CREX: Measurements of the Neutron Radius of ^{48}Ca

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Outline

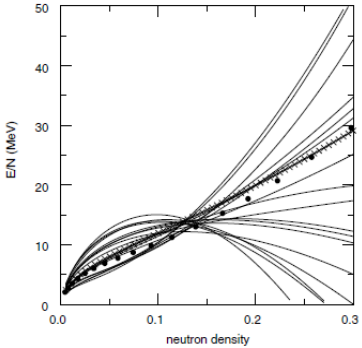
- Motivation
- Setup and Experiment
- Results and Uncertainties

Theoretical Overview

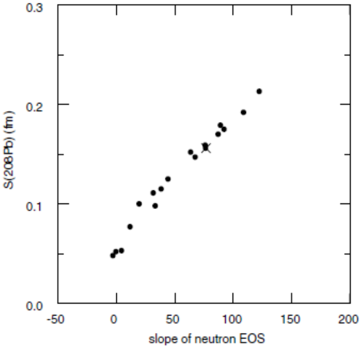
- Both proton and neutron structure is important to understanding the strong nuclear force
- Calculations are difficult due to non-pQCD regime complicated by many-body physics
- Interesting for
  - Fundamental nuclear structure
  - Isospin dependence and nuclear symmetry energy
  - Dense nuclear matter and neutron stars
- Proton radius is relatively easy - electromagnetic probes
- Neutron radius is difficult
  - Weakly couples to electroweak probes
  - Hadronic probes have considerable uncertainty
  - Theory has range of $R_n - R_p$ for various nuclei

- Constraints on neutron EOS

E vs. ρ



^{208}Pb Skin vs. $dE/d\rho|_{\rho=0.1\ \mathrm{fm}^{-1}}$



B. Alex Brown, PRL 85, 5296 (2000)

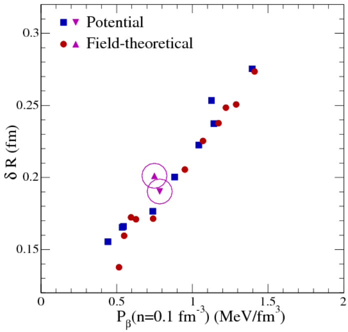
- Slope of EOS can be used to constrain potential models
- Correlated to ρ dependence of symmetry energy

Neutron Stars

- Neutron star structure is also better understood with measurements on R_n
- Larger R_n correlates with larger pressure
- X-ray observations from neutron stars have predictions $\delta R_{Pb} = 0.15 \pm 0.02$ fm
- Structure can influence properties such as gravity waves

A. W. Steiner *et al.*,

Phys Rep 411, 325 (2005)



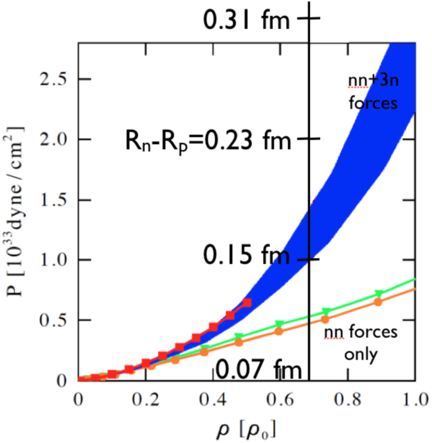
- Additionally, symmetry energy governs proton fraction
  - Direct Urca cooling depends on processes

$$
\begin{aligned}
n &\rightarrow p + e^- + \bar{\nu} \\
e^- + p &\rightarrow n + \nu
\end{aligned}
$$

Three Neutron Forces

- Microscopic calculations for ^{48}Ca are just now becoming available
- Indirect calculations show a 1% difference in radius is induced by three-neutron forces
- CREX would help test these assumptions and provide constraint

P vs ρ for uniform neutron matter



Accessing Neutron Radii in Nuclei

Hadronic Probes

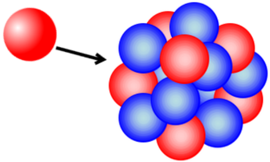
- Elastic pN, $\vec{p}N$, nN, $\pi^{\pm}N$
- Alpha scattering
- GDR/dipole polarizability
- Antiproton scattering

