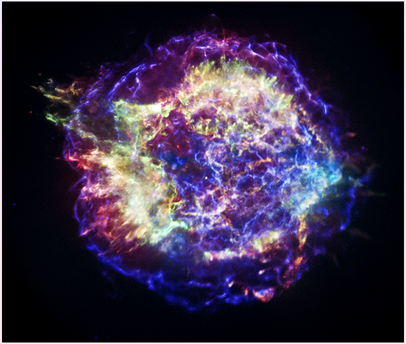
Pygmies, Giants, and Skins: Reaction Theory Informing Nuclear Structure

Reactions and Structure of Exotic Nuclei
INT Workshop – March, 2015



Cassiopeia A (circa 1675) – *Giant (Hercules) Awakes and Drives off the Pygmies,* by Lucas The Younger Cranach (1551)

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- Karim Hasnaoui
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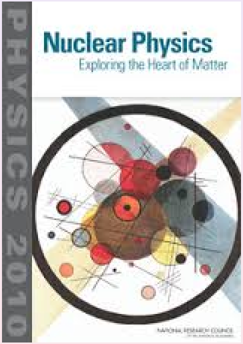
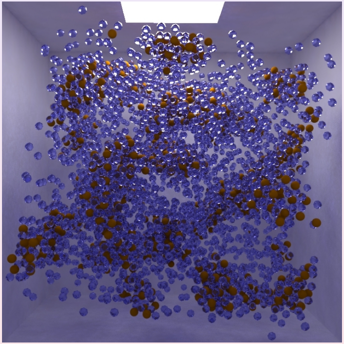
A Grand Challenge: How does subatomic matter organize itself?

"Nuclear Physics: Exploring the Heart of Matter" **(2010 Committee on the Assessment and Outlook for Nuclear Physics)**

- Consider A nucleons and Z leptons in a fixed volume V at $T \equiv 0$
  ... cold fully catalyzed matter in thermal and chemical equilibrium
- Enforce charge neutrality *protons = electrons + muons*
- Enforce chemical (i.e., beta) equilibrium: $n \to p + e^- + \bar{\nu}; \quad p + e^- \to n + \nu$

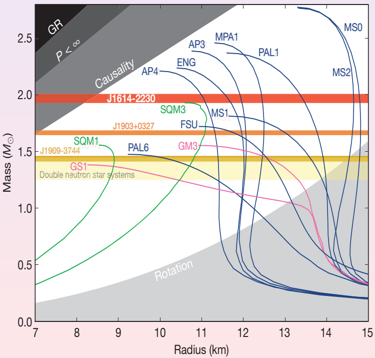




Impossible to answer such a question under normal laboratory conditions — as such a system is in general unbound!

Neutron Stars as Nuclear Physics Gold Mines

- Neutron Stars are the remnants of massive stellar explosions
  - Are bound by gravity NOT by the strong force
  - Satisfy the Tolman-Oppenheimer-Volkoff equation ($v_{\rm esc}/c \sim 1/2$)
- Only Physics sensitive to: Equation of state of neutron-rich matter
  - EOS must span about 11 orders of magnitude in baryon density
- Increase from $0.7 \to 2 M_{\odot}$ must be explained by Nuclear Physics!



$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

Need an EOS: $P = P(\mathcal{E})$ relation

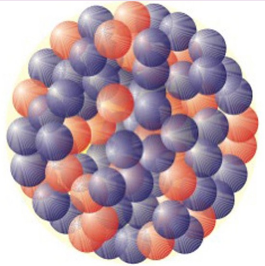
Nuclear Physics Critical

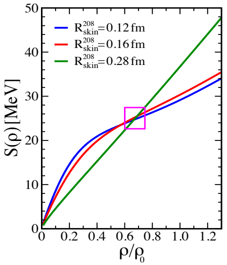
Where do the extra neutrons go?

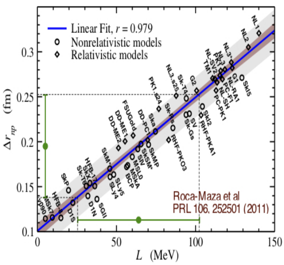
- The EOS of asymmetric matter $\left[\alpha \equiv (N-Z)/A,\ x \equiv (\rho-\rho_0)/3\rho_0\right]$

$$\mathcal{E}(\rho,\alpha) \approx \mathcal{E}_0(\rho) + \alpha^2 \mathcal{S}(\rho) \approx \left(\epsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + \boxed{L}\, x + \frac{1}{2}K_{\rm sym} x^2\right)\alpha^2$$

