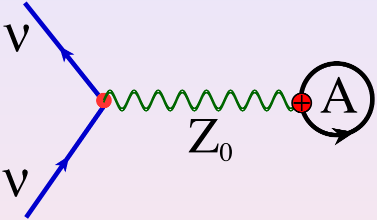
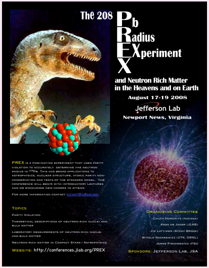
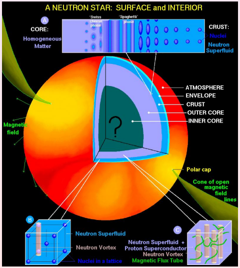
Neutron Densities and Neutron Stars

ν-Coherent Theory Workshop
NCState - January 11-12, 2015







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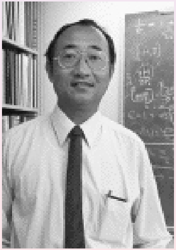
Density Functional Theory (W. Kohn: 1998 Chemistry Nobel Prize)

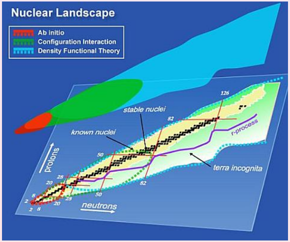
- DFT enormously successful in chemistry/condensed-matter physics
  Hohenberg, Kohn, Sham, ...
- DFT shifts the emphasis from the wave function to the density
  from the 3N-dimensional $\Psi(\mathbf{r}_1, \ldots, \mathbf{r}_N)$ to 3-dimensional $\rho(\mathbf{r})$
- Ground-state properties uniquely determined by an electron density
- Electron density obtained by minimizing a suitable energy functional
- In principle, DFT incorporates all many-body effects (Kohn Nobel lecture)

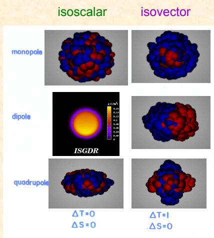


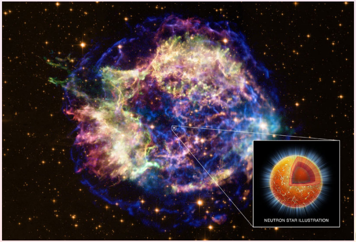



Nuclear Density Functional Theory

- ab-initio calculations of heavy nuclei remain a daunting task
- Search for an energy functional valid through the entire nuclear chart:
  to compute ground-state properties, collective excitations, ...
  to compute neutron-star structure, dynamics, composition, ...
- Incorporate physical insights into the construction of the functional
- Empirical constants directly fitted to many-body observables
  ... such as masses, charge radii, giant resonances, ...
- Complicated many-body dynamics encoded in the empirical constants
- Empirical constants obtained from the optimization of a quality measure

