Impact of Terrestrial Facilities on the Structure of the Neutron Star Crust

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The Neutron Star Crust and Surface
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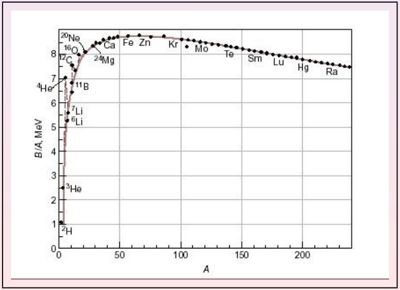
Outline

1. **Nuclear Physics 101**
   - Back (way back!) to Basics
2. **The Jefferson Laboratory**
   - The Parity Radius Experiment (PREX)
3. **Facility for Rare Isotope Beams (“FRIB”)**
   - Matter in the Crust of Neutron Stars
4. **The Overriding Question**
   - The Wigner Crystal to Fermi Liquid Transition
5. **Searching for the Answer**
   - Two Complementary Theoretical Approaches
     - Density Functional Theory
     - Semi-classical Molecular Dynamics

Back (way back!) to Basics (*circa 1935*)

Bethe-Weiszäcker Mass Formula

- $B(Z,N) = -a_{\rm v}A + a_{\rm s}A^{2/3} + a_{\rm c}Z^2/A^{1/3} + a_{\rm a}(N-Z)^2/A + \ldots$
- Nuclear forces saturate $\rightarrow$ equilibrium density.
- Nuclei penalized for developing a surface.
- Nuclei penalized by Coulomb repulsion.
- Nuclei penalized whenever $N \neq Z$.



$a_{\rm v} \simeq +16.0$ MeV

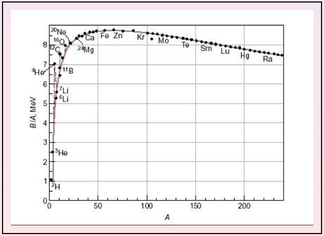
$a_{\rm s} \simeq +17.2$ MeV

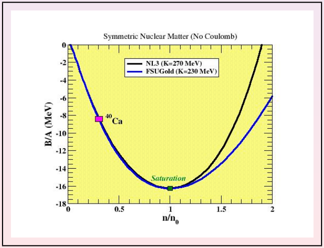
$a_{\rm c} \simeq +0.7$ MeV

$a_{\rm a} \simeq +23.3$ MeV

Making a surface costs energy ...

- $B(Z,N) = -a_{\rm v}A + a_{\rm s}A^{2/3} + \ldots$
- Nuclei penalized for developing a surface.
- Incompressibility controls how rapidly the energy increases.
- At $n \lesssim n_0/2$ the uniformity of the system is broken.
- Mixture of heavy clusters (nuclei) and nucleons (gas).





Neutron-Star Composition

Repeat above arguments for $N \neq Z$

- $B(Z,N) = -a_{\rm v}A + a_{\rm s}A^{2/3} + a_{\rm a}(N-Z)^2/A + \ldots$
- Neutron stars contained neutron-rich — not symmetric — matter.
- Nuclei penalized whenever $N \neq Z$.
- Density dependence of the symmetry energy poorly known.

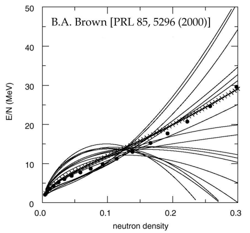


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

- Symmetry energy constrained close to saturation density.
- The slope (Pressure) completely unconstrained.

Why is PREX Important?

- First electroweak (*i.e.*, clean!) measurement of R_n.
- Fixes the pressure of neutron matter around saturation density.
- "Educated" extrapolation to high — and low — densities.

Determination of the Neutron Form Factor ($E = 850$ MeV and $\theta = 6^\circ$)

$$A_{\rm PV} \approx \frac{G_{\rm F} Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)} \,.$$

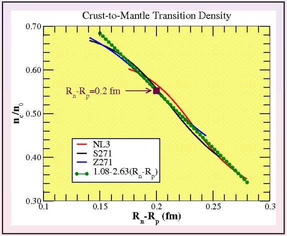
	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

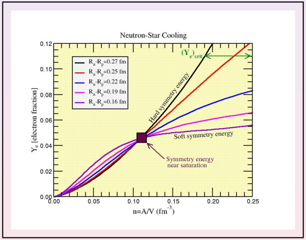
$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

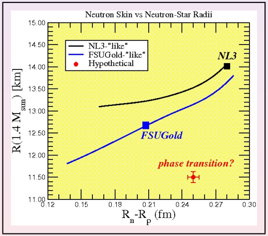
Why is PREX Important? (continuation ...)

(Some) Correlations to Neutron Star Properties

- Crust-to-Core transition density.
- Electron fraction and URCA cooling.
- Neutron star radius (Mass *vs* Radius).



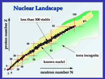




Impact on the Structure of the Neutron Star Crust

- Softer symmetry energy reaches drip lines first ...

