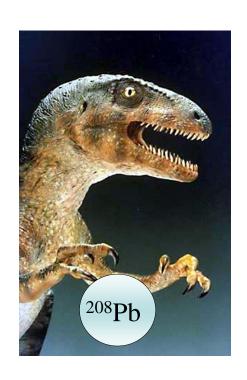
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Measurement of the Neutron Radius of ²⁰⁸Pb through Parity Violation in Electron Scattering (PREX)

> S. Abrahamyan et al., Phys. Rev. Lett. 108, 112502 (2012)

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Lead (²⁰⁸Pb) Radius Experiment: PREX

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Measurement of the Neutron Radius of ²⁰⁸Pb through Parity Violation in Electron Scattering

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(PREX Collaboration)

Abstract

We report the first measurement of the parity-violating asymmetry A_{PV} in the elastic scattering of polarized electrons from ²⁰⁸Pb, 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.

Measurement of the Neutron Radius of 208 Pb through Parity Violation in Electron Scattering

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We report the first measurement of the parky-violating asymmetry A_{PV} in the clustic scattering of polarized dectrons from ³⁸ Pb. A_{PV} is sensitive to the radius of the neutron distribution (R_s) . The result $p_{\rm ANT} = 0.656 \pm 0.060(s/m) \pm 0.014 (sprt)$ gen corrasponds to a difference between the radii of the neutron and proton distributions $R_{\rm c} = R_{\rm p} = 0.33^{+0.11}_{-0.11}$ fm and provides the first electro-weak observation of the neutron side which is expected in a heavy, neutron-order nacions.

PACS numbers 21 10 Gr. 21 65 Df. 25 30 Df. 27 80 es

Nuclear charge densities have been accurately measured th electron scattering and have become our picture of the omic nucleus, see for example [1]. In contrast, our nowledge of neutron densities comes primarily from had ron scattering experiments involving, for example, pions [2], protons [3-5], or antiprotons [6,7], the interpretation of th requires a model-dependent description of the non-irhative strong interaction. Because of the fact that the yeak charge of the neutron is much larger than that of the proton, the measurement of parity violation in electron extering provides a model-independent probe of neutron lensities that is free from most strong-interaction uncer-

inties [8].

In the Born approximation, the parity-violating crosssection asymmetry for longitudinally polarized electrons elastically scattered from an unpolarized nucleus, A_{PV} , is proportional to the weak form factor $F_{\Psi}(Q^2)$. This is the neutron density can be extraording and increasing large x_{00} in the x_{00} in above your interesting large measurement [8]. $A_{pq} = \sum_{\sigma_{g} + \sigma_{g}} \sum_{i=1,\dots,j} \sum_{i=1,\dots,j} \sum_{j \in O(1)} (1)$ once vanished to a proper color of the property of t

where $\sigma_{R(L)}$ is the differential cross section for elastic where σ_{RD} is the differential cross section for elastic scattering of right (R) and left (L) handed longitudinally polarized electrons, G_P is the Fermi constant, α the fine structure constant, and $F_R(G)$ is the Future transform of the known charge density. However, the Born approxima-tion is not valid for a heavy nucleus and Coulomb-distortion effects must be included. These have been accurately calculated [9] because the charge density is well known, and many other details relevant for a mactical

was known, and many other decision reservant for a practicul parity-violation experiment to measure neutron densities have been discussed in a previous publication [10]. One system of particular interest is the doubly-magic nucleus. ⁸⁸ fb., which has 44 more neutrons than protons; some of fiese extra neutrons are expected to be found in the surface, where they form a neutron-rich skin. The thickness of this skin is sensitive to nuclear dynamics and provides fundamental nuclear structure information.

A number of mean-field-theory models have been developed that agree with the world's body of data on nuclear charge distributions and other nuclear properties [11–15]. For ²⁰⁰Ph, these are consistent with a radius of the pointneutron distribution R, between 0.0 and 0.4 fm larger than that of the point-proton distribution R., In this Letter, we report a first measurement of A_W from ²⁶Pb, which is sensitive to the existence of the neutron skin. The value of the neutron makes of ²⁶Pb has important

implications for models of nuclear structure and their application in atomic physics and astrophysics. There is a strong correlation between R_n of 100 Pb and the pressure of neutron matter P at densities near 0.1 fm⁻¹ (about 2/3 of nuclear density) [16]. A larger P will much neutrons out nuclear density) [16]. A target P will pain nearthest out against surface tension and increase R_n . Therefore, measuring R_n constrains the equation of state (EOS), the pressure as a function of density, of nearton matter.

The correlation between R_n and the radius of a neutron

there has been great say observations. From tal [18] find r_{NS} is very density which is suggestive of a transition to an exob phase of QCD. In contrast, Steiner et al. [19] conclude that $r_{\rm NS}$ is near 12 km, leaking to a prediction that $R_a - R_p = 0.15 \pm 0.02$ fm for ²⁰⁸Ph. This implies a stiffer BOS which leaves little morn for softening due to a phase

transition at high density.

Recently, Hebeler et al. [20] used chiral perturbation theory to calculate the EOS of neutron matter including important contributions from three-neutron forces. From their EOS, they predict $R_1 - R_2 = 0.17 \pm 0.03$ fm, for also find sensitivity to three-neutron forces. The measurement of R. provides an important check of fundamental neutron matter calculations, and constrains three-neutron

The EOS of neutron-rich matter is closely related to the symmetry energy S. There is a strong correlation between

 R_{μ} and the density dependence of the symmetry energy $dS/d\rho$, with ρ as the baryon density. The symmetry energy can be probed in heavy-ion collisions [22]. For example, $dS/d\rho$ has been extracted from isospin diffusion data [23]

using a transport model.

