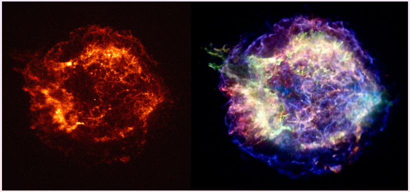
The Nuclear Physics of Neutron Stars

5th ANL/MSU/JINA/INT Workshop
Bulk Nuclear Properties

MSU November 19-22, 2008



Collaborators:

- C.J. Horowitz, D. Berry, J. Carriere, H. Dussan, M.A. Pérez-Garcia (IU)
- B. Futch, X. Roca, J. Taruna, B.G. Todd-Rutel, G. Toledo-Sánchez (FSU)

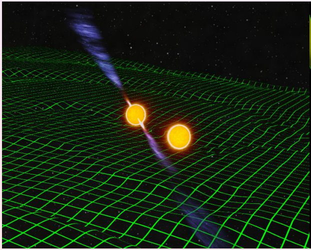
Outline

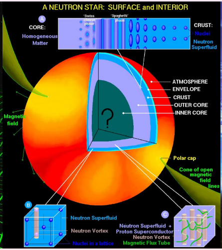
1. **Motivation**
2. **Relativistic Density Functional**
3. **The Anatomy of a Neutron Star**
    - Outer Crust: The physics of neutron-rich nuclei
    - Inner Crust: The physics of the “nuclear pasta"
    - Outer/Inner Core: The physics of neutron-rich (quark?) matter
4. **Heaven on Earth: Future Experiments and Facilities**
    - PREX@JLAB
    - Facility for Rare Isotope Beams (FRIB)
5. **Conclusions and Outlook**

Motivation

- Neutron Stars are bound by gravity not by the strong force
- Gravity is the catalyst for the formation of novel states of matter
  Coulomb crystal of neutron-rich nuclei
  Coulomb frustrated pasta structures
  Color superconductivity in quark matter

Neutron stars are the natural meeting place of astro, atomic, condensed-matter, nuclear, and particle, physics.





Relativistic Density Functional: The Effective Lagrangian Density

$$\mathcal{L}_{\rm int} = g_{\rm s}\bar{\psi}\psi\phi - g_{\rm v}\bar{\psi}\gamma^{\mu}\psi V_{\mu} - \frac{g_{\rho}}{2}\bar{\psi}\gamma^{\mu}\boldsymbol{\tau}\cdot\mathbf{b}_{\mu}\psi - e\bar{\psi}\gamma^{\mu}\tau_{p}\psi A_{\mu}$$

$$-\frac{\kappa}{3!}(g_{\rm s}\phi)^{3} - \frac{\lambda}{4!}(g_{\rm s}\phi)^{4} + \frac{\zeta}{4!}g_{\rm v}^{4}(V_{\mu}V^{\mu})^{2} + \Lambda_{\rm v}(g_{\rm v}^{2}V^{\mu}V_{\mu})(g_{\rho}^{2}b^{\mu}b_{\mu})$$

- Host of ground-state observables computed at the MF level
- FSUGold incorporates constraints from collective modes (RPA)
- Model parameters encode correlations beyond MF

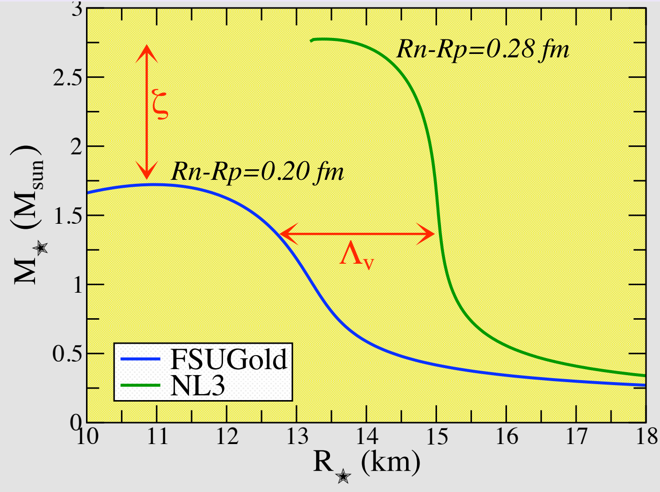
Bulk Parameters: $x \equiv (\rho - \rho_0)/3\rho_0$

$$E_{\rm PNM}(x) \simeq E_{\rm SNM}(x) + S(x) = \left(\varepsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + Lx + \frac{1}{2}K_{\rm sym}x^2\right)$$

Model	$\rho_0({\rm fm}^{-3})$	ε_0(MeV)	K_0(MeV)	J(MeV)	L(MeV)	$K_{\rm sym}$(MeV)
FSU	0.148	-16.30	230.00	32.59	60.51	-51.29
NL3	0.148	-16.24	271.54	37.29	118.19	$+100.89$