- In ^{208}Pb, 82 protons/neutrons form an isospin symmetric spherical core
  Where do the extra 44 neutrons go?
- Competition between surface tension and **density dependence** of $\mathcal{S}(\rho)$
  Surface tension favors placing them in the core where $\mathcal{S}(\rho_0)$ is large
  Symm. energy favors pushing them to the surface where $\mathcal{S}(\rho_{\rm surf})$ is small
- If difference $\mathcal{S}(\rho_0) - \mathcal{S}(\rho_{\rm surf}) \propto L$ is large, then neutrons move to the surface
  The larger the value of L the thicker the neutron skin of ^{208}Pb

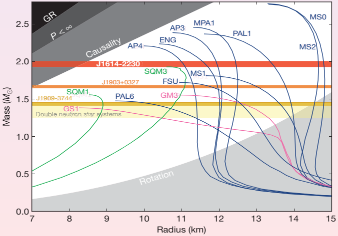


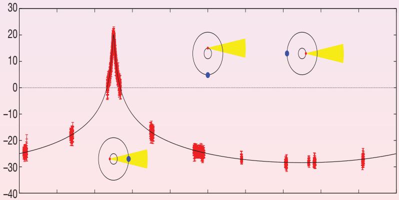




Heaven and Earth: Nuclear Physics Informing Neutron Stars

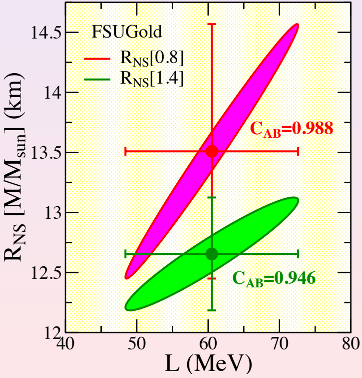
- Neutron-star radii sensitive to one fundamental parameter of the EOS
  The slope of the symmetry energy at saturation density $L \propto P_{PNM}$
- Symmetry energy approximately equal to $S \simeq E_{PNM} - E_{SNM}$
- Heavy nuclei — such as ^{208}Pb — develop a neutron-rich skin
  Thickness of the neutron skin $(R_n - R_p)$ is also sensitive to L
- Same pressure creates neutron-rich skin and NStar radius
  Correlation among observables differing by 18 orders of magnitude!
- **PREX-II places a significant constraint on neutron-star radii!**
  $R^{208}_{\rm skin} = (0.207 \pm 0.037)\,$fm; $R^{0.8}_{NS} = (13.509 \pm 1.060)\,$km; $R^{1.4}_{NS} = (12.655 \pm 0.470)\,$km

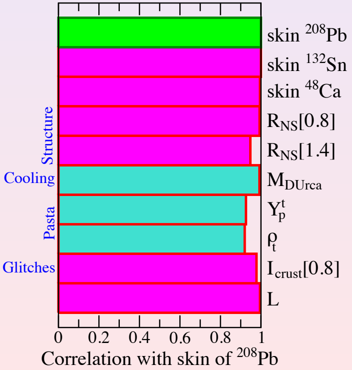




The Enormous Reach of the Neutron Skin: Covariance Analysis

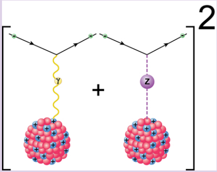
- Neutron skin as proxy for neutron-star radii . . . and more!
- Calibration of nuclear functional from optimization of a quality measure
- Predictions accompanied by meaningful theoretical errors
- Covariance analysis least biased approach to uncover correlations
- Neutron skin strongly correlated to a myriad of neutron star properties:
  Radii, Enhanced Cooling, Moment of Inertia, . . .





Parity Violation in Elastic e-Nucleus Scattering (JLab and Mainz)

- Charge (proton) densities known with exquisite precision
  charge density probed via parity-conserving eA scattering
- Weak-charge (neutron) densities very poorly known
  weak-charge density probed via parity-violating eA scattering



$$A_{\rm PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[\underbrace{1-4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

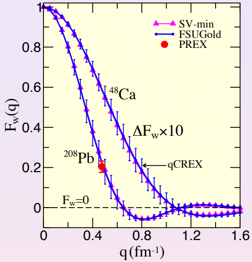
- Use parity violation as Z_0 couples preferentially to neutrons
- PV provides a clean measurement of neutron densities (R_n^{208})

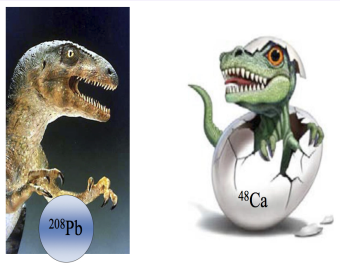
	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

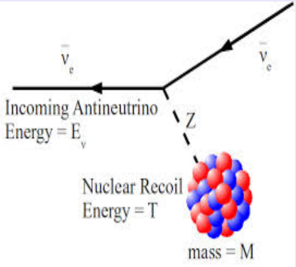
$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

PREX: The Lead Radius EXperiment Abrahamyan et al., PRL 108, (2012) 112502

- **Ran for 2 months: April-June 2010**
- First electroweak observation of a neutron-rich skin in ^{208}Pb
- Promised a 0.06 fm measurement of R_n^{208}; error 3 times as large!