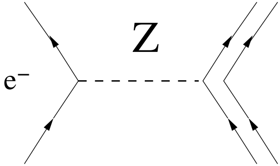
Have uncertainty in extraction due to strong force interactions

Electroweak Probes

- Parity violating electron scattering
- Atomic parity violation
- "Clean" measurements, fewer systematics

Technically challenging due to small weak force interactions





Parity Violating Electron Scattering

- e^- also exchange Z, which is parity violating
- Primarily couples to neutron:

$$Q_{\text{weak}}^{\text{proton}} \propto 1 - 4\sin^2\theta_{\text{W}} \approx 0.076, \quad Q_{\text{weak}}^{\text{neutron}} \propto -1$$

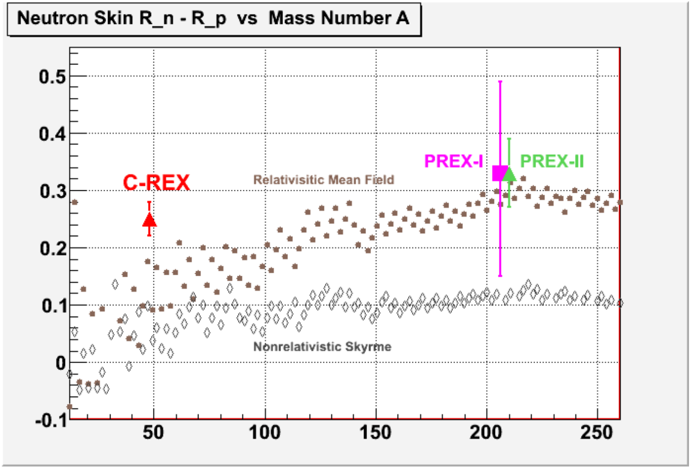
- Detectable in parity violating asymmetry of electrons with different helicity
- In Born approximation, $Q^2 \ll M_Z^2$, from $\gamma - Z$ interference:

$$A_{\text{PV}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

- For fixed target exp., typical $A_{\text{PV}} \sim 10^{-7} - 10^{-4}$

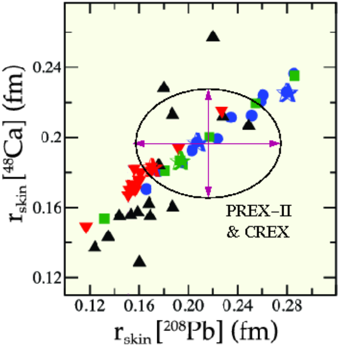
CREX vs. PREX

- PREX Measurement on ^{208}Pb published in December gave $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm
- PREX-II approved to reduce error bars to 0.06 fm

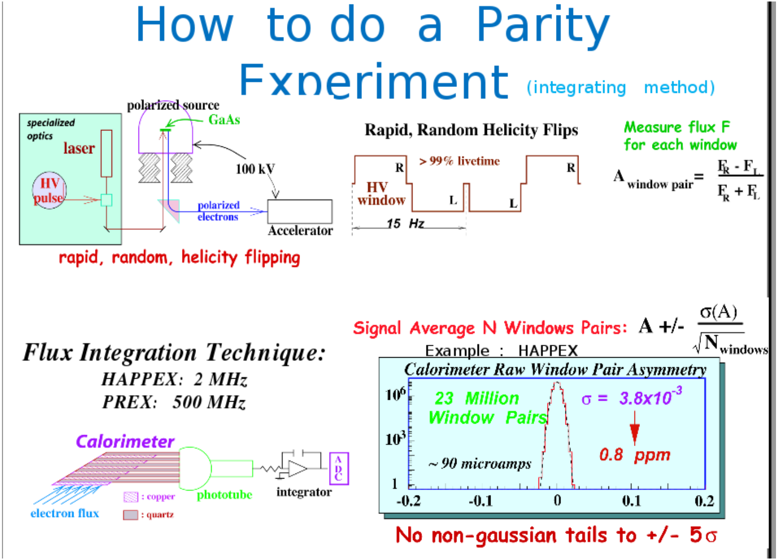


CREX vs. PREX

- PREx is more direct measurement for dense nuclear matter
- Models show correlation between predictions of skin
  - 1% on ^{208}Pb is about 1% on ^{48}Ca
  - Uncorrelated uncertainties give advanced precision

