Working Group Summary on "Neutron Stars and Dense Matter"
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Introduction: Einstein's theory of General Relativity links space-time geometry with the internal properties of matter, specifically the relationship between the pressure and energy density which constitutes the equation of state (EOS) of macroscopic objects. A marvelous example of this link is encountered both in the observation and observed properties of neutron stars. The confluence of theory and astronomical observations concerning neutron stars is truly remarkable. The entry of neutron stars in theorists minds dates back to 1930's whereas their discovery had to wait till the 1960's. Since then, it has been realized that all known forces of nature, strong, weak, electromagnetic and gravitational, play key roles in the formation, evolution, and the composition of neutron stars. Research on the physics and astrophysics of neutron stars has been the forerunner in the study of extreme energy density physics, spurring other activities such as relativistic heavy-ion collisions in which high energy density is investigated at much higher temperatures than encountered in neutron stars. These astrophysical investigations are being complemented by concomitant accelerator experiments. Such a strong connection between laboratory experiments and astrophysical observations bodes well to delineate the properties of neutron stars in which the ultimate energy density of observable cold matter is found.

Major recent accomplishments: *Key astronomical observations* of neutron stars that have been made and their implications studied theoretically include:

• The observation of 1.97 ± 0.04 $M_\odot$ neutron star (radio pulsar PSR J1614-2230). This discovery has enabled us to eliminate a number of theoretical possibilities for the EOS;
• The rapid cooling of the 330 year old neutron star in Cassiopeia A from 2.12×10^6 K to 2.04×10^6 K over a period of 10 years has confirmed the occurrence of neutron superfluidity and proton superconductivity in the dense interiors of neutron stars;
• Thermal X-ray emission from the surfaces of many isolated neutron stars has been detected which has placed bounds on their radii, thus the EOS;
• Detection of absorption features in the spectra of several neutron stars have stressed the need for in-depth studies of neutron star atmospheres;
• Observations of intermittent X-ray bursts from several neutron stars have spurred intense theoretical studies to correlate the masses and radii of neutron stars;
• The post-accretion of thermal radiation (in X-rays) from several neutron stars has not only confirmed the theoretical prediction that neutron stars have crusts, but are also beginning to shed light on the elastic and transport properties of crystalline structures in neutron star surfaces.
• Observations of pulse profiles from radio millisecond pulsars have placed the restriction that the radius of a 1.4 $M_\odot$ is greater that 10.7 km.

Laboratory experiments involving nucleon-nucleon scattering and neutron-rich nuclei provide the basis upon which our basic understanding of neutron-star matter is built. Much knowledge has been gained even with current restrictions (due to lack of facilities) to small neutron-proton asymmetries from accelerator experiments involving heavy-nuclei. Of great importance is the behavior of the energy of a system of unequal number of neutrons and protons, the so-called symmetry energy, as the densities increase to those found in neutron stars of increasing masses. The density dependence of the nuclear symmetry energy not only determines the structure (particularly the radius) of a neutron star, but also governs its thermal evolution (detected in multi-wavelength photon emissions) through various neutrino emitting processes which relentlessly cool the star.

Many recent laboratory experiments have provided initial constraints on the density dependence of the nuclear symmetry energy and on the EOS of neutron-rich matter at near-saturation and sub-saturation densities. These constraints have been extracted from measurements of:

- nuclear masses and excitation energies of isobaric analog resonances;
- energies and strength functions of giant monopole and dipole resonances;
- electric dipole strength functions and electric dipole polarizability (σ_2) sum rules;
- energies and strengths of pigmy electric dipole resonances; and
- measurements of neutron skin thicknesses.

Experiments have also probed the differential flows of neutrons and protons during nuclear collisions to constrain the symmetry energy at sub-saturation densities. Relevant observables are:

- diffusion of isospin between projectile and target nuclei in binary collisions, and
- comparisons of the spectra and flows of mirror nuclei, such as neutrons vs. protons, or tritons vs. helions (^{3}He).

Impressive accomplishments have been made on the *theoretical front* both in first principle calculations and in applications to neutron star phenomenology. Areas of significant progress in the former category include:

- Ab-initio calculations of neutron matter highlighting the role of three-nucleon forces on the density dependence of the nuclear symmetry energy;
- Application of effective field theory methods to calculations of low density superfluid and solid matter of practical importance in calculating transport (particularly thermal conductivity) and elastic properties (shear and bulk modulii) of a neutron stars crust;
- Using a maximally compact EOS, model-independent upper limits to thermodynamic properties in neutron stars, such as energy density, pressure, baryon number density and chemical potential, which depend upon the neutron star maximum mass, have been established; and
- Classical and quantum molecular dynamical simulations of neutron star crusts and their transport properties.