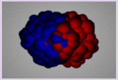
We report the first measurement of the parity-violating asymmetry A_{PV} in the elastic scattering of polarized electrons from ^{208}Pb. A_{PV} is sensitive to the radius of the neutron distribution (R_n). The result $A_{PV} = 0.656 \pm 0.060(\text{stat}) \pm 0.014(\text{syst})$ ppm corresponds to a difference between the radii of the neutron and proton distributions $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nucleus.

A Physics case for PREX-II, CREX, and ...
Coherent ν-nucleus scattering

The Isovector Giant Dipole Resonance in ^{208}Pb (RCNP, GSI/FAIR, S-DALINAC)

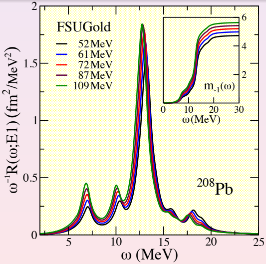
- IVGDR: *Coherent oscillations of protons against neutrons*

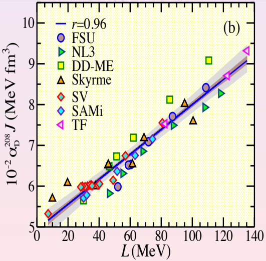
  Nuclear symmetry energy acts as the restoring force for this mode

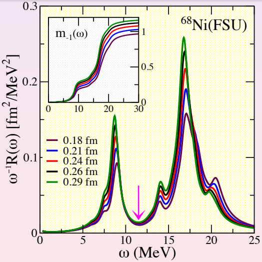


- Oldest Nuclear Giant Resonance; γ-absorption (1937)
- Electric dipole polarizability sensitive to slope of symmetry energy *L*
- Ongoing campaigns to measure dipole polarizability in exotic nuclei

  Pygmy resonance as an exotic mode in exotic nuclei







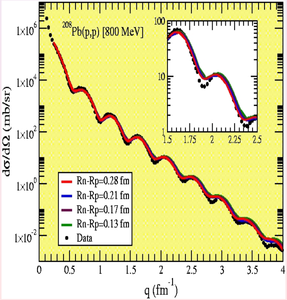
Electric Dipole Polarizability as a Fundamental Complement to Neutron Skins!

PREX-II, CREX, and ν-Coherent as Anchors for FRIB Physics

"One of the main science drivers of FRIB is the study of nuclei with neutron skins 3-4 times thicker than is currently possible. JLab uses parity violation to measure the neutron radius of stable isotopes. Studies of neutron skins at JLab and FRIB will help pin down the behavior of nuclear matter at densities below twice typical nuclear density" Exploring the Heart of Matter

The Traditional Approach: Proton-Nucleus Scattering

- Large and uncontrolled uncertainties in the reaction mechanism
- Enormous ambiguities yield an energy dependent neutron skin
- FRIB will scatter protons from radioactive nuclei in inverse kinematics
- FRIB must use PREX-II, CREX, and ν-Coherent as calibrating anchors!



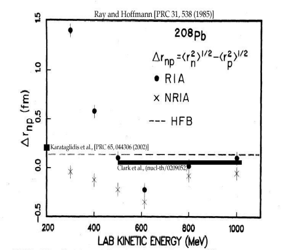
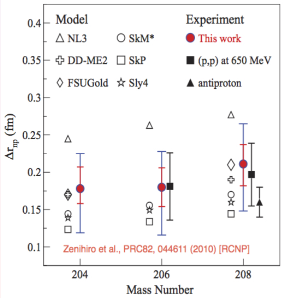


FIG. 10. Same as Fig. 8 except that the ^{208}Pb results are shown. The theoretical value of 0.13 fm (Ref. 39) is indicated by the dashed line.



Food for thought: A few open questions ...

Studies of Neutron Skins at JLab and FRIB will help pin down the behavior of nuclear matter ...

- Can PREX-II and CREX play the role of calibrating anchors?
- How does one reliably separate the nuclear structure from the reaction mechanism?
- What are the most serious challenges facing reaction theory?
- How does one validate models and quantify theoretical uncertainties?
  Use your model to quantify statistical uncertainties
  Use many models to quantify sytematic uncertainties
  "Neutron densities of ^{204,206,208}Pb via proton elastic scattering at $E_p = 295$MeV"
- How does one impress upon the community the importance of reaction theory?
- How does one attract young talent to the field?
- What have we learned from TORUS?