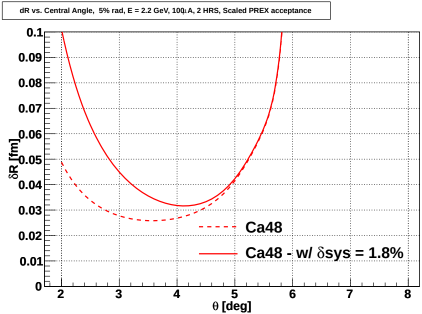


- ^{48}Ca can have microscopic calculations performed
- Directly tests assumptions/parameters based into models
- Different Z, allows more reliable extrapolation between nuclei


How to do a Parity Experiment (integrating method)
specialized optics
laser
HV pulse
polarized source
GaAs
100 kV
polarized electrons
Accelerator
rapid, random, helicity flipping
Rapid, Random Helicity Flips
> 99% livetime
R
L
R
L
HV window
15 Hz
Measure flux F for each window
A window pair = (F_R - F_L) / (F_R + F_L)
Signal Average N Windows Pairs: A +/- σ(A) / √N windows
Flux Integration Technique:
HAPPEX: 2 MHz
PREX: 500 MHz
Calorimeter
electron flux
: copper
: quartz
phototube
integrator
ADC
Example : HAPPEX
Calorimeter Raw Window Pair Asymmetry
23 Million Window Pairs
σ = 3.8x10^-3
0.8 ppm
~ 90 microamps
10^6
10^3
1
-0.2
-0.1
0
0.1
0.2
No non-gaussian tails to +/- 5σ

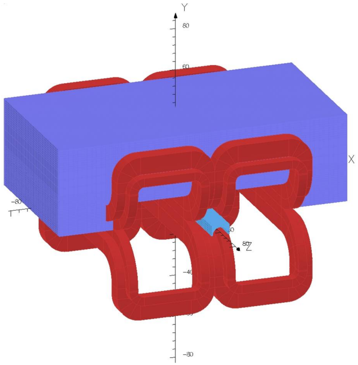
Optimize Kinematics

- Compete against falling rates with higher asymmetry as Q^2 grows
- Need to optimize to sensitivity of A to marginal changes in radius



- For 2.2 GeV beam, $\theta \approx 4^\circ$
- $\delta R_n \approx 0.03\ \mathrm{fm}$ with 30 days beamtime and anticipated systematics

Septum Magnet

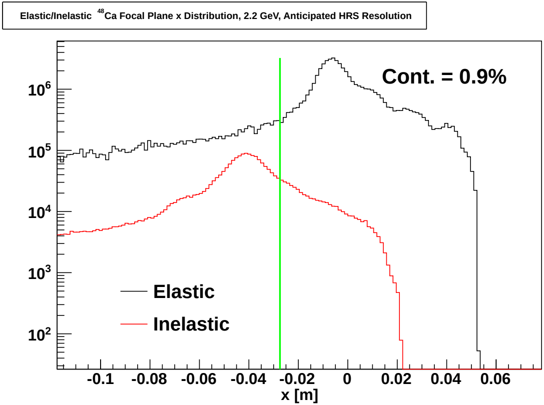


Septum Magnet Requirements

- HRS only go to 12.5°, require septum to reach 4°
- Sufficient hardware resolution must be maintained, need pure dipole
- Need to reach 1350 $\mathrm{A/cm^2}$ with 2-coil configuration
- Require new power supply, LCW pumps

