Neutron Skins in Nuclei
31st Annual HUGS Program
(Jorge Piekarewicz - FSU)

The 208 PbEXperiment
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 208Pb. 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 coming to attend. For more information contact: hawton@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 Hogwitz (Indiana)
Kees de Jager (JLAB)
Jim Lattimer (Stony Brook)
Witold Nazarewicz (UTK, ORNL)
Jorge Piekarewicz (FSU)

Sponsors: Jefferson Lab, JSA
Conclusions and Outlook

Astrophysical Constraints on the EOS

The impact of the neutron skin of $^{208}$Pb on the physics of neutron stars
Neutron Stars: Unique Cosmic Laboratories

- Neutron stars are the remnants of massive stellar explosions (CCSN)
  - Bound by gravity — NOT by the strong force
  - Catalyst for the formation of exotic state of matter
  - Satisfy the Tolman-Oppenheimer-Volkoff equation ($v_{\text{esc}} / c \sim 1/2$)

- Only Physics that the TOV equation is sensitive to: Equation of State
  - EOS must span about 11 orders of magnitude in baryon density

- Increase from 0.7 → 2 Msun transfers ownership to Nuclear Physics!
  - Predictions on stellar radii differ by several kilometers!

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

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

Nuclear Physics Critical
The Equation of State of Neutron-Rich Matter

- The EOS of asymmetric matter: $\alpha = (N-Z)/A; \ x = (\rho - \rho_0)/3 \rho_0; \ T=0$
  - $\rho_0 \approx 0.15 \text{ fm}^{-3} \ — \ saturation \ density \ ↔ \ nuclear \ density$
  - $\epsilon(\rho, \alpha) \approx \epsilon_0(\rho) + \alpha^2 S(\rho) \approx \left( \epsilon_0 + \frac{1}{2} K_0 x^2 \right) + \left( J + Lx + \frac{1}{2} K_{\text{sym}} x^2 \right) \alpha^2$

- Symmetric nuclear matter saturates:
  - $\epsilon_0 \approx -16 \text{ MeV} \ — \ binding \ energy \ per \ nucleon \ ↔ \ nuclear \ masses$
  - $K_0 \approx 230 \text{ MeV} \ — \ nuclear \ incompressibility \ ↔ \ nuclear \ “breathing” \ mode$

- Density dependence of symmetry poorly constrained:
  - $J \approx 30 \text{ MeV} \ — \ symmetry \ energy \ ↔ \ masses \ of \ neutron-rich \ nuclei$
  - $L \approx ? \ — \ symmetry \ slope \ ↔ \ neutron \ skin \ (R_n-R_p) \ of \ heavy \ nuclei$
Bayes’ Theorem
Thomas Bayes (1701-1761)

\[ P(A|B) = \frac{P(B|A)P(A)}{P(B)} \]

A simple example: “False Positives”
- A: Individual is infected with the HIV virus
- B: Individual tests positive to HIV test

The priors and the likelihood
- \( P(A) = 1/200 \) ("prior" knowledge; 0.5% of population is infected)
- \( P(B|A) = 98/100 \) (likelihood of the evidence; accuracy of test)
- \( P(B) = \frac{(1/200)*(98/100)+(199/200)*(2/100)}{100*200} = 496/(100*200) \)

The odds: the posterior probability
- \( P(A|B) = 49/248 \approx 20\% \) (odds have increased from 0.5% but still very far away from 98%)
Bayes’ Theorem: Application to Model Building

QCD is the fundamental theory of the strong interactions!
M: A theoretical MODEL with parameters and biases
D: A collection of experimental and observational DATA

The Prior $P(M)$: An insightful transformation in DFT
\[(g_s, g_V, g_\rho, \kappa, \lambda, \Lambda_V) \leftrightarrow (\rho_0, \epsilon_0, M^*, K, J, L)\]

The Likelihood $P(D|M) \approx \exp(-\chi^2/2)$
\[
\chi^2(D, M) = \sum_{n=1}^{N} \left( \frac{O_n^{(th)}(M) - O_n^{(exp)}(D)}{\Delta O_n^2} \right)^2
\]

The Marginal Likelihood: overall normalization factor
Searching for L: The Strategy

$P_{PNM} \approx L \rho_0/3$ is not a physical observable

Establish a powerful physical argument connecting L to $R_{skin}$

- Where do the extra 44 neutrons in $^{208}\text{Pb}$ go? Competition between surface tension and the difference $S(r_0) - S(r_{surf}) \approx L$.
  