The symmetry energy S helps determine the composition of a neutron star. A large S at high density would imply a large proton fraction, which would allow the direct Urc a process [24] of rapid neutrino cooling. If $R_n = R_p$ in ^{26}Pb were large, it is likely that massive neutron stars would cool quickly by direct Urea. In addition, the transition density from a solid neutron star crust to the liquid in prior

is strongly correlated with $R_a = R_p$ [25]. Reinhard and Nazarewicz claim that $R_a = R_p$ is tightly correlated with the dipole polarizability α_D [26] and Tamii et al. use this correlation to infer R. - R. from a new essurement of α_D [27]. Atomic parity violation (APV) is also sensitive to R_n

[10,28,29]. A figure low-energy test of the standard model may involve the combination of a precise APV experiment along with PV electron scattering to constrain R_a [28]. Alternative ly, measuring APV for a range of isotopes could

Thomas Jefferson National Accelerator Facility. The ex-Thomas Jetterson National Accelerator Facility. The ex-perimental configuration is similar to that used previously for studies of the weak form factor of the proton and ⁴He [31–33]. A 50 to 70 μ A continuous-wave beam of longi-tudinally polarized I D6 GeV electrons was incident on a 0.55 mm thick isotopically pure 30 Pb target foil. A 4×4 mm square beam ratter prevented the target from melting. Two 150 μm diamond foils sandwiched the lead meting. I've 130 µm diamont ions summerced the leaf foil to improve thermal conductance to a copper frame coded to 20 K with cryogenichelium. Einstically scattered electrons were focused onto thin quarte detectors in the twin High-Resolution Spectrometers (HRS) [34]. The addition of a pair of dipole septum magnets between the target and the HRSs allowed us to achieve a forward scattering angle of $\theta_{ab} \sim 5^{\circ}$. The HRS momentum resolution ensured that only elastic events (and a negligible fraction of inelastic events from the 2.6 MeV first excited state) were accepted by the quartz detectors. Cherenkov light from each quartz har traversed air light guides and were detected by 2-inch quartz-window photomulti-

The polarized electron be am originated from a strained I are potential electron term originates about a strains GAASP photocathode illuminated by circularly polarized light [35]. The accelerated beam was directed into Hall A, where its intensity, energy, polarization, and trajectory on larget were inferned from the response of several monitoring devices. The sign of the laser circular polarization on beliefy: this was held constant for periods of 8.33 ms, referred to as "windows". The integrated responses of detector PMTs and beam monitors were digitized by an 18-bit analog-to-digital converter and

econfed for each window. Two "window qualenter" the 60 Hz line nower thus canceling powerline noise from the to the mer power, thus cancering powering noise from the asymmetry measurement. The right-fielh felicity asym-metry in the integrate detector-response, normalized to the beam intensity, was computed for sets of complementary helicity windows in each qualitaplet to form the new asym-

mercy A_m. The sequence of these patterns was chosen with a pseudorandom number generator. Loose requirements were imposed on beam quality, removing periods of position, energy, or beam-intensity instability. No belicity dependent cuts were amilied, leavinstalishly. No behavily-dependent cats were applied, leav-ing a final data sample of 2×10° helicity-window quad-nalets. The design of the apparatus ensured that, after all corrections, the fluctuations in the fractional difference of the BMT response between a pair of successive windows was dominated by ac attered-electron counting statistics for rates up to 1 GHz. This facilitated the ability to achieve an App precision significantly better than 100 parts per billion (ppb) in a reasonable length of time. Careful attention to the design and configuration of the photocathode laser optics [36] ensured that spurious beam-induced asymme-tries were under control at this level.

Random fluctuations in beam position and energy conremains inclination in the imposition and energy con-tributed the largest source of noise beyond counting statis-tics in $A_{\rm acc}$. Typical beam pitter in window quadruplets was less than 2 pasts per million (gpm) in energy, and 20 μ m in position. This noise contribution was reduced by measuring window differences A x; using beam position monitors and applying a correction $A_{lean} = \sum_{c} c_{c} \Delta z_{c}$. The c_{c} 's were measured several times each hour from calibration data in which the beam was modulated by using steering coils and which the team was mediatated by thing state for the c/x was accelerating cavity. The largest of the c/x was ~ 50 ppm/ μ m. The noise in the resulting $A_{\rm cur} = A_{\rm pos} = A_{\rm cur}$ as 210 (180) ppm per quadrulpet, for a beam current of 50 (70) $\mu A_{\rm c}$ dominated by counting statistics (~ 1 GHz at 70 μ A). Nonuniformities in target thickness due to thermal damage caused window-to-window laminosity fluctuations from variations in the target area sampled by the rastered beam, leading to the degradation of $A_{\rm sur}$ by $\sim 40\%$. This source of noise was eliminated by of A_{sst.} by ~~y_s. Institute or notice was communically locking the noter pattern frequency to a multiple of the helicity frequency. Low-current calibration data, triggered on individual scattered electrons, were regularly collected to evaluate the thickness of leaf relative to diamond.

Sensitivity of A_{new} to a transverse component of the beam polarization, coupled to the vector analysing powers (A_T) for ³⁸Pb and 12 C, was studied using special runs with fully transverse beam polarization. The symmetry of the detector configuration as well as the measured Av values (to be published separately) resulted in an upper bound for a possible correction to A_{ner} of 0.2%. The A_{ner} and A_{ner} window-pair distributions for the two complete data samples had need with non-Gaussian tails over more than

PHYSICAL REVIEW LETTERS PRI 108 112502 (2012) 4 orders of magnitude. To test the accuracy of error asymmetry A_{pq} is formed from A_{mp} by correcting for the calculations and general statistical behavior of the data, A_{mp} strong as an attachmical errors were statisfied for typical asymmetries A_i .

one-hour runs, consisting of ~50 k quadruplets each. This one-nite trans, constaining of "500 k again white clean. The corresponding statistical error, populated a Gaussian distribution of unit swirmer, as expected. A half-wave (A/2) plate was periodically inserted into the injector later optical path, receiving the sign of the electron beam polinization relative to both the electronic These corrections are summarized in Table II.

helicity control signals and the voltage applied to the polarized source laser electro-optics. Roughly equal statis-

g maye mossible sources of systematic determined by the many standard electrowesk coursely in 17 miles of beliefer reveal age of the specific processing the measured of the specific processing the measured processing the discourse of the specific processing feasible with a pair tematic control. R field remond the chemin beam belong while the beam order, which days of the solid state of the control of the solid state of th field revened the

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The spin eventuals resulted in common been position and energy of only many the perfutable been position and energy of only many the perfutable been position and energy of only many the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and energy of only many that the perfutable been position and the perfutable

