh (UK)

The first measurement of the parity-violating asymmetry A_{PV} in the elastic scattering of polarized electrons from ^{208}Pb. A_{PV} is sensitive to the radius of the neutron distribution, R_n. The result A_{PV} = 0.656 ± 0.060 (stat) ± 0.014 (syst) ppm corresponds to a difference between the radii of the neutron and proton distributions R_n-R_p = 0.33 + 0.16 - 0.18 fm and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nuclei [1]. This measurement was carried out in Hall A at the Thomas Jefferson National Accelerator Facility, Newport News, VA (USA) and shows the potential of future measurements that will be carried out at the same facility.

[1] S. Abrahyam *et al*. (PREX Collaboration), *Phys. Rev. Lett*. 108, 112502 (2012).

LOFT - Large Observatory for X-ray Timing

Silvia Zane, University College London (UK), on behalf of the LOFT consortium

High-time-resolution X-ray observations of compact objects provide direct access to strong-field gravity, black hole masses and spins, and the equation of state of ultra-dense matter. They provide unique opportunities to reveal for the first time a variety of general relativistic effects, and to measure fundamental parameters of collapsed objects. They gain unprecedented information on strongly curved space times and matter at supra-nuclear densities and in supercritical magnetic fields.
LOFT is one of the four missions selected by ESA for an Assessment Phase as an M3 (possible launch in 2022-2024). LOFT is specifically designed to study the very rapid X-ray flux and spectral variability that directly probe the motion of matter down to distances very close to black holes and neutron stars. The main instrument on board LOFT is a Large Area Detector (LAD) with 10 square meters of effective area, *i.e*. 20 times the collecting area of RXTE, operating in the 2-30 keV range. Additionally, LOFT will have on board a Wide Field Monitor (WFM) with few mCrab sensitivity in a day, 5′ angular resolution, and a 3 steradian field of view, operating in the 2-50 keV energy range.

With its 20 fold area leap, LOFT has the capability to make dramatic advances and open up new fields in X-ray astronomy. The LAD will allow timing measurements of unprecedented sensitivity, having the capability to measure the mass and radius of neutron stars with ~5% accuracy, or to reveal blobs orbiting close to the marginally stable orbit in active galactic nuclei. The WFM will monitor a large fraction of the sky potentially accessible to LAD, discovering new transients and triggering LAD observations on their most extreme states. In this talk, we will illustrate the scientific goals and the unique potential of the mission and the major role played by MSSL and UK scientists in the LOFT team.

Three-nucleon forces in exotic open-shell isotopes

Carlo Barbieri, University of Surrey (UK)

As *ab initio* calculations of atomic nuclei enter the A=40-100 mass range, nuclear theory faces the great challenge of providing accurate predictions for the vast majority of open-shell isotopes. Here we discuss advances in *ab initio* calculations based on self-consistent Green's function theory. The method allows first principle calculations of truly open shell, semi-magic nuclei and has been applied successfully up to ^{74}Ni with soft low-momenutm interactions. Adding realistic three-nucleon interactions to the state of the art Green's function theory, we find that physics of neutron driplines is reproduced with good quality for isotopes around the oxygen and calcium chains. The Gorkov approach presented here substantially extends the scope of *ab initio* theory in the medium mass region from a few tens of closed shells cases to hundreds of open shell isotopes. The main output of the formalism is the single-particle spectral function, which describes processes involving the addition or knockout of a nucleon and provides a theoretical optical potential for elastic scattering. The talk will give examples of applications and discuss first results regarding the implication of three-nucleon forces on the evolution of correlations with proton-neutron asymmetry, with particular emphasis on neutron rich pf-shell isotopes.

Neutrino interactions in neutron matter

Andrea Cipollone, University of Surrey (UK)

Neutrino flow is the most efficient driven mechanism of energy transfer inside and outside a neutron star (NS). The uncertainties of NS evolution simulations depend heavily on the values of neutrino-nucleon and neutrino-nucleus cross section used as input [1]. I will present recent results on the quantitative description of low-energy (up to 10 MeV) neutrino interactions in pure neutron matter [2]. The Neutrino Mean Free path is evaluated as a function of both density and temperature near zero temperature. This range turns out to be crucial in the early stages of a NS evolution. Neutrino-matter dynamical equations decouple and many-body corrections can be consistently treated within the linear response theory, once an effective interaction in the medium has been stated.

