The Equation of State

Tantalizing Possibility

- Laboratory Experiments suggest large neutron radii for Pb \( \gtrsim 1\rho_0 \)
- Gravitational Waves suggest small stellar radii \( \gtrsim 2\rho_0 \)
- Electromagnetic Observations suggest large stellar masses \( \gtrsim 4\rho_0 \)

Exciting possibility: If all are confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?)
PREX, PREX-II, MREX

A statistical fluke or Interesting Physics?

That is why you play the game...
Stable beam conditions by July 2026
First run to reach PREX sensitivity ($\Delta R_{\text{skin}} \approx 0.07$ fm) 250 hours beam time
Result announced around mid 2027 (likely to combine PREX-MREX data)
Final MREX result ($\Delta R_{\text{skin}} \approx 0.03$ fm) likely by the end of 2028
Nuclear Excitation Modes

Laboratory measurements on nuclei | Astronomical observations of neutron stars
---|---
Radius | PREX, CREX | NICER
Polarizability | Electric dipole | Gravitational deformability

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The Isovector Giant Dipole Resonance in $^{208}$Pb

JP et al., PRC85, 041302 (2012); Roca-Maza et al., PRC88, 024316 (2013)

IVGDR: Coherent oscillations of protons against neutrons

Nuclear symmetry energy acts as restoring force for this mode

Energy weighted sum rule largely model independent

$\propto \frac{N_Z}{A}$

Electric dipole polarizability (IEWSR) sensitive to $L$:

$\alpha \propto a + bL$

Electric dipole polarizability a powerful complement to neutron skin

$5 \leq t \leq 10$

$R(t;E_1)$ ($\text{fm}^2/\text{MeV}$)

$E_1$ [MeV]

$208_{\text{Pb}}$

$52\text{MeV}$ $61\text{MeV}$ $72\text{MeV}$ $87\text{MeV}$ $109\text{MeV}$

$0 \leq t \leq 15$

$R(t)$ ($\text{fm}$)

$208_{\text{Pb}}$

$R^2_{\text{skin}}$ ($\text{fm}$)

$400 \leq R^* \leq 1400$

$1.4 \leq R_{\star} \leq 2.8$

Electric dipole polarizability from coulomb excitation. Potential systematic error from sum over excited states. Encourage ab initio calculations.

LIGO measured gravitational deformability (quadrupole polarizability) of NS from tidal excitation. Statistics limited but systematic errors controllable.

Laboratory measurements on nuclei

Astronomical observations of neutron stars

How Does Subatomic Matter Organize Itself?

MSU – October 1, 2014 19 / 20

Very clean electromagnetic experiment

Theory is lagging slightly behalf

Nuclear Excitation Modes
More generally, the nature of neutron stars, their crust, and layers, involve nuclear matter significantly more neutron-rich than normal matter and its properties are relevant for interpreting a wealth of astronomical data [Sch13, Oer17]. All of these observations point to the importance of the most neutron-rich isotopes and the need for FRIB400.

The following sections show that with the extended reach of 400 MeV/u beam production, FRIB400 will be poised to answer many of the key questions, such as: What do gravitational waves tell us about the neutron-matter EOS? What do neutrino signals reveal about supernova evolution? What do neutron-star cooling rates and astronomical X-ray data tell us about the structure of neutron stars? What are the sites of the $r$ process and how does it proceed to produce the heavy elements?

1.1 The nature of neutron stars and the nuclear equation of state

The EOS of nuclear matter relates temperature, pressure, and density of a nuclear system. It governs not only properties of nuclei and neutron stars but also the dynamics of nucleus-nucleus collisions and neutron-star mergers. The EOS also determines the amount of ejected matter from a neutron-star merger, which subsequently undergoes nucleosynthesis to form heavy elements up to uranium and beyond [Ros99, Bov17, Kas17, Fuj18, Hor19]. The ultimate fate of a neutron-star merger is also impacted by the EOS, determining whether the colliding neutron stars collapse promptly into a black hole, remain a single neutron star, or form a transient neutron star that collapses later into a black hole [Bat17]. The recent observation of GW170817 demonstrated that the gravitational-wave signal from neutron-star merger events encodes the properties of nuclear matter and its EOS through the tidal deformabilities of the neutron stars during in-spiral [Abb17a, Zha18, Pie19, Car19]. FRIB400 will allow laboratory study of asymmetric nuclear matter at twice normal nuclear density. Understanding dense, neutron-rich matter is important for interpretation of multi-messenger data from neutron-star mergers.

Given this sensitivity, the interpretation of multi-messenger observations from neutron-star mergers and their nucleosynthesis therefore requires a better understanding of the nuclear EOS. This makes experiments with FRIB400, which can probe the important higher density regime, particularly timely. In addition, given that gravitational-wave signals from neutron-star mergers offer unique new opportunities to directly constrain the nuclear EOS for very neutron-rich matter, laboratory constraints from measurements with neutron-rich nuclei at FRIB400 will provide additional constraints that will yield opportunities for significant new insight and discovery.

While the temperature dependence of the EOS is important for the description of mergers after the neutron stars make contact [Rad16, Han17], it builds on the understanding of cold nuclear matter. The EOS of homogeneous, cold nuclear matter can be expressed in terms of the density-dependent energy of the system. In leading order, the energy per nucleon...
The Facility for Rare Isotope Beams (FRIB) will be the world’s premier rare-isotope beam facility. It will make the majority (~80%) of the isotopes predicted to be bound available for experiments. These isotopes will allow researchers to understand atomic nuclei and their role in the Universe. The tremendous discovery potential of FRIB can be further extended with an energy upgrade of the FRIB linear accelerator to 400 MeV/u for uranium and to higher energies for lighter ions (FRIB400). This document outlines the outstanding and timely scientific opportunities made possible by FRIB400.

Intellectual challenges from 2013 NRC Decadal Study and the 2015 NSAC Long Range Plan

How does subatomic matter organize itself and what phenomena emerge?

How did visible matter come into being and how does it evolve?

Are fundamental interactions that are basic to the structure of matter fully understood?

How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

Specific questions included in the challenges

What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?

What is the origin of simple patterns in complex nuclei?

What is the nature of neutron stars and dense nuclear matter?

What is the origin of the elements in the Cosmos?

What are the nuclear reactions that drive stars and stellar explosions?

Why is there now more matter than antimatter in the Universe?

What are new applications of isotopes to meet the needs of society?

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FRIB400 will help to answer the challenges formulated for the field

17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research, 11 will benefit from FRIB400

| 2. Superheavy nuclei | 7. r process | 10. Medical |
| 16. rp process | 17. Weak interactions | 15. Mass surface |

FRIB400 will open new opportunities across all fields of rare-isotope science
We have entered the golden era of neutron-star physics; Many communities with one overarching goal!

Multi-messenger Astronomy with Gravitational Waves

- Binary Neutron Star Merger
- X-rays/Gamma-rays
- Neutrinos
- Visible/Infrared Light
- Radio Waves

Nuclear EOS Density Ladder
Each rung on the ladder relies on other methods for measuring the EOS that are often piggybacking on a neighboring one.

- pQCD
- Pulsar Timing: GW
- Pulse Profile: GW
- HIC: Pulse Profile
- PVES: IVGDR
- Chiral-EFT

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