5.5 pp. 1 to symboly on a single first part of the control of A_{con}, we is 0.2 ± 13 pp. with the cart determined using the confined of A_{con}, we is 0.2 ± 13 pp. with the cart determined using the confined of the confined errors for each of the reversal states. The reduced x2 for cross for each of the reversal states. The realized χ^{2} for A_{mn} shigh wrenges is close to 1 in every case, indicating that any residual beam-related systematic effects were small and automized over the time period of $\lambda/2$ eversals. The final result is $A_{mn} = 94 \pm 50$ (as $\mu \pm 9$ (syst) ppb where the systematic uncertainty includes possible effects from Alexan nonlinearity in the detectors or beam total systematic uncertainty of the asymmetry. Using a calculation by Horowitz [9], dApp/dQ² is approximately tors, and transverse asymmetry. The physics

TABLE I. Values of $A_{m\pi}$ and the statistical error, for each helicity reversal state and for the grand average. The χ^2 per degree of freedom for each average is also shown.

A/2 plate	Spin rotator	A_ (pph)	&4 (ppb)	$\chi^2/d\alpha$
our	RIGHT	606	1.13	1.03
IN	REGHT	492	107	0.74
OUT	LEFT	565	95	1.12
IN	LEFT	687	92	1.03
Av mage		594	50	0.99

ion of the absolute value

 $A_{IV} = \frac{1}{P_b} \frac{1}{1 - \sum f_t}$

These corrections are summare of in Table 1. The fraction of the accepted flux from 12 C in the detectors varied with time due to changes in the target; averaged over the run, the fraction $f = (6.3 \pm 0.6)\%$. The asymmetry of this background was determined to be $A\beta \gamma = 817 \pm$

rget were negligible. To compare to predictions, one must integrate the theoretical asymmetr predictions, one mass transpara to the recursor as symmetry and the Q^2 over $s(\theta)$. The systematic error in $s(\theta)$ was evaluated from reasonable variations in the parameters of the simulation and resulted in an additional equivalent error in $\langle Q^2 \rangle$ of 0.8%. Added in quadrature to the error arising from knowledge of (θ) , we obtain an overall error in (O1) of 1.3%. We do not include this uncertainty in the

Correction	Absolute (pph)	Relative(%)
Beam Charge Normalization	-84.0 ± 1.5	-128 ± 02
Beam Any mmetries A	39.0 ± 7.2	59 ± 1.1
Target Backing	-8.8 ± 2.6	-1.3 ± 0.4
Detector Nonlinearity	0 ± 7.6	0 ± 1.2
Transverse Asymmetry	0 ± 1.2	0 ± 0.2
Polarization P _b	70.9 ± 8.3	10.8 ± 1.3
Total	17.1 ± 13.7	26±21%

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FIG. 1 (color). Result of this experiment (red square) vs near tron point radius R. in 2009b. Distorted-wave calculations to

30 pm/GeV*, which would correspond to an aditional systematic uncertainty on A_p of 3 pb (0.5% of A_{pp}). The beam polarization was continuously monitored by a Compton polarization Helicity-dependent asymmetries in the integrated signal from backcisater of Compton photons yielded P_φ = (88.2 ± 0.1 ± 1.0)% averaged over the duyieunar $P_{\mu} = (98.2\pm0.1\pm1.0)^{12}$ whenged over the distribution of the run. The beam polarization was stable within systematic errors. An independent Multer polarimeter making nine measurements at different times during the run gave $P_{\phi} = (90.3\pm0.1\pm1.1)\%$. We used an average of these two measurements, $P_k = (89.2 \pm 1.0)\%$ which conservatively accounts for the correlated systematic er

30 ppm/GeV2, which would correspond to an additional

$A_{cb}^{ph} = 656 \pm 60 (stat) \pm 14 (syst) ppb,$ at $(Q^2) = 0.008 80 \pm 0.000 11 \text{ GeV}^2$. This result is dis-

layed in Fig. 1, in which mode is predicting the point-curron radius illustrate the correlation of $A_{N}^{B_{c}}$ and R_{a} [39]. Seven nonrelativistic and relativistic mean-field models The second agreement was considered as a second sec

 (G_k^2) is the Fourier transform of the proton (neutron electric from factor. The Dirac equation was solved, 191 execute from accurate from ρ spation was solved by for an electron scattering from ρ , and the experimental ρ _{th} [1], and the resulting $A_{W}(\theta)$ integrated over the acceptance, Eq. (3), to yield the open circles in Fig. 1. The importance of Grutomb distortions is emphasized by in-

ting results from plane-wave calculations, which are tained within the vertical axis range of the figure least squares fit of the model results yields $R_a \approx 156 + 1.675(A) - 3.420(A)^2$ fm (with (A) in ppm), as Instructed. Comparing this to the measured A_{s0}^{∞} implies a slue for $R_{s} = 5.78_{-0.05}^{+0.05}$ fm. More details of this analysis, along with additional information such as the weak charge form factor and weak natius, will be presented in a future publication [40]. onding to the measured charge radius of 5.50 fm [1]

on is 1 8 relarges than the f the protons $R_a - R_p = 0.33^{+616}_{-618}$ fm [39] 427). A future run is planned which will reduce the quoted stainty by a factor of 3 [43], to discriminate between nodels and allow predictions relevant for the description f neutron stars and parity violation in atomic systems. We wish to thank the entire staff of JLab for their efforts develop and maintain the polarized beam and the eximental apparatus. This work was supported by the U.S. per mention appear and. Into work was supprinted by the Use Department of Energy, the National Science Foundation, and from the French CNRS/IN2F9 and ANR. Jefferson Science Associates, LLC, operains Jefferson Lab for the U.S., DOE under U.S. DOE Contact No. DE-ACOS-