We find that neutrino opacity is deeply affected by many-body correlations induced by nucleon-nucleon (NN) interactions, both in the Fermi (CP conserving) and in the Gamow-Teller (CP violating) channel. We employ the formalism of correlated basis functions theory at the two-body cluster expansion to handle the NN short-range correlations. The evolved potential reduces to the bare potential in the limit of vanishing density and it is therefore strongly constrained by the experimental information on the two nucleon system [3].

The long-range part is treated within the Landau theory of a normal Fermi liquid. This formalism, while being strictly applicable only in the regime where the excitations of the system can be described in terms of quasiparticles, allows for a consistent treatment of both coherent (collective modes) and incoherent contribution. From a microscopic point of view, the Landau-Boltzmann equation allows to sum up all particle-hole excitations in the ring approximation.

[1] A. Burrows et al, *ApJ* 640, 878 (2006)
[2] O. Benhar and A. Cipollone, *Phys. Rev.* C 87, 014601 (2013)
[3] O. Benhar and M. Valli, *Phys. Rev. Lett*. 99, 232501 (2007)

Methods for simulating the shattering of the neutron star crust

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Although the neutron star crust contributes only a small fraction to the total mass of the star, it is expected to affect the dynamics of systems where interface or crustal modes are excited, such as during binary neutron star mergers, where excitation of these modes could lead to tidal shattering of the crust. To model such systems, we have developed a general relativistic conservation-law formalism for nonlinear elasticity; this allows us to use high-resolution shock-capturing methods to resolve strong shocks. We plan to use this formalism, along with appropriate methods for treating the solid-fluid and solid-vacuum interfaces at the edges of the crust, to simulate a toy-model evolution of discontinuities caused by shattering and refreezing of the crust.

The ASY-EOS experiment at GSI: investigating symmetry energy at supra-saturation densities

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The elliptic flow ratio of neutrons with respect to protons or light complex particles in reactions of heavy ions at pre-relativistic energies is proposed as an observable sensitive to the strength of the symmetry term in the nuclear equation of state at supra-saturation densities. Placing constraints on the strength of the symmetry energy is essential for understanding neutron star structure and binary mergers. The results from the FOPI/LAND experiment for ^{197}Au+^{197}Au collisions at 400 MeV/nucleon favour a moderately soft symmetry term when compared with UrQMD and Tubingen QMD [1] models, but suffer from considerable statistical uncertainty [2]. The ASYEOS collaboration performed an experiment at GSI in May 2011 [3] with the goals of reducing the statistical uncertainty on the FOPI/LAND data whilst extending the study to other systems. The setup included LAND, the Aladin ToF-Wall, the Si-CSI KraTTA, the Microball and 4 rings of the CHIMERA detector. The flows of neutrons, protons and light complex particles were measured for ^{197}Au+^{197}Au, and also for ^{96}Ru+^{96}Ru, ^{96}Zr+^{96}Zr all at 400 MeV/nucleon. The current status of the analysis will be reported.

[1] M.D. Cozma*, Phys. Lett.* B 700, 139 (2011).
[2] P. Russotto et al., *Phys. Lett.* B 697 , 471 (2011).
[3] P. Russotto et al., arXiv:1209.5961 [nucl-ex].

Constraints on the equations of state of cold dense matter from nuclear physics and astrophysics

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The equation of state of cold dense matter is studied using a family of generalized Skyrme functionals that have been recently developed. Various constraints on the equation of state are discussed, coming from both nuclear physics and astrophysics. In particular, the nuclear physics constraints include atomic masses, the analysis of experimental data from heavy-ion collisions, neutron skins in nuclei, giant dipole resonances, dipole polarizability measurements, as well as microscopic calculations of homogeneous neutron matter and symmetric nuclear matter. Alternatively, astrophysical observations provide valuable constraints on the high-density part of the equation of state, especially neutron-star mass measurements.

Bar-mode instability in relativistic rotating stars

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We present results of the dynamics and the onset of the classical bar-mode (m=2) instability of differentially rotating relativistic star models in presence of non zero magnetic fields. The study is carried out performing 3D ideal magneto-hydrodynamics simulations in full General Relativity, superimposing purely poloidal magnetic fields of different strength (in the range 10^{13}-10^{16} G) to initial matter equilibrium configurations. For all models, we observe the sudden formation and linear growth of a toroidal magnetic field component that rapidly overcomes the original poloidal field. This is a consequence of the winding of the magnetic field lines dragged by differential rotation, and hence the total magnetic energy inside the star is amplified. Magnetic fields of order 10^{14} G or less have negligible effects on both stable and unstable models, while larger magnetic fields are able to completely suppress the hydrodynamical instabilities present in the demagnetized case. The threshold is different for different unstable models.

