Neutron stars

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Neutron star objectives

- What happens to matter when it is compressed?
  - What is the maximum density present in nature, before matter (as we know it) collapses to a black hole?
  - How are quarks confined?
  - What are neutron stars made of? Is this a unique form of matter found no where else in nature?
- How does matter interact with large magnetic fields, intense neutrino fluxes, and strong gravity?
- What is the nature of compact and energetic astrophysical objects and what determines their E+M, neutrino, and GW radiations?
- What is the origin of the chemical elements?

What happens to matter when it is compressed?

- Up to what density does chiral effective field theory converge: for pure neutron matter? for symmetric nuclear matter? [$<n_0$] Can we predict the saturation density of nuclear matter? [no]

- Is there an effective way to constrain phenomenological three or more nucleon interactions at densities where chiral EFT does not converge? [no]

- Fundamental limitations of theory to predict dense EOS greatly increases importance of observations.

EOS of dense matter

- Discovery of 2 M_{sun} NS(s) most important recent observation. Provides *Lower* limit for maximum NS mass and rules out all soft EOS.

- Observation of NS radii provide important EOS information.

  - Present observations have important systematic errors.

  - New X-ray missions such as NICER, Athena+ should significantly improve radius determinations. Need to work with astrophysics.

  - Should pursue independent GW observations of radii.

- Opportunity to determine fate of NS mergers (prompt collapse, metastable, stable massive NS) with multi-messenger observations. Provides important EOS information. Example: observation of BH formation sets *Upper* limit on maximum NS mass.

Role of laboratory experiments

- Symmetry energy allows extrapolation of slightly neutron rich laboratory data to very neutron rich astrophysical systems.

- Neutron skin thickness of heavy nuclei closely related to density dependence of symmetry energy and pressure of neutron matter at $\sim 2/3 n_0$.

- Symmetry energy at high densities, if it can be extracted from heavy ion collisions, ***is single laboratory observable most closely related to the structure of neutron stars***.

Neutron skin measurements

- Neutron skin thickness important observable closely related to pressure of neutron matter.

- Parity violating electron scattering provides most theoretically clean determination. PREX-II on ^{208}Pb and CREX on ^{48}Ca planed at JLAB. Additional possibilities at Mainz.

- Other strong and E+M probes may have significant systematic errors. However, if confirmed

What are neutron stars made of?

- Measurements of NS masses and radii determine EOS (P vs rho). They do not determine composition.

- $2M_{sun}$ NS says P is high at high rho. But high P could be from strongly interacting nucleons or from strongly interacting quarks.

- Attractive hyper-nuclear binding energies suggest hyperons significantly reduce P, perhaps too much for $2M_{sun}$ NS. Solution likely to be repulsive three baryon forces involving one (or more) hyperons.

- Need additional observables such as NS cooling, that depend on transport properties of dense matter, to distinguish composition.

Need calculations and observations of transport properties

- Transport properties such as thermal conductivity, electrical conductivity, shear viscosity, bulk viscosity, … probe dense matter.

- Sensitive to composition, phase, pairing properties, impurities…

- Neutron star cooling probes neutrino emissivity.

- Rapid rotation and r-mode stability probes damping from bulk, shear viscosity.

Neutron Star Crust

- Many E+M observables filtered by crust properties.
- Deep crustal heating probes electron capture and pycnonuclear reactions.
- X-ray observations of crust cooling after extended periods of accretion sensitive to thermal conductivity and heat capacity of crust. Observed rapid cooling suggest high thermal conductivity with few impurities.
- Superburst ignition probes crust temperatures. We don't understand how crust gets warm enough?
- What is role of URCA processes or other neutrino emissivity in crust?
- Nuclear pasta: complex shapes expected at crust core transition. Disordered pasta could reduce electrical conductivity (leading to B field decay) and thermal conductivity.

Origin of chemical elements

- What makes neutrons needed for r-process?

- Neutrinos from NS birth: What are supernova ν_e and anti-ν_e spectra and n/p ratio in neutrino driven wind? What elements are made in wind? Need good SN ν_e detector (for example large underground liquid Ar such as LBNE(F)). Also important for ν oscillations.

- Gravity during NS death: How much n rich material, of what proton fraction, is ejected during NS mergers? Need better numerical relativity simulations of mergers with detailed EOS. Also need close collaboration between nuclear physicists and LIGO science collaboration.

- Important to search for new transient events such as Kilonovae.

Neutron star needs

- Clean measurements of neutron skins of heavy nuclei.
- Robust attempt to determine symmetry energy at high densities from HI collisions.
- Better calculations of transport properties.
- Better predictions of E+M, neutrino, and GW observables.
- New X-ray observatories.
- Good supernova $\boldsymbol{\nu}_e$ detector.
- Better numerical relativity simulations with detailed microphysics. Close collaboration between nuclear physicists and LIGO.
- Very broad FRIB nuclear theory group / program to study nuclear structure, neutron star structure, astrophysical nucleosynthesis sites …