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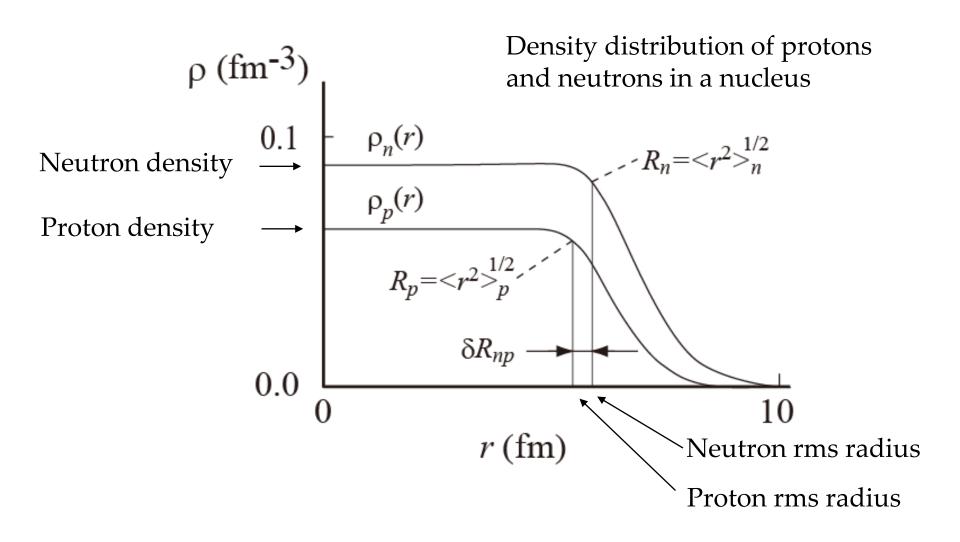
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Motivation

Proton/Neutron Density Distribution, Neutron Skin



Nuclear charge density (distribution)

Studied by electron (elastic) scattering [1]

Neutron density (distribution)

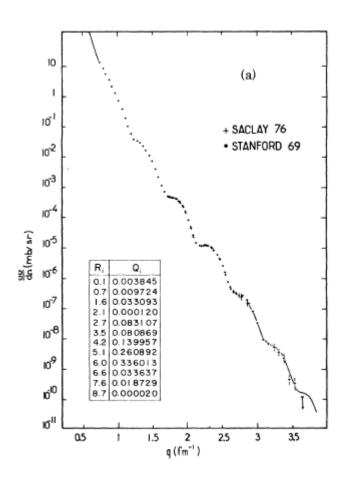
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Studied by hadron scattering
pion scattering [2]
proton scattering [3-5]
anti-proton absorption (X-ray observation) [6,7]
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requires model-dependent description of strong interaction.



Charge Density (Electron Scattering)

[1] B. Frois et al, PRL38, 152(1977)



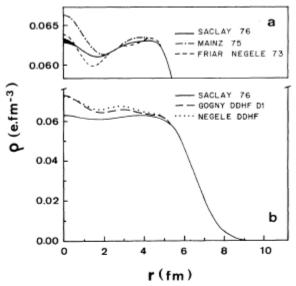


FIG. 2. (a) Charge density determined by present analysis and Refs. 7 and 8. The systematical uncertainties of the data allow an overall shift of $\pm 0.8\%$ for (r < 4 fm) without sizeable influence on the details of the structure. (b) Present density compared to density-dependent HF densities of Refs. 13 and 22. The scale of (a) is expanded by a factor of 4.

charge radius: 5.50 fm point proton radius: 5.45 fm (by using formula in [41])

Neutron Density (Proton Scattering)

Nucleus

204Pb

206Pb

²⁰⁸Pb

 r_{ch}

5.479(2)

5.490(2)

5.503(2)

Not Referred

 δr_n^{std}

+0.029

-0.020

+0.026

+0.026

-0.029

 r_n

5.598

5.613

5.653

 δr_n^{mdl}

+0.047

-0.059

+0.048

+8054

-0.063

[4] V.E. Starodubsky et al., PRC18, 2641(1994)

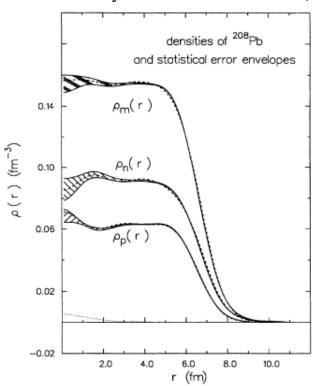
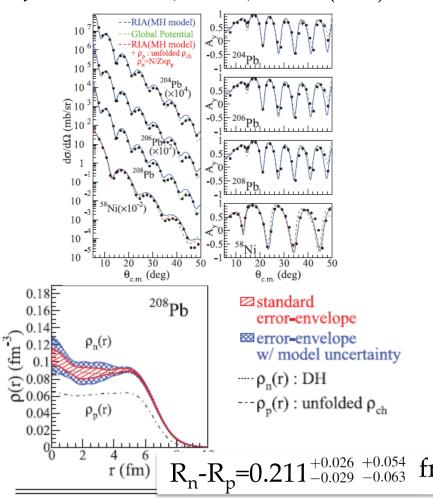


FIG. 6. Extracted neutron and matter densities for ²⁰⁸Pb lying in the middle of the corresponding statistical error bands (the hatched areas). The HF proton, neutron, and matter densities are depicted by the dashed lines. The proton density obtained by unfolding the charge density of Ref. [43] is also shown with its statistical error envelope. The dotted line at the bottom is for the statistical error band obtained with the SOG method of Ref. [23].

 R_{ch} =5.503(2), R_{p} =5.458, R_{n} =5.655(42) fm R_{n} - R_{p} =0.197(42) fm

J. Zenihiro et al., PRC82, 044611 (2010)



5.420(2)

5.433(2)

5.442(2)

Neutron Density (anti-protonic atom X-ray)

Not Referred

[6] A. Trzcinska et al., PRL87, 082501(2001)

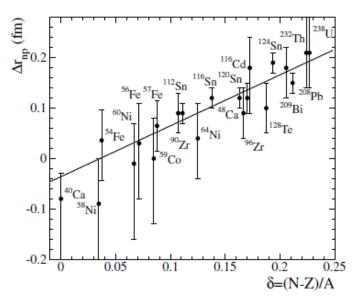


FIG. 4. Difference Δr_{np} between the rms radii of the neutron and proton distributions as deduced from the antiprotonic atom x-ray data, as a function of $\delta = (N-Z)/A$. The proton distributions were obtained from electron scattering data [41] (Sn nuclei) or from muonic atom data [38,42,43] (other nuclei). The full line represents the linear relationship between δ and Δr_{np} as obtained from a fit to the experimental data.