Neutron star oscillations from starquakes

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Glitches - sudden increases in spin rate - are observed in many pulsars. One mechanism that has been proposed to account for these is the starquake model, in which glitches are triggered by a loss of strain in the solid crust of the star. This decreases the ellipticity of the star, producing the observed spin-up. Starquakes can be expected to excite some of the oscillation modes of the neutron star. These oscillations are of interest as a source of gravitational waves. We discuss some order-of-magnitude estimates for the amplitude of these oscillations and the corresponding gravitational wave emission, and then move on to describing a more detailed toy model we are developing. In this model, we consider the simplified case of a solid, incompressible star, where much of the calculation can be carried out analytically. In particular, we can find the spectrum of oscillation modes of the star, and their corresponding eigenfunctions. Our current model for the glitch is a sudden removal of strain from the whole star. Given this, we calculate the change in properties of the star at the glitch. We then project this data against a basis of normal modes of the star after the starquake, in order to find the amplitude of the oscillations excited by the glitch.

Oscillations of maturing neutron stars

Christian Krueger, University of Southampton (UK)

We investigate the oscillation spectrum of maturing neutron stars, where our calculations aim to be as realistic as possible. To date, we account for density discontinuities, a composition gradient and the elastic crust; we are using a modern, realistic equation of state and our calculations include thermal pressure. We calculate the region in which the crust is crystallised by assuming a one-component plasma. All calculations are carried out in the framework of general relativistic perturbation theory and we investigate the effect of temperature on the different oscillation modes as the neutron star cools over time.

Quantum few body systems and dissociation

Tomokazu Miyamoto, University of Surrey (UK)

Some astrophysical processes involve nuclear reactions with relatively low temperature, and it is not easy to investigate such processes. Low energy experiments have had difficulties in obtaining accurate experimental values due to the uncertainty of stability and backgrounds. In particular, the cloud of atomic electrons, which behaves in a different manner in actual star cores, makes a significant effect on the electromagnetic force coming from the nucleus. This leads to uncertainties on the low energy data in laboratory experiments. The Coulomb dissociation approach removes these difficulties, using relatively high energy projectiles and thick targets, enhancing the rates and isolating the elastic breakup, where the target remains in a ground state. Measurement of E1 transition probability tells us about the information of halo nuclei with soft E1 excitation. Recent experimental projects have conducted exclusive Coulomb dissociation experiments for ^{19}B and ^{22}C, both of which have two neutron halos.
Here, we analyze the Efimov states of those nuclei with the hyperspherical formalism and Faddeev methods, provided there is no 3-body interaction. The Borromean nature of the 3-body projectile system appears only when the core of the two-halo nucleus can be regarded as a point-like object, whereas in reality the core is not point-like. It is also of interest to approximate the wave functions of the few body system by Darwin or higher-order Hamiltonians in a numerically more feasible way.
The collision of a two-halo projectile and a target and the subsequent dissociation process can be described by the Glauber method and other frameworks where final state interactions can be considered. The compatibility of composite projectiles with Lorentz-covariance is discussed, and the validity of the eikonal and non-relativistic hyperbolic trajectory is assessed in the intermediate energy region.

Gogny interactions for infinite nuclear matter

Rosh Sellahewa, University of Surrey (UK)

Different Gogny interactions have been analysed in order to determine which of these interactions give values of the symmetry energy slope, L, and isoscalar compressibility, K, which fall within the experimentally constrained values. Symmetry energies have been calculated via two different methods, using either numerical differences or analytically via a Taylor expansion of the energy. L has also been calculated with the two methods. Most of the interactions provide a value of L that is in the region of 25 MeV, much lower than most experimentally accepted values for the slope parameter.

Neutron and nuclear matter with simplified Argonne nucleon-nucleon potentials

Artur Polls, University of Barcelona (Spain)

We present calculations of the energy per particle and the equation of state of pure neutron and symmetric nuclear matter with simplified Argonne nucleon-nucleon potentials for different many-body theories [1]. We compare critically the Brueckner-Hartree-Fock results to other formalisms, such as the Brueckner-Bethe-Goldstone expansion up to third order, the self-consistent Green's functions method, auxiliary field diffusion Monte Carlo, and the Fermi hypernetted chain approach. We evaluate the importance of spin-orbit and tensor correlations in the equation of state and find these to be important in a wide range of densities.

[1] M. Baldo, A. Polls, A. Rios, H.J. Schulze and I. Vidaña, *Phys. Rev. C* 86, 064001 (2012).

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