Advances in theoretical analyses of neutron star data have provided answers to many longstanding issues, as for example:

- Neutron stars with masses above 1.4 $M_\odot$ likely have radii in the range $10-13$ km; this conclusion stems from analyses of thermal emission from isolated neutron stars, of transient X-ray bursts, and of pulse profiles from millisecond radio pulsars;
- Independent analyses of the surface temperatures of neutron stars that confirm the presence of superfluidity and superconductivity with associated neutrino emission processes.
- Analyses of crustal cooling data have highlighted the crucial role of thermal conductivity.

Compelling open questions: Notwithstanding the advances mentioned above, many longstanding questions and new ones raised by recent discoveries require answers. Beginning with questions related to astrophysical issues,

- What are the maximum and minimum masses of a neutron star? The maximum neutron star mass has profound implications for the minimum mass of a hadronic-material black hole (and the total number of black holes in our Universe, of much concern to Cosmology), the mass of the progenitor star that gave birth to it, and the equation of state of hadronic matter. The minimum neutron star mass raises questions about stellar evolution and how it could even be formed in the current paradigm of core collapse supernovae.
- What is the radius of a neutron star whose mass is accurately measured? To date, data on

radii to the same level of accuracy that radio pulsar measurements on masses of neutron stars have afforded us do not exist. *Precise measurements of the mass and the radius of the same neutron star would be a first and an outstanding achievement in neutron star research. Such data on several, say a magnificent seven, individual stars would pin down the EOS without recourse to models (see next section).*

• What are neutron star cooling curves telling us? Superfluidity tends to slow down cooling, under most conditions, while extra degrees of freedom (e.g., hyperons, quarks) hasten it.

• Flares associated with intense surface magnetic fields as large as 10^{15} gauss, found in many neutron stars (termed "magnetars"), continue to baffle us. What is the microscopic origin of such fields and what are their magnitudes in the interiors of neutron stars? What can be learned from the modeling of Quasi Periodic Observables (QPO's) in magnetar flares?

• What phases are there in the phase diagram of dense matter at low temperatures? How do we use neutron star observations to learn about those phases? How do we make good theoretical predictions about those phases?

• What is the nature of absorption features detected from isolated neutron stars?

• Is there a limit to the spin frequency of milli-second pulsars? If so, why?

• What is the emission process for X-ray bursts? What precisely controls the durations of these bursts and of inter-bursts?

• Is unstable burning of Carbon (C) the real cause of super bursts, especially as the ignition condition for unstable C burning cannot be met within our understanding of the C-C fusion?

• Is there real evidence for enhanced neutrino cooling in high mass neutron stars?

• What are glitches and why do they occur? What is the trigger that couples the superfluid to the crust over a timescale of less than one minute? What are the relevant dissipative processes?

• How does one link the microphysics of transport, heat flow, superfluidity, viscosity, vortices/flux tubes to average macro-modes in neutron star phenomenology?

Turning to issues associated with neutron-rich nuclei,

• What is the incompressibility of neutron-rich matter? Can laboratory experiments vastly improve the accuracy with which the iso-spin asymmetric compression modulus be determined by measurements of giant resonances?

• Can measurements of dipole polarizabilities be extended to more cases of neutron-rich nuclei?

• Can neutron skin thicknesses of many nuclei be measured through parity-violating experiments to better accuracy than currently available?

• Can data from collisions involving neutron-rich nuclei better constrain the density dependence of the symmetry energy at sub-saturation and supra-saturation densities?

• How precisely can three-body forces be pinned down from first-principle calculations of dense neutron-rich matter? What experimental constraints can be imposed?

• What advances are needed for first-principle calculations of finite temperature nuclear matter?

Addressing the open questions:

Laboratory experiments: The importance of the symmetry energy increases for nuclei and nuclear matter that is more neutron-rich; thus more precise constraints can be obtained by experiments with extremely neutron-rich beams at advanced Facilities for Rare Isotope Beams (FRIB). Fast beams at such facilities also allow the possibility of extending constraints on the symmetry energy and EOS to supra-saturation densities that can only be achieved in laboratory-controlled experiments by colliding and compressing nuclei in central collisions. Such collisions have already provided constraints on the EOS of symmetric matter at supra-saturation densities.

Calculations predict that comparisons of the emission and flows of different members of isospin multiplets such as $(\mathrm{K}^0, \mathrm{K}^-)$, (π^+, π^-), (p, n), and $(^3\mathrm{He}, \mathrm{t})$ in collisions between neutron-rich nuclei can allow such constraints to be extrapolated to neutron rich matter in astrophysical environments such as neutron stars and core collapse supernovae. Constraints on the isospin splitting between the neutron and proton effective masses will also be obtained, which is key to understanding the thermal properties of dense neutron rich matter. Such measurements are planned at fast rare isotope facilities like FRIB and requires the expeditious completion of FRIB.