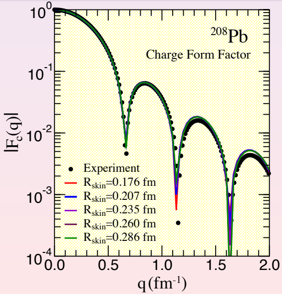


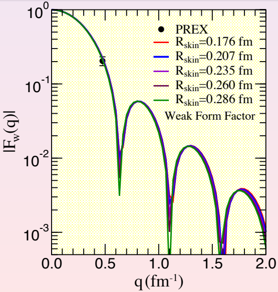


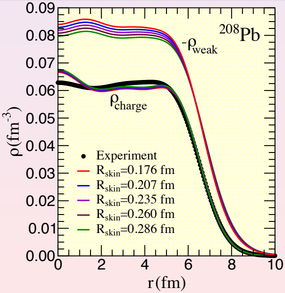


Neutron Skins and Density Dependence of the Symmetry Energy

- Neutron densities are as fundamental as proton (charge) densities
  Yet, still elusive after more than 80 years of nuclear physics
- Hinders our understanding of density dependence symmetry energy
  Penalty for breaking $N\!=\!Z$ symmetry $[B(Z,N) = -a_{\rm a}(N-Z)^2/A + \ldots]$
- Neutron skin strongly correlated to the symmetry pressure $L \propto P_{\rm PNM}$
  Slope (pressure) of pure neutron matter poorly constrained
- Symmetry pressure pushes against surface tension $\Rightarrow$ n-skin
- Symmetry pressure pushes against gravity $\Rightarrow$ neutron star radius





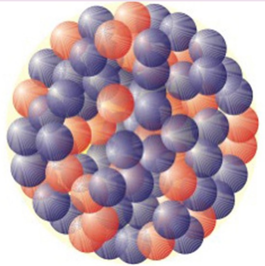


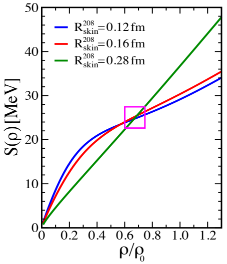
Where do the extra neutrons go?

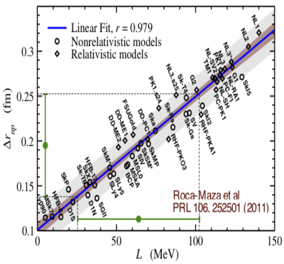
- The EOS of asymmetric matter $\left[\alpha \equiv (N-Z)/A,\ x \equiv (\rho-\rho_0)/3\rho_0\right]$

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

- 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



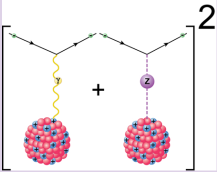




The Modern Approach: PV in Elastic Electron-Nucleus Scattering

Donnelly, Dubach, Sick, NPA 503, 589 (1989); Abrahamyan PRL 108, (2012) 112502; Horowitz PRC 85, (2012) 032501

- Charge (proton) densities known with enormous 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



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

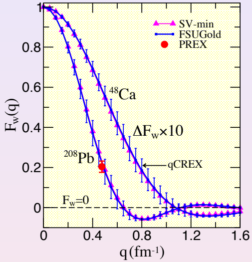
- Use parity violation as Z_0 couples preferentially to neutrons
- PV provides a clean measurement of neutron densities (R_n^{208})

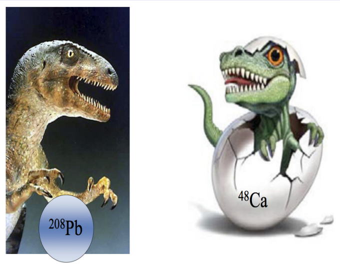
	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

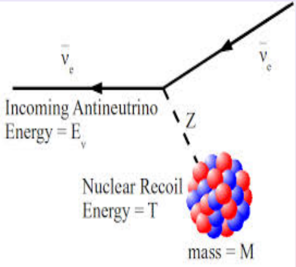
$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

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.

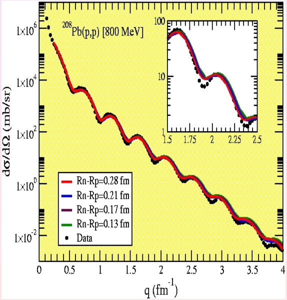
A Physics case for PREX-II, CREX, and ...
Coherent ν-nucleus scattering

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!