Facility for Rare Isotope Beams (FRIB)



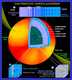
From NSAC Long Range Plan (Galveston, May 2007)

- *"We recommend construction of the Facility for Rare Isotope Beams (FRIB) a world-leading facility for the study of nuclear structure, reactions, and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society."*

Other *FRIB-like* Facilities Around the World

- ISAC @ TRIUMF in Vancouver, Canada.
- SPIRAL2 @ GANIL in CAEN, France.
- FAIR @ GSI in Darmstadt, Germany.
- RIB @ RIKEN in Wako, Japan (see also JUSTIPEN).

Wigner Crystal, Nuclear Pasta, and Fermi Liquid



The Crust-to-Core Transition

- At low densities (large distances) Coulomb interaction dominates
  Formation of a Wigner crystal in the outer core
- Rapid increase of electron energy with density yields
  Wigner crystal of progressively more neutron-rich nuclei
- At a density of $n_{\rm drip} = 4.3 \times 10^{11}\ {\rm g/cm^3}$
  Neutron-drip line is reached (just beyond ${}^{118}_{36}{\rm Kr}_{82}$)
- At higher densities crystal “melts” into **Nuclear Pasta**
  Nuclei coalesce into exotic shapes immersed in a neutron vapor
- At even higher densities uniformity is restored
  Uniform Fermi liquid of neutron-rich matter

The Overriding Question(s):

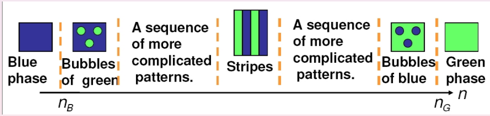
What characterizes the crust-to-core transition and what are the phases between the Fermi Liquid and the Wigner Crystal?

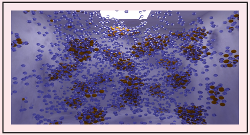
Steve Kivelson with Reza Jamei and Boris Spivak (UW)

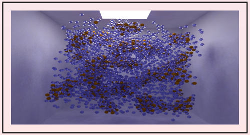
"Phases Intermediate Between the Two Dimensional Fermi Liquid and the Wigner Crystal"

A Universal Theorem:

"In the presence of long range interactions $V(r) \sim r^{-x}$, no first order phase transition is possible for $d-1 \leq x \leq d$. Rather, in place of the putative first order phase transition there are intermediate microemulsion phase(s)"







Density Functional Theory (DFT)

- Propose a suitable non-relativistic or relativistic DFT
- Calibrate the parameters of the DFT to reproduce large body of experimental data (Masses, Radii, Collective Excitations ...)
- Map the neutron drip lines to determine the sequence of neutron-rich nuclei in the outer crust
  $E_{\rm tot}(N,Z,B/V) = E_{nucleus} + E_{\rm lattice} + E_{\rm electronic}$
- Compute the EoS beyond neutron drip: nuclear lattice immersed in a vapor of superfluid neutrons (Wigner-Seitz, Band Theory, ...)
- Compute the crust-to-core transition density ($\checkmark$)
- Compute the EoS in the core assuming only “conventional” degrees of freedom (n, p, e, μ)($\checkmark$)

A single DFT — updated and properly calibrated — to compute the EoS from the outer crust to the inner core ...

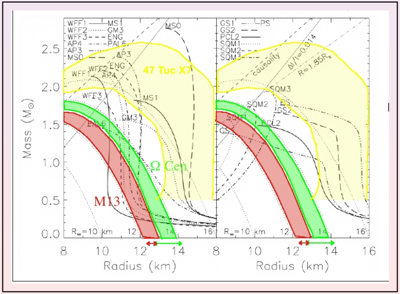
Semi-Classical Molecular Dynamics (MD)

- Propose a suitable non-relativistic interaction
  $V_{\text{total}} = V_{\text{nuclear}} + V_{\text{Coulomb}} + V_{\text{Pauli}} + \ldots$
- Calibrate (via MD) the parameters of the model to reproduce large body of data (Saturation properties, Masses, Radii, ...)
- Elucidate the crust-to-core transition
- What characterizes the transition (Universality?)
- What are the phases between the Fermi Liquid - Wigner Crystal?
- What is the impact on the nuclear pasta on transport properties?
- ...

Complimentary to DFT approach: no quantum correlations but other dynamical effects treated exactly. (Semi-classical calculation justified based on the large size of the clusters)

From Chicago's Long Range Plan Meeting

- *"The Mass-Radius relationships calculated with proposed EOSs, — and the theoretical ambiguousness as to which is preferred — are commonly cited in X-ray observing proposals. Guidance from the nuclear community in the viability of proposed EOSs motivates granting X-ray observations by telescope allocation committees. This returns constraints on the EOS to the nuclear physics community."*



- Let's keep the partnership alive!
- Let's pursue young talent:
  Students love the cosmic connection!