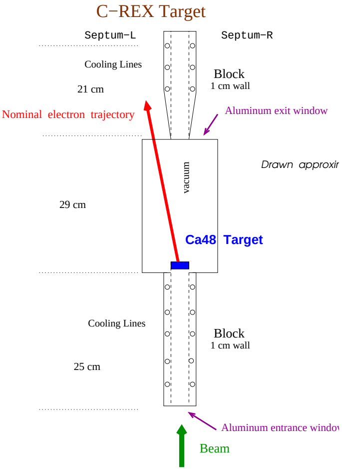
HRS and Quartz Detectors

- HRS has hardware resolution 10^{-3}, use to separate inelastic states



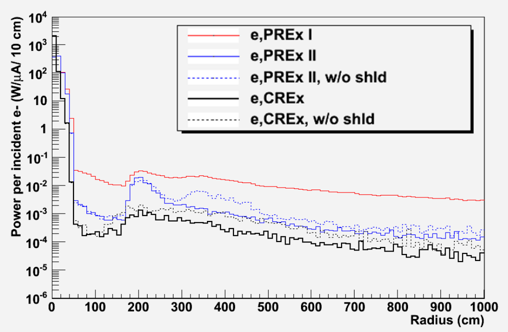
- Place quartz Cerenkov detectors to minimize inelastics
- Several states, but kept to $< 1\%$. Asymmetries calculable to some level and subtracted

^{48}Ca Target



- 1 $\mathrm{g/cm^2}$, 5% radiator (much less than PREX!)
- Oxidizes when exposed to air, must remain isolated
- End windows (Al or steel) contribute background, must remove from acceptance
- Collimators degrade e^- energy by 20 MeV
- Prototype and test with ^{40}Ca target, add in to ladder during PREx-II

Radiation Impact



- CREX is at higher beam energy (less forward peaked), target is half rad. thickness
- Radiation simulations show order of magnitude lower than PREX-II
- Further simulations will be performed to optimize any shielding

Beam Request and Proposed Data

Energy	2.2 GeV
Current	100 μA
Polarization	Full, $\sim$ 85%

Production	30 days
Commissioning	5 days
Pol, calib., A_T	5 days

- Require full longitudinal and (vertically) transverse beam

Measured Asymmetry (p_e A)	2 ppm
Scattering Angle	4°
Detected Rate (each HRS)	80 MHz
Statistical Uncertainty of A_{PV}	2.8%
Systematic Uncertainty of A_{PV}	1.8%
Statistical Uncertainty of A_T	0.4 ppm

Systematic Uncertainties

Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Non-linearity	1.0%
Transverse	0.1%
Polarization	1.2%
Inelastic Contribution	0.5%
Effective Q^2	0.8%
Total	1.8%

- Polarimetry errors could improve with planned advances for Moller and SoLID
- CREX more sensitive to Q^2 uncertainty than PREX, angular resolution demonstrated using elastic *ep*

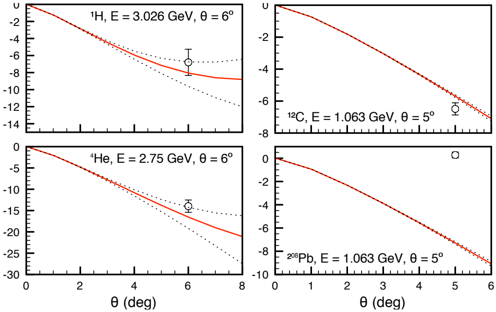
Conclusion

- Neutron radius densities are challenging to measure, but provide important information for nuclear structure and astrophysics
- Parity-violating electron scattering provides a clean method to measure such a distribution
- The CREX measurement aims to measure δR_n to a precision of 0.03 fm with 40 days

BACKUP

Transverse Asymmetries

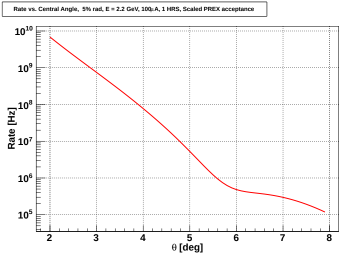
- Vertically transverse beam asymmetries sensitive to two photon effects
- Asymmetries are highly suppressed, few ppm for $Q^2 \sim 10^{-2}\ \mathrm{GeV}^2$

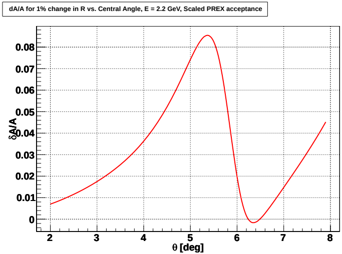


- Very latest calculations: agreement with measurements on low Z nuclei
- ^{208}Pb is significantly off - Coulomb distortions?