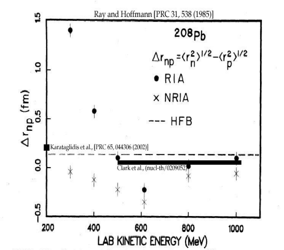
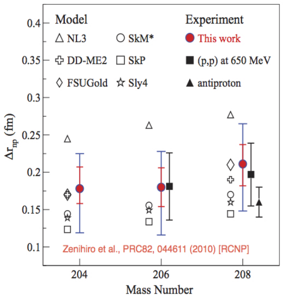
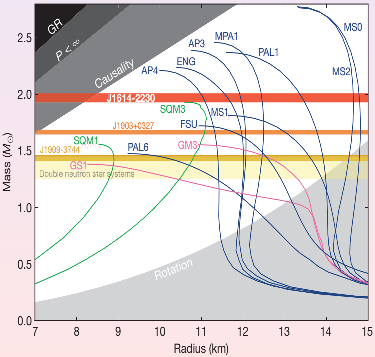


FIG. 10. Same as Fig. 8 except that the ^{208}Pb results are shown. The theoretical value of 0.13 fm (Ref. 39) is indicated by the dashed line.



Gravitationally Bound Neutron Stars as Physics Gold Mines

- Neutron Stars are bound by gravity NOT by the strong force
- Neutron Stars satisfy the Tolman-Oppenheimer-Volkoff equation
  GR extension of Newtonian gravity: $v_{\rm esc}/c \sim 1/2$
- Only Physics sensitive to is: **Equation of State**
- EOS must span 10-11 orders of magnitude in baryon density
- Increase from $0.7 \rightarrow 2 M_{\odot}$ 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

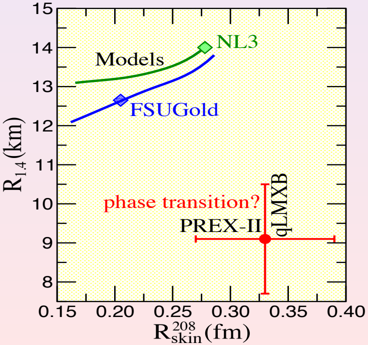
Nuclear Physics Critical

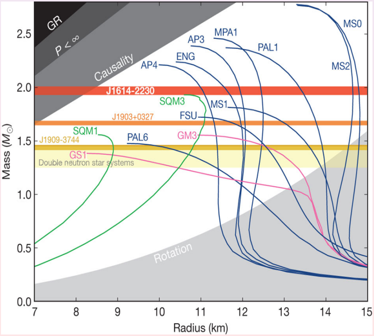
Heaven on Earth: Neutron Skins and Neutron Stars

Demorest *et al.*, Nature 467, 1081 (2010); Antoniadis *et al.*, Science 340, (2013)

- Same dynamical origin to neutron skin and NS radius $\Rightarrow L$
- Correlation among observables differing by 18 orders of magnitude!
- **The larger the neutron skin, the larger the neutron-star radius ...**
- Enormous uncertainty in the prediction of neutron-star radii
- **PREX-II and Coherent ν-nucleus scattering place significant constraints on neutron-star radii!**

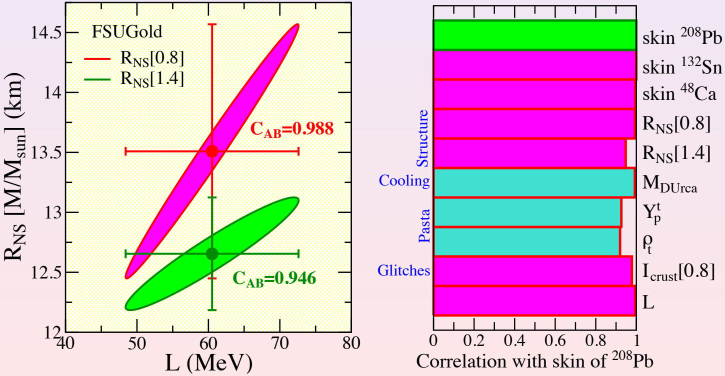
$R_{\rm skin}^{208} = (0.207 \pm 0.037)\,{\rm fm}$; $R_{NS}^{0.8} = (13.509 \pm 1.060)\,{\rm km}$; $R_{NS}^{1.4} = (12.655 \pm 0.470)\,{\rm km}$