Neutron Stars: Mass-Radius Relationship

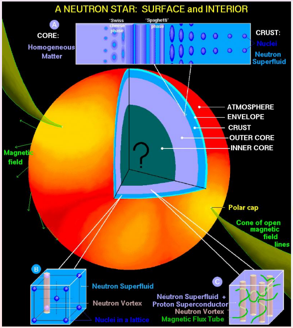
- Model independent constraint on the EoS of cold dense matter
- Parameter ζ used to tune maximum mass
- Parameter Λ_v used to tune radii

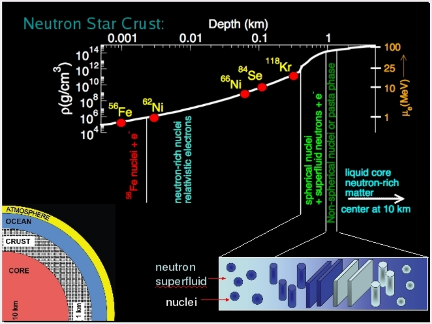


Anatomy of a Neutron Star

From Crust to Core (Figures courtesy of Dany Page and Sanjay Reddy)

- Outer Crust: $10^{-10}\rho_0 \lesssim \rho \lesssim 10^{-3}\rho_0$
  "Coulomb Crystal" of progressively more neutron-rich nuclei
- Inner Crust: $10^{-3}\rho_0 \lesssim \rho \lesssim 10^{-1}\rho_0$
  "Nuclear Pasta" Exotic shapes immersed in a neutron vapor
- Outer/Inner Core: $10^{-1}\rho_0 \lesssim \rho \lesssim 10\rho_0$
  "Fermi Liquid" of uniform neutron-rich matter (*"Exotic Phases?"*)

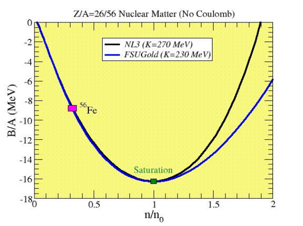


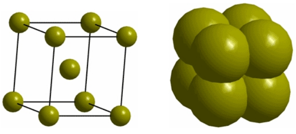


The Outer Crust: $10^{-10}\rho_0 \lesssim \rho \lesssim 10^{-3}\rho_0$

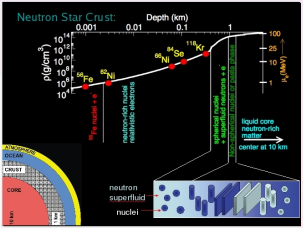
Non-Uniform Nuclear Matter

- At $\rho \lesssim \rho_0/2$, $B/A(\mathrm{uniform}) \simeq B/A(^{56}\mathrm{Fe})$
- Broken symmetry (non-uniform) state energetically favorable
- Nuclear Crystal immersed in a uniform Fermi sea of electrons
- $E/A_{\mathrm{tot}} = M(N,Z)/A + 3/4\,Y_e^{4/3} k_{\mathrm{Fermi}} + \mathrm{lattice}$
- As density increases in the outer crust, ^{56}Fe, ^{62}Ni, ..., $^{118}_{36}\mathrm{Kr}_{82}$(?)





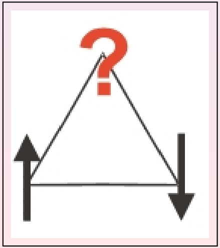
Iron : a body-centered cubic (bcc) lattice

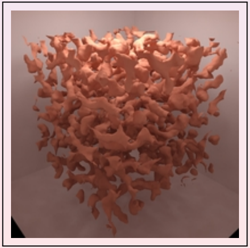


The Inner Crust: $10^{-3}\rho_0 \lesssim \rho \lesssim 10^{-1}\rho_0$

"Dynamical Frustration and Nuclear Pasta"

- Emerges from a dynamical competition
- Impossibility to minimize all elementary interactions
- Emergence of a multitude of competing (quasi)ground states
- Universal in complex systems (nuclei, low-D magnets, proteins,...)
- Short-range attraction and long-range (Coulomb) repulsion
- Emergence of complex topological shapes *"Nuclear Pasta"*





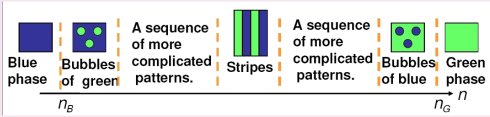
Theory of Electronic Micro-Emulsions (2D Electron Gas)

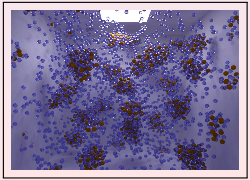
Steve Kivelson, Reza Jamei, and Boris Spivak