Widths and shifts of the levels due to the strong interaction → antiproton-nucleus optical potential assumes two-parameter Fermi distribution

B. Kłos et al., PRC76, 014311(2009)

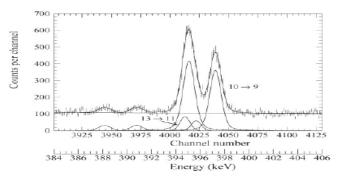


FIG. 3. Part of the antiprotonic x-ray spectrum measured for ^{208}Pb using the detector with the $1035~\text{mm}^2 \times 14~\text{mm}$ crystal. The fit to the broadened $10 \to 9$ transition is also shown. The $13 \to 11$ line is admixed to the $10 \to 9$ line.

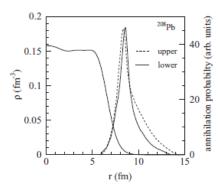


FIG. 10. \bar{p} annihilation probability (arbitrary units) from the upper and lower states for the antiprotonic 208 Pb atom. The matter density (DD-ME2) in 208 Pb is also shown. The calculations of the annihilation probability were done with the Batty zero-range potential and 2pF parametrization of the DD-ME2 density (cf. Table VI).

$$R_n-R_p = 0.16 \pm (0.02)_{stat} \pm (0.04)_{syst}$$

Nuclear charge density (distribution)

Studied by electron (elastic) scattering [1]

Neutron density (distribution)

Studied by hadron scattering

pion scattering [2] proton scattering [3-5] anti-proton absorption (X-ray observation) [6,7]

requires model-dependent description of strong interaction.



Parity violating (PV) electron scattering by weak interaction: "model-independent probe"



Parity Violating (PV) Cross Section Asymmetry in Electron Scattering [8]

$$\sigma \approx \left| \begin{array}{c} e^{-\frac{1}{208}} + e^{-\frac{1}{208}} \\ \end{array} \right| \begin{array}{c} 2 \\ \text{and interference} \end{array}$$

$$A_{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\rm ch}(Q^2)},\tag{1}$$

R (L): Right (Left) helicity longitudinal polarization

 G_F : Fermi coupling constant

 α : fine structure constant

Q: four-momentum transfer (ω ,**q**)

 F_W : weak form factor

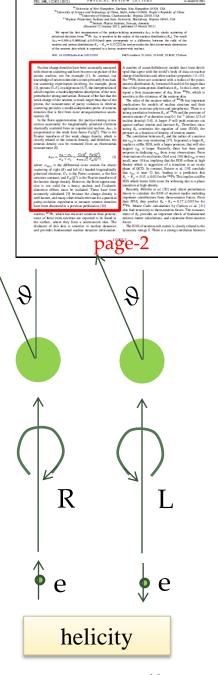
 F_{ch} : charge form factor

interference between EM and weak interactions

in PWBA

Fourier transform of the weak charge density

Coulomb distortion effect is included in the real analysis [9], also other effects [10].



Weak Charge

J-F. Rajotte, arxiv:1110.2218v1

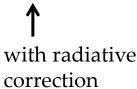
TABLE I: Electroweak Couplings of u and d Quarks and Nucleons as Function of the Weak Mixing Angle θ_W

Particles	EM Charge	Weak Charge
u	$+\frac{2}{3}$	$1-\frac{8}{3}\sin^2\theta_W$
d	$-\frac{1}{3}$	$-1 + \frac{4}{3}\sin^2\theta_W$
p(uud)	+1	$1 - 4\sin^2\theta_W$
n(udd)	0	-1

in the standard model

~ 0.08 0.0721

-0.9878



 $\vartheta_{\rm w}$: Weinberg Angle or Weak Mixing Angle $\sin^2 \vartheta_{\rm w}$ =0.23116(12) c.f. PDG 2012

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

Weak charge distribution is primarily determined by the neutron distribution

BUT weak interaction is VERY weak...

 $APV \sim 656 \text{ ppb} = 0.000000656$

Backup Slides

Standard Model

TABLE 13.1
Weak Isospin and Hypercharge Quantum Numbers of Leptons and Quarks

Lepton	T	T^3	Q	Y	Quark	T	T^3	Q	Y
ν_e	$\frac{1}{2}$	$\frac{1}{2}$	0	-1	\mathfrak{u}_L	$\frac{1}{2}$	$\frac{1}{2}$	2/3	$\frac{1}{3}$
e_L^-	$\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	d_L	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$
					u_R	0	0	$\frac{2}{3}$	$\frac{4}{3}$
e_R^-	0	0	-1	-2	d_R	0	0	$-\frac{1}{3}$	$-\frac{2}{3}$

$$Q = T^{3} + \frac{Y}{2}$$

$$j_{\mu}^{em} = J_{\mu}^{3} + \frac{1}{2}j_{\mu}^{Y}.$$

Electro-weak Interaction

Backup Slides

$$-i g(J^{i})^{\mu} W_{\mu}^{i} - i \frac{g'}{2} (j^{Y})^{\mu} B_{\mu}.$$

charged fields

$$W_{\mu}^{\pm} = \sqrt{\frac{1}{2}} \left(W_{\mu}^{1} \mp i W_{\mu}^{2} \right)$$

neutral fields (mass eigenstates)

$$A_{\mu} = B_{\mu} \cos \theta_{W} + W_{\mu}^{3} \sin \theta_{W}$$
 (massless), \Longrightarrow Electro-Magnetic Field $Z_{\mu} = -B_{\mu} \sin \theta_{W} + W_{\mu}^{3} \cos \theta_{W}$ (massive),