The Enormous Reach of the Neutron Skin

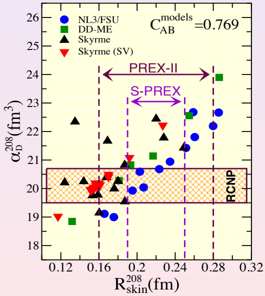
- Neutron skin as proxy for neutron-star radii . . . and more!
- Calibration of nuclear functional from optimization of a quality measure
- Predictions accompanied by meaningful theoretical errors
- Covariance analysis least biased approach to uncover correlations
- Neutron skin strongly correlated to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

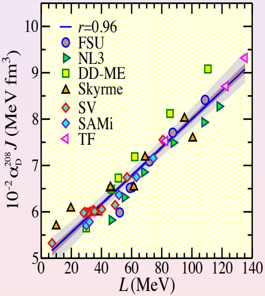


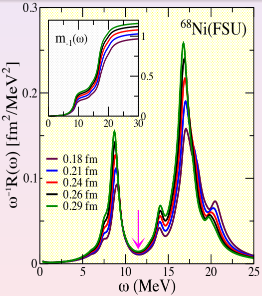
The Electric Dipole Polarizability in ^{208}Pb

Reinhard and Nazarewicz PRC81, 051303 (2010); RCNP: Tamii *et al.*, PRL107, 062502 (2011)

- IVGDR: *Coherent oscillations of protons against neutrons*
  Oldest Nuclear Giant Resonance; γ-absorption (1937)
  Nuclear symmetry energy acts as the restoring force
- Pioneering measurement of E1-polarizability at RCNP
  ω^{-2} moment of the γ-absorption cross section
- E1 polarizability as a complement to $R_{\rm skin}^{208}$ in the search for L



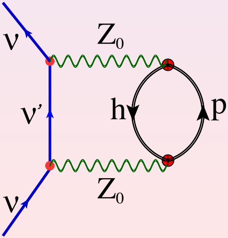


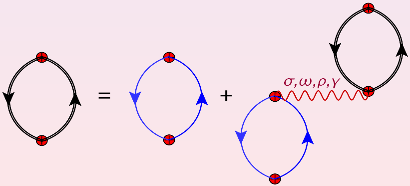


Electric Dipole Polarizability a Fundamental Complement to Neutron Skins

Nuclear Density Functional Theory ... continuation

- Densities determined by minimizing a suitable energy functional
- Small-density oscillations around the minimum $\Rightarrow$ inelastic response
- RPA formalism provides the consistent response of MF ground state
  - Required to preserve current conservation
  - Required for the decoupling of spurious modes
- Residual *ph* interaction must be consistent with MF interaction
- Empirical constants constrained from the calibration procedure
  - Coupling constants and ranges associated with σ, ω, ρ
  - Isovector sector poorly constrained – especially π-ρ-g'
- Inelastic ν-Nucleus scattering formalism largely in place
  - Except for large uncertainties in the isovector sector





$$\Pi_{RPA} = \Pi_0 + \Pi_0 V \Pi_{RPA}$$

Conclusions and Outlook

- Coherent ν-A scattering a fundamental probe of neutron densities
  Electroweak measurements critical
  Complement to PREX/CREX at JLAB
  Anchor for future hadronic experiments at FRIB
- Coherent ν-A scattering as a constraint on neutron-star structure
  Same dynamical origin to neutron skin and stellar radius
  Access to a fundamental bulk parameter of the EOS $\Rightarrow L$
  L strongly correlated to various neutron-star observables
- InCoherent ν-A scattering as a constrain on the isovector sector
  Relativistic RPA formalism largely in place (dipole excitations)
  However, large uncertainties in the isovector residual interaction

The Coherent ν-A reaction addresses a suite of compelling and fundamental science questions!