Optimize Kinematics

- Compete against falling rates with higher asymmetry as Q^2 grows
- Need to optimize to sensitivity of A to marginal changes in radius

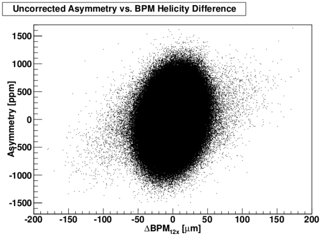


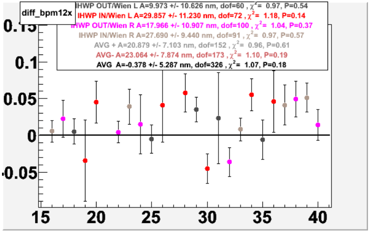


$$\mathrm{FOM} = R \times A^2 \times \left(\frac{dA/A}{dR_n/R_n} \right)^2$$

Parity Quality Beam

- Requirements less strict than PREx (or any 12 GeV parity experiment)
  - Higher Q^2 ($\times 2$), larger asymmetry ($\times 4$)
  - Cross section changes $\times 6$ more slowly with angle

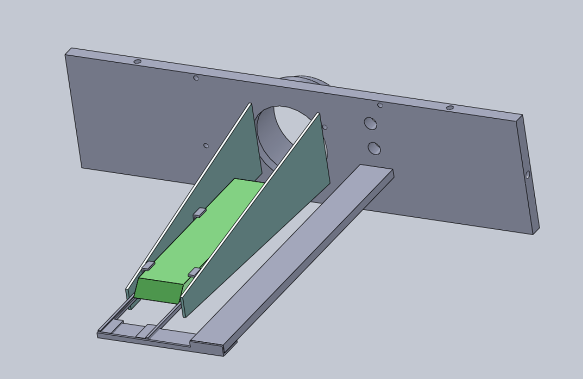




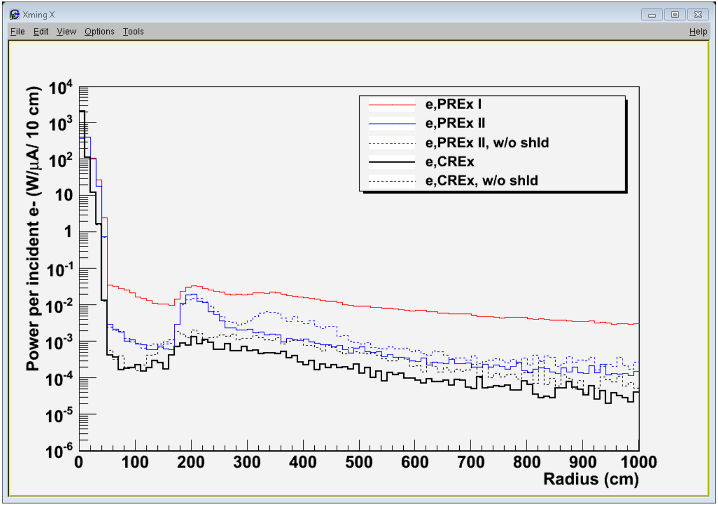
- Use double-Wien, HWP insertions to control systematics
- PREX demonstrated corrections < 40 ppb, $\delta x < 4$ nm
- Polarization monitored to 1% with Moller and Compton

HRS and Quartz Detectors

- Quartz Cerenkov detectors will be used as in PREx
- Integrate signal from PMT over helicity windows