Electro-weak neutral current interaction

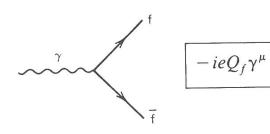
$$\begin{split} -igJ_{\mu}^{3}(W^{3})^{\mu} - i\frac{g'}{2}j_{\mu}^{Y}B^{\mu} \\ &= -i\left(g\sin\theta_{W}J_{\mu}^{3} + g'\cos\theta_{W}\frac{j_{\mu}^{Y}}{2}\right)A^{\mu} \qquad \Longrightarrow \qquad -iej_{\mu}^{en}A^{\mu} \\ &-i\left(g\cos\theta_{W}J_{\mu}^{3} - g'\sin\theta_{W}\frac{j_{\mu}^{Y}}{2}\right)Z^{\mu}. \qquad \Longrightarrow \qquad -i\frac{g}{\cos\theta_{W}}J_{\mu}^{NC}Z^{\mu} \\ &g\sin\theta_{W} = g'\cos\theta_{W} = e \\ &J_{\mu}^{NC} \equiv J_{\mu}^{3} - \sin^{2}\theta_{W}j_{\mu}^{em} \end{split}$$

Electro-magnetic interaction

Backup Slides

Vector coupling

$$-i e (j^{em})^{\mu} A_{\mu} = -i e (\bar{\psi} \gamma^{\mu} Q \psi) A_{\mu}$$

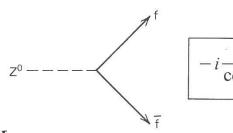


Vector coupling

Electro-weak neutral current interaction

$$-i\frac{g}{\cos\theta_W} \left(J_\mu^3 - \sin^2\theta_W J_\mu^{em}\right) Z^\mu =$$

$$-i\frac{g}{\cos\theta_W}\bar{\psi}_f\gamma^\mu\left[\frac{1}{2}(1-\gamma^5)T^3-\sin^2\theta_WQ\right]\psi_fZ_\mu$$



$$-i\frac{g}{\cos\theta_W}\gamma^{\mu_{\frac{1}{2}}}(c_V^f-c_A^f\gamma^5).$$

TAF The $Z \to f\bar{f}$ Vertex Factors, (13.41), in the Standard Model (with $\sin^2 \theta_W = 0.234$)

33			
\overline{f}	Q_f	c_A^f	c_{V}^{f}
$ u_{\rm e}, \nu_{\mu}, \dots$	0	1/2	$\frac{1}{2}$
$\underline{e}^-, \mu^-, \dots$	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W \simeq -0.03$
u, c,	<u>2</u> 3	$\frac{1}{2}$	$\frac{\frac{1}{2} - \frac{4}{3}\sin^2\theta_W}{-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W} = 0.19$
d, s,	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W = -0.34$

V-A coupling

produces parity-violation

=L-helicity projection operator

Neutron Skin Thickness of ²⁰⁸Pb

Doubly magic nucleus

Predicted in the range of 0.0-0.4 fm by various mean-field models. [11-15]

Neutron skin thickness:



sensitive to nuclear dynamics, fundamental nuclear-structure information atomic physics astrophysics

strong correlation

$$R_n-R_p (^{208}Pb)$$

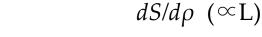


Pressure of neutron matter at ρ ~0.1 fm⁻³

neutron matter EOS



Density dep. of the symmetry energy dS/dz (\propto I)





Neutron star radius (r_{NS})

Neutron Star, Neutron Matter EOS

Neutron Star Mass and Radius (r_{NS})

~10 km x-ray burst observation (Ozel [18])

softer EOS at high ρ ... exotic phase of QCD (strangeness)

~12 km neutron star model and nuclear EOS (Steiner [19])

stiffer EOS (does not support the exotic phase)

$$R_n - R_p = 0.15 \pm 0.02$$
 fm for ²⁰⁸Pb

Observation of a two-solar mass neutron star, P.B. Demorest et al., Nature 467, 1081(2010)

Not Referred

most of EOS inc. the exotic phase fail to reproduce the existence.

Chiral perturbation theory from few-body calc. inc. 3NF (Hebeler [20], Carlson [21])

$$R_n - R_p = 0.17 \pm 0.03$$
 fm for ²⁰⁸Pb

Again the former production of the groups of the state o

Initial Semilisity of A_{∞} to a transverse component of the property of th

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[18] F. Ozel et al., PRD82,101301(2010)

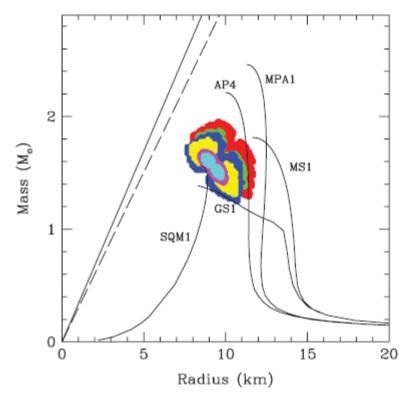


FIG. 1 (color). The 1- and $2-\sigma$ confidence contours for the masses and radii of three neutron stars in the binaries 4U 1608 – 248 (green/red), EXO 1745 – 248 (yellow/blue), and 4U 1820 – 30 (cyan/magenta), compared with predictions of representative EoS (see text for details). The details of the measurements are described in Ref. [3]. The diagonal lines are the black-hole event horizon (solid line) and Buchdahl (dashed line) [29] limits.

AP4: AV18+UIX-3NF+rel.boost

MPA1: Dirac Brueckner Hartree Fock

MS1: Relativistic Mean Field

GS1: RMT plus kaons

SQM1: u,d,s quark matter

[19] A.W. Steiner et al., Astro J. 722_33(2010)

A.W. Steiner et al., arXiv:1205.6871v1

"Ozel et al. [6] considered only PRE sources, but these may be subject to considerable systematic errors [7, 9, 10]." PRE: photospheric radius expansion

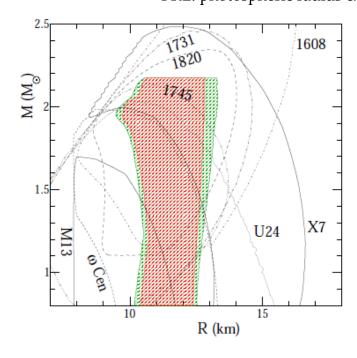


FIG. 1: A comparison of the predicted M-R relation with the observations. The shaded regions outline the 68% and 95% confidences for the M-R relation; these include variations in the EOS model and the modifications to the data set (see Table I) but not the more speculative scenarios. The lines give the 95% confidence regions for the eight neutron stars in our data set.