Astronomical observations:

• A concerted effort to accumulate accurate masses of more neutron stars from radio and X-ray pulsars would greatly benefit. It would also be good to find other massive stars in excess of 2 $\mathrm{M}_\odot$. These observations require sensitive radio telescopes such as the Green Bank Telescope (GBT) and Arecibo; future facilities such as the Square Kilometer Array (SKA) will also provide many more mass measurements.
• Precise measurements of the masses and radii of several individual stars would revolutionize this field. Theoretical techniques to invert the structure equations from mass-radius information to obtain the pressure-energy density relation are in place waiting for data to emerge.
• Better statistics of X-ray burst oscillations (their time-resolved spectra and variability evolution) will help in better understanding bursts and place tighter constraints on masses and radii.
• Better statistics of accretion flows can shed light on QPO's and accretion flows onto accreting milli-second X-ray pulsars. These two goals will be well-served by the proposed Large Observatory for X-ray Timing (LOFT) mission as well as the existing Chandra Observatory and the X-ray Multi-Mirror (XMM) mission while they last.
• In order to delineate the interior composition of neutron stars and the associated neutrino emission processes, we need a future generation of time and energy sensitive X-ray observatories.
• Observations of thermal emission from neutron stars after glitches would strongly constrain glitch models if a thermal wave were to be detected.
• Time resolved magnetar glitches could be undertaken at the next generation of observatories.
• Time resolved X-ray pulsars, say with LOFT, can add information on how these systems spin and constrain the dynamics of r-modes.
• Radio observations with Lofar and SKA can give a more detailed picture of pulsar glitches to the point where models can be tested.
• Gravitational wave detections with advanced Laser Interferometer Gravity Observatories (LIGO) can get masses and perhaps radii through measurements of quadrupole and higher polarizabiliteis (Love numbers, and, their associates). Detections from individual neutron stars coming from internal oscillations would directly probe the interiors.

Theretical goals: Do we have a strong-force theory for cold matter as useful as General Relativity is for gravity? Yes, QCD; developments for its application to cold matter are beginning to emerge, but to be "useful" will require advances both in ideas (the sign problem) and computational efforts.

In the mean time, plausible guesses for the phases of dense matter and calculations of their properties with improved techniques are continuing and much progress has been (and will be) made. As Prakash is fond of saying, "It's because the Wright brothers tinkered with their engines, humans began flying as early as they did".

Needs of fields

To take leaps in our understanding in this multi-disciplinary field , we desperately need better X-ray telescopes, both in terms of resolution and sensitivity, for observations of thermal emission, X-ray bursts, and pulse profiles. And there should be a concerted effort to prevent the closing of radio observatories that are discovering and observing pulsars. We need more measurements of neutron star masses to do statistics for evolution as well as for the maximum mass. The measurement of a moment of inertia would be important, but is in jeopardy with the proposed cuts. Glitch observations are also very important and need continuous timing.

Equally important is the completion of Facilities for Rare Isotope Beams (FRIB) that benefit a variety of areas in Nuclear Astrophysics (formation of stars, supernovae of all kinds, the all-important question of nucleosynthesis, etc.), including the physics and astrophysics of neutron stars. As many new phenomena (halo-nuclei, possible new shell closures, etc.) have already been discovered in the world of neutron-rich nuclei and are shedding much light on the matter likely to exist in neutron stars, the promise of exciting new discoveries is very high.

Currently, personnel support for theoretical investigations is woefully pathetic. This situation calls for drastic measures beginning **right now**!

Community involvement

Traditionally, astronomers, laboratory experimentalists, and theoretical physicists engaged in research involving compact objects have generally supported each other's efforts. Notwithstanding such close ties, explicit opinions were expressed on this subject:

- "Nuclear theorists and experimentalists involved in the physics and astrophysics of neutron stars (broadly interpreted) should get behind the astronomers to support existing radio and proposed X-ray observatories, just like astronomers got behind certain laboratory experiments. The observations to date have driven the theory, which certainly would have stagnated."
- "We clearly need a continued and better dialogue between people in the different areas. Don't think we are doing badly here, but there is perhaps not a wide consensus of the issues."
- Researchers should promote sharing students and post-docs for extended periods with other groups so that young researchers acquire expertise in overlapping subjects and a broad outlook.

Intersection with other subfields:

Advances in the field of neutron star physics and astrophysics have traditionally been highly inter-disciplinary and continues to be so. An interesting suggestion was made by Bennet Link:

"Could we convince our condensed matter colleagues to study glitches and pinning in superfluid helium with geometries appropriate to neutron stars (spheres, not cylinders)? I think such experiments could be extremely useful. This would be very interesting cross-disciplinary science."

Names of contributors from across the world:

In addition to those who attended the town meeting and contributed in terms of presentations, discussion and active participation at all sites of the meeting, several colleagues from across the world sent thoughtful comments to be shared as deemed fit to the cause of Nuclear Astrophysics. Their names are:

James Lattimer, Chris Pethick, Dima Yakovlev, Mark Alford, Anna Watts, Craig Heinke, Bennet Link, Dany Page, George Pavlov, Ben Owen, Nils Andersson, Bao-An Li, Maria, Massimo Di Toro, and Yingxun Zhang.

This document has greatly benefitted by inputs from all the above.