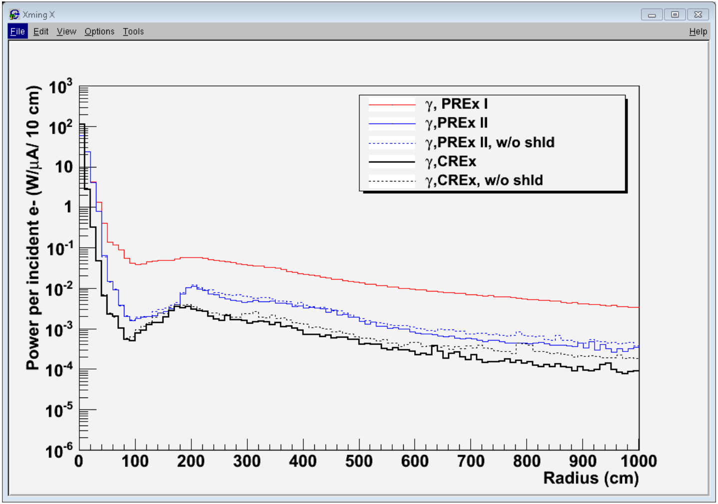


Radiation: e^-

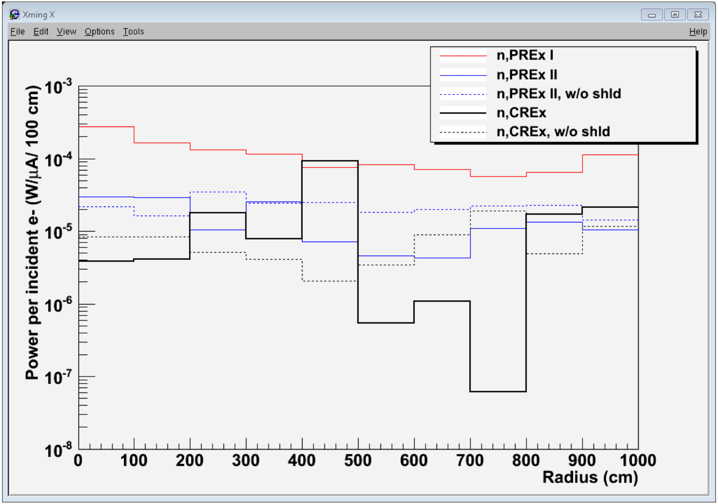


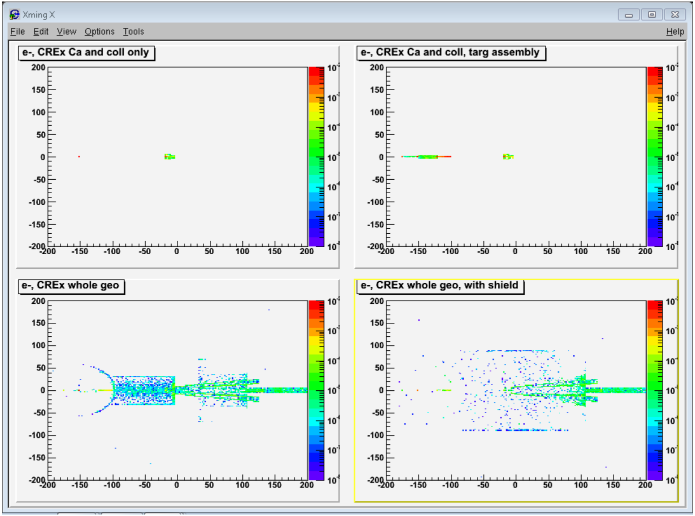
Xming X
File Edit View Options Tools
Help
e,PREx I
e,PREx II
e,PREx II, w/o shld
e,CREx
e,CREx, w/o shld
Power per incident e- (W/μA/ 10 cm)
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
100
200
300
400
500
600
700
800
900
1000
Radius (cm)

Radiation: γ



Radiation: n


Xming X
File Edit View Options Tools
Help
n,PREx I
n,PREx II
n,PREx II, w/o shld
n,CREx
n,CREx, w/o shld
Power per incident e- (W/μA/ 100 cm)
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
0
100
200
300
400
500
600
700
800
900
1000
Radius (cm)


Xming X
File Edit View Options Tools Help
e-, CREx Ca and coll only
e-, CREx Ca and coll, targ assembly
e-, CREx whole geo
e-, CREx whole geo, with shield

Nuclear Symmetry Energy

- Nuclear symmetry energy governs energy of systems from symmetric nuclear matter to pure neutron matter
  Bethe-Weizsäcker SEMF:

$$E_b = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \delta(A, Z)$$

- Neutron EOS strongly governed by symmetry energy
- R_n provides constraints and has empirical correlations with density dependence on the symmetry energy