  *The larger the value of L, the thicker the neutron skin of $^{208}\text{Pb}$*

Ensure that “your” accurately-calibrated DFT supports the correlation

- Statistical Uncertainty: Theoretical error bars and correlation coefficients
- What precision in $R_{skin}$ is required to constrain L to the desired accuracy?

Ensure that “all” accurately-calibrated DFT support the correlation

- Systematic Uncertainty: As with all systematic errors, much harder to quantify
  
  (… “all models are equal but some models are more equal than others”)

New era in Nuclear Theory where predictability will be typical and uncertainty quantification will be demanded …
PREX@JLAB: First electroweak evidence in favor of $R_{\text{skin}}$ in Pb (error bars too large!)

Precision required in the determination of the neutron radius/skin?
As precisely as “humanly possible” - fundamental nuclear structure property (cf. charge density)
To strongly impact Astrophysics?

Is there a need for a systematic study over “many” nuclei?
PREX, CREX, SREX, ZREX, …

Is there a need for more than one $q$-point?
Radius and diffuseness … or the whole form factor?

These questions were just addressed at the MITP Program “Neutron Skins of Nuclei”
Mainz, May 17-27, 2016
Heaven and Earth
The enormous reach of the neutron skin

- Neutron-star radii are sensitive to the EOS near $2\rho_0$
- Neutron star masses sensitive to EOS at much higher density

- Neutron skin correlated to a host of neutron-star properties
  - Stellar radii, proton fraction, enhanced cooling, moment of inertia

We are at a dawn of a new era ... *the train has left the station*
Predictability typical and uncertainty quantification demanded!

![Graph showing correlation with skin of $^{208}\text{Pb}$](image)
Have We Discovered Quark Stars?

Core-collapse supernovae generates hot (proto) neutron star $T \approx 10^{12} \text{K}$

Neutron stars cool promptly by $\nu$-emission (URCA) $n \rightarrow p + e^- + \bar{\nu}_e$...

Direct URCA process cools down the star until $T \approx 10^9 \text{K}$

Inefficient modified URCA takes over $(n) + n \rightarrow (n) + p + e^- + \bar{\nu}_e$...

Neutrino “enhanced” cooling possible in exotic quark matter

Unless ... symmetry energy is stiff: large $Y_p$ $\Leftrightarrow$ large neutron skin

Assume $R_n - R_p \lesssim 0.18 \text{ fm}$ and $M(3C58) \lesssim 1.3M_\odot$

Then the pulsar in 3C58 may indeed be a quark star
George Gamow and URCA Cooling?

URCA is not an acronym but rather, the name of a Casino in Rio de Janeiro where George Gamow commented to the Brazilian astrophysicist Mario Schonberg: “The energy disappears in the nucleus of the supernova as quickly as the money disappears at the roulette table”

In Gamow’s Russian dialect, “urca” also means a pickpocket, someone that can steel your money in a matter of seconds!
Addressing Future Challenges

- Same dynamical origin to neutron skin and NS radius
  - Same pressure pushes against surface tension and gravity!
  - Correlation involves quantities differing by 18 orders of magnitude!
  - NS radius may be constrained in the laboratory (PREX-II, CREX, …)

- However, a significant tension has recently emerged!
  - Stunning observations have established the existence of massive NS
  - Recent observations has suggested that NS have small radii
  - Extremely difficult to reconcile both; perhaps evidence of a phase transition?

Time delay due to NS radiation dipping into gravitational well of WD!

\[ 9.1^{+1.3}_{-1.4} \text{ km (90\% conf.)} \]

Guillot et al (2013)

WFF1 violates causality!
"We have detected gravitational waves. We did it"  
David Reitze, February 11, 2016

- The dawn of gravitational wave astronomy
- Initial black hole masses are 36 and 29 solar masses
- Final black hole mass is 62 solar masses, 3 solar masses radiated in GW
What Will We Learn from Neutron-Star Mergers

Tidal polarizability scales as $R^5$ ...

NS radius measured to better than 1km!
Conclusions: It is all Connected

- Astrophysics: What is the minimum mass of a black hole?
- Atomic Physics: Is pure neutron matter a unitary Fermi gas?
- C.Matter Physics: Is there a Coulomb crystal to Fermi liquid transition?
- General Relativity: Can NS mergers constrain stellar radii?
- Nuclear Physics: What is the EOS of neutron-rich matter?
- Particle Physics: What exotic phases inhabit the dense core?

*Neutron Stars are the natural meeting place for interdisciplinary, fundamental, and fascinating physics!*