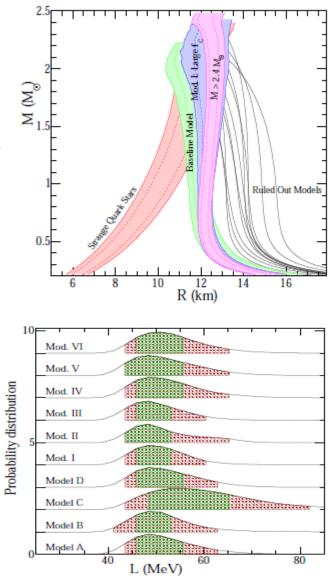


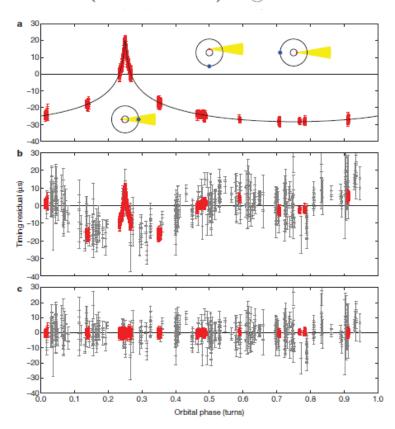
FIG. 4: The limits on the density derivative of the symmetry energy, L. The single-hatched (red) regions show the 95% confidence limits and the double-hatched (green) regions show the 68% confidence limits.

Observation of a Two Solar-Mass Neutron Star Excludes EOS Models with Strangeness

P.B. Demorest et al., Nature 467, 1081(2010)

J1614-2230

$$(1.97 \pm 0.04) M_{\odot}$$



Observation of Shapiro-delay of pulser signals of a neutron star - white dwarf binary.

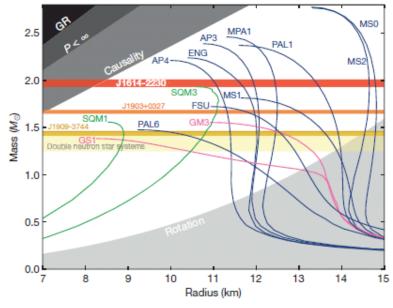


Figure 3 | Neutron star mass-radius diagram. The plot shows non-rotating mass versus physical radius for several typical EOSs²⁷: blue, nucleons; pink, nucleons plus exotic matter; green, strange quark matter. The horizontal bands show the observational constraint from our J1614-2230 mass measurement of $(1.97 \pm 0.04) M_{\odot}$, similar measurements for two other millisecond pulsars^{8,28} and the range of observed masses for double neutron star binaries². Any EOS line that does not intersect the J1614-2230 band is ruled out by this measurement. In particular, most EOS curves involving exotic matter, such as kaon condensates or hyperons, tend to predict maximum masses well below $2.0 M_{\odot}$ and are therefore ruled out. Including the effect of neutron star rotation increases the maximum possible mass for each EOS. For a 3.15-ms spin period, this is a $\lesssim 2\%$ correction²⁹ and does not significantly alter our conclusions. The grey regions show parameter space that is ruled out by other theoretical or observational constraints². GR, general relativity; P, spin period.

Blue: nucleons

Pink: nucleons and exotic matter

Green: strange quark matter

Symmetry Energy, ρ -dependence

Heavy Ion Collision (HIC) [22], isospin diffusion [23] requires nuclear EOS and symmetry energy. or constrains the EOS

Neutron star structure:

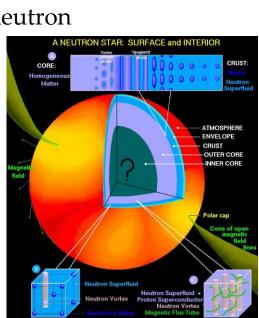
proton fraction is determined by the symmetry energy ⇔chemical potential difference between a proton and a neutron

solid neutron crust $\leftarrow \rightarrow$ liquid interior transition \Rightarrow Strongly correlated with R_n - R_p

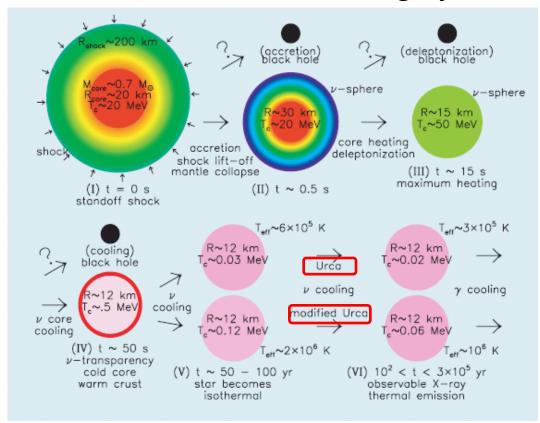
Neutron star cooling:

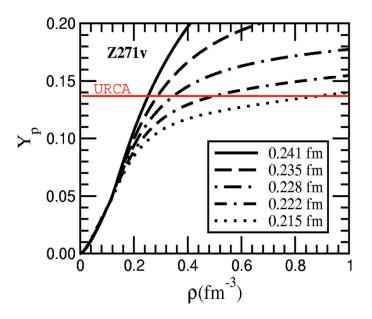
large R_n-R_p

⇒rapid cooling of massive n-star by direct Urca process



Neutron Star Cooling by Neutrino Emission





Urca was named after a casino in Rio de Janeiro where gamblers continuously lost money.

Lattimer and Prakash, Science 304, 536 (2004).