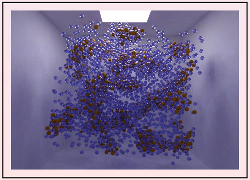
“Phases Intermediate Between the Two Dimensional Fermi Liquid and the Wigner Crystal”

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)”


Blue phase
Bubbles of green
A sequence of more complicated patterns.
Stripes
A sequence of more complicated patterns.
Bubbles of blue
Green phase

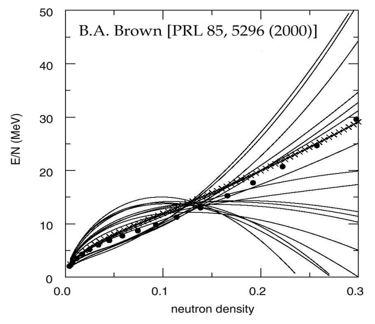




The Outer/Inner Core: $10^{-1}\rho_0 \lesssim \rho \lesssim 10\rho_0$

Fixing the density dependence of the symmetry energy ...

- Uniform neutron-rich matter in chemical equilibrium
  neutrons, protons, electrons, muons, ???
- Structurally the most important component of the star
  $\sim$ 90% of the radius and all the mass reside in the core
- Density dependence of the symmetry energy poorly known
  $B(Z,N) = \ldots a_{\rm a}(N-Z)^2/A + \ldots$ $[E_{\rm PNM} \approx E_{\rm SNM} + SymmE]$

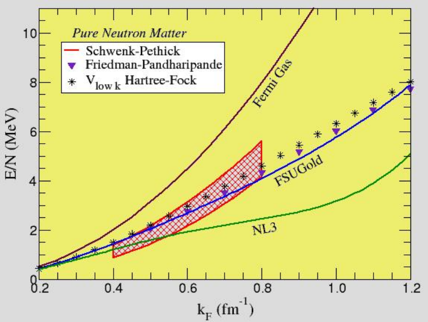


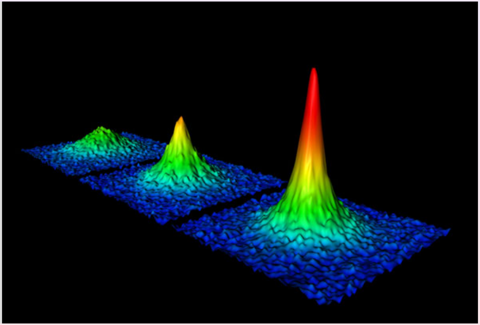
- Symmetry energy $a_{\rm a}$ constrained at $\rho \approx \rho_0$
- The slope (Pressure P) unconstrained at $\rho \approx \rho_0$
- One-to-one correlation between P and the neutron radius of a heavy nucleus!

Theoretical Constraints: Fermi gases at (or close to) unitarity

J. Carlson *et al.*, Nishida&Son; Schwenk&Pethick; ...

- Universality of $a \to \infty$ dilute Fermi gases: $E = \xi E_{\rm FG}$ $(\xi \approx 0.4)$
- Pure neutron matter displays strong pairing correlations
- Pure neutron matter $|r_e/a| \approx 0.15$: $E = \xi(k_{\rm F} r_e) E_{\rm FG}$





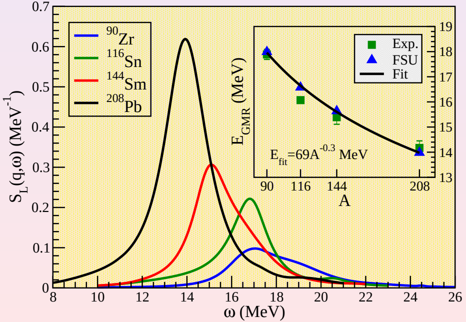
Consistent with $L \simeq 60$ MeV and $R_n - R_p \simeq 0.2$ fm

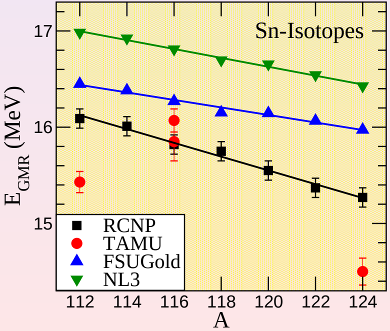
Experimental Constraints: Compressibility of Neutron-Rich Matter

U. Garg *et al.*, G. Colò, H. Sagawa *(“Why is Tin so Fluffy?”)*

Quite generally, it is found that for $\alpha \equiv (N-Z)/A \neq 0$:

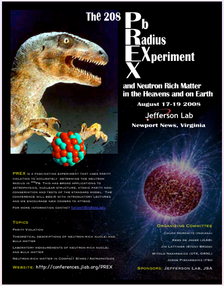
- The saturation density is reduced
- The binding energy weakens
- The nuclear incompressibility softens:
  $K(\alpha) = K_0 - |K_\tau|\alpha^2 \quad (K_\tau \approx K_{\rm sym} - 6L)$





PREX@JLAB: Michaels, Souder, Urciuoli, C. J. Horowitz, S. J. Pollock

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



The 208 Pb Radius EXperiment X

and Neutron Rich Matter in the Heavens and on Earth

August 17-19 2008

Jefferson Lab

Newport News, Virginia

PREX is a fascinating experiment that uses parity violation to accurately determine the neutron radius in ^{208}Pb. This has broad applications to astrophysics, nuclear structure, atomic parity non-conservation and tests of the standard model. The conference will begin with introductory lectures and we encourage new comers to attend.

For more information contact horowit@indiana.edu

Topics

Parity Violation

Theoretical descriptions of neutron-rich nuclei and bulk matter

Laboratory measurements of neutron-rich nuclei and bulk matter

Neutron-rich matter in Compact Stars / Astrophysics

Website: http://conferences.jlab.org/PREX

Organizing Committee

Chuck Horowitz (Indiana)

Kees de Jager (JLAB)

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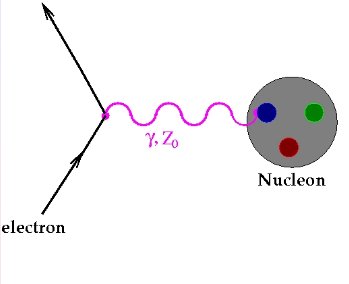
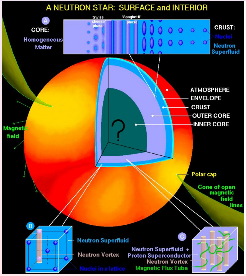


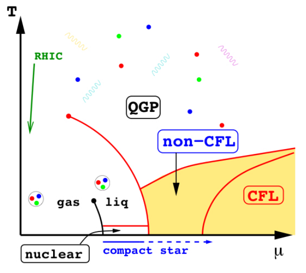
	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

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

Color superconductivity in quark matter (Alford, Rajagopal, Wilczek ...)

- At small distance scales QCD becomes asymptotically free
- At high densities Color Coulomb interaction is weak and attractive
- At *ultra-high* densities u, d, s quarks are effectively massless
- Ground state: a *color-flavor locked (CFL)* superconductor
  Complete pairing of all quarks: $\langle q_i^{\alpha} q_j^{\beta} \rangle \sim \Delta \epsilon_{ijA} \epsilon^{\alpha\beta A}$
- If $m_s \simeq \mu$ it is unclear what is the most favorable pairing pattern?
- How does the BCS state evolves as the spin populations become unbalanced? Fulde-Ferrell–Larkin-Ovchinnikov (FFLO) state?

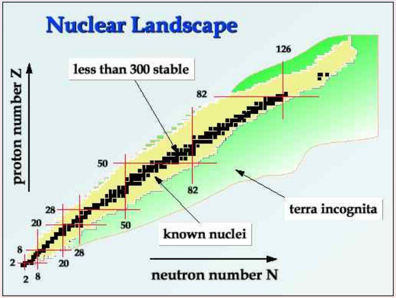




Facility for Rare Isotope Beams

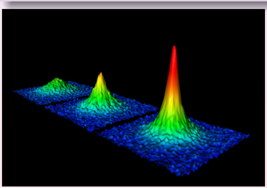
From NSAC Long Range Plan (Galveston, May 2007)

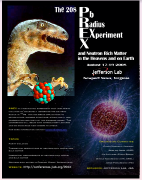
- *"We recommend construction of the Facility for Rare Isotope Beams (FRIB) a world-leading facility for the study of nuclear structure, reactions, and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements 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."*

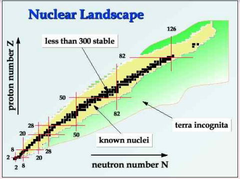


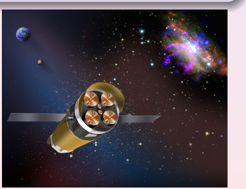
Conclusions and Outlook

- What is the drip density and drip nucleus in a neutron star?
  Sensitive only to drip-line nuclear masses
  FRIB: The future of nuclear structure
- Understanding the physics of frustration: Nuclear Pasta
  What are its unique signatures?
  Can one avoid pasta formation in 3D?
- Understanding high-density matter:
  Color superconductors?
  The role of heavy-ion experiments?
  The promise and reliability of present/future missions?









The physics of neutron stars is a goldmine of problems in astro, atomic, condensed-matter, nuclear, and particle physics!