Direct Urca Process

$$n \rightarrow p + e^- + \bar{v_e}, \quad p \rightarrow n + e^+ + v_e$$

takes place only if proton fraction Y_p is large

Modified Urca Process

$$n + (n, p) \rightarrow p + (n, p) + e^{-} + \bar{v}_{c}.$$

 $p + (n, p) \rightarrow n + (n, p) + e^{+} + v_{c}$

Dipole Polarizability (α_D)

Dipole Polarizability is strongly correlated with R_n - R_p [26]

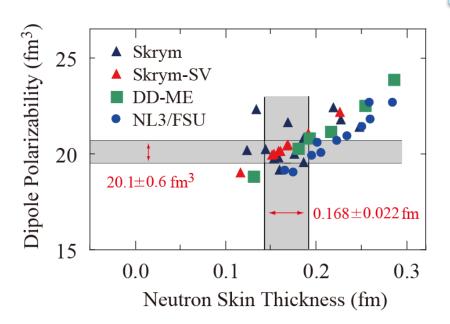
$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$

$$R_n - R_p = 0.168 \pm 0.022$$
 fm for ²⁰⁸Pb

Determination of α_D by an

including model uncertainty.

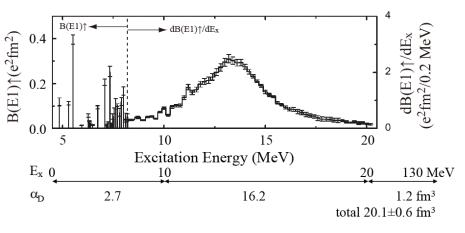
Electro-Magnetic Probe



J. Piekarewicz et al., PRC85, 041302(2012)







AT et al. PRL107,062502(2011) [27]

At the density dependence of the presence of section of the control of the contr

page-3

Experiment:

Parity Violating Electron Scattering from ²⁰⁸Pb at J-Lab.

Thomas Jefferson National Accelerator Facility (Jefferson-Lab)



Hall A at Jefferson Lab



Thomas Jefferson National Accelerator Facility (Jefferson-Lab) Hall-A

Continuous Electron Beam Accelerator Facility

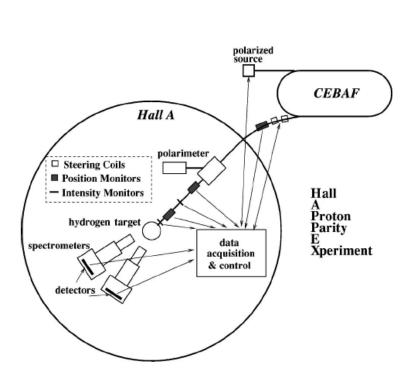


FIG. 1. Schematic overview of the HAPPEX experiment.

K.A. Aniol et al., PRC69, 065501 (2004)

Gain switched diode lasers
499 MHz

Pockels cell

Thomas Jefferson National Accelerator Facility

J. Grames - Jub Summer Detector Series, July 7, 2008

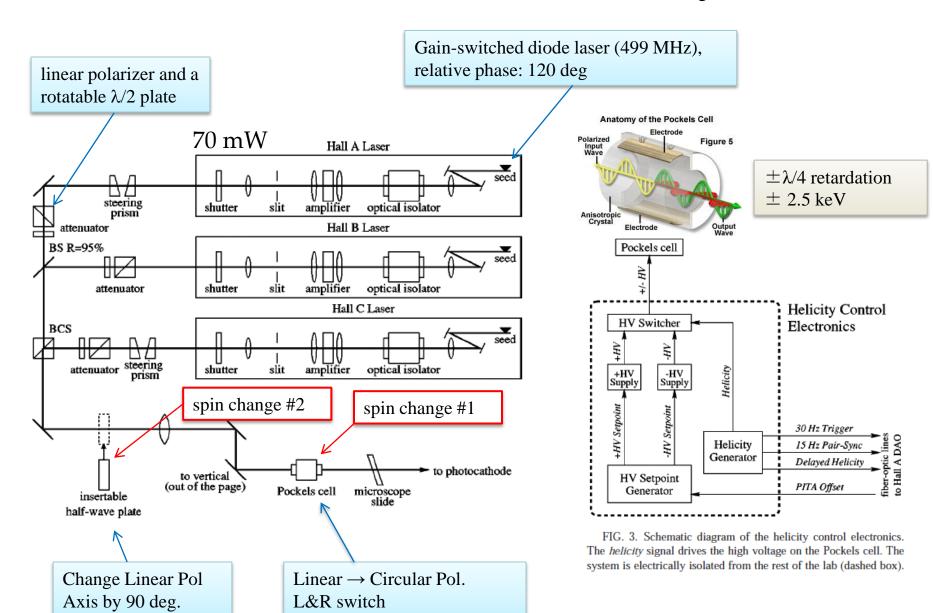
electron beam:

50-70 μ A, longitudinal pol., 1.06 GeV normal spot size 50 μ m $4 \times 4 \text{ mm}^2$ beam rastering

HAPPEX: Hall A Precision Parity EXperiment

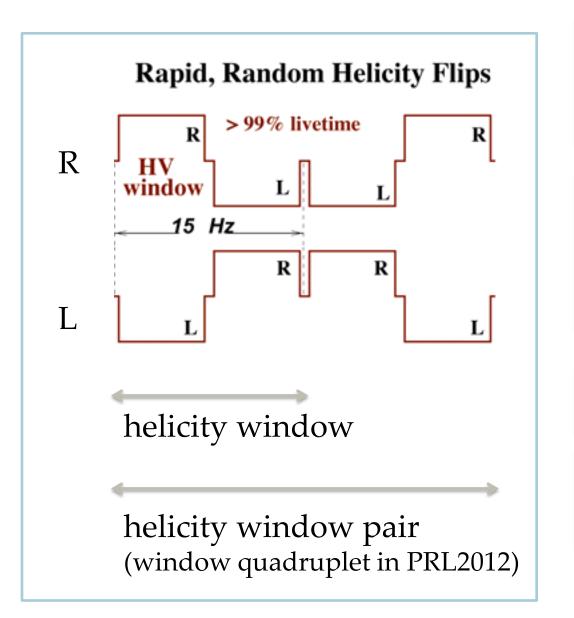
in PREX, PRL108,112502(2012)

Pol. Electron Sources (Laser System)



Helicity Window

helicity control electronics (with Pockels cell)



Helicity window pair (window quadruplet in PRL2012) R or L is chosen by a pseudo-random generator.

According to PRL2012, HV window is 8.33 msec (120Hz), thus window quadruplet 33.3 msec (30Hz), i.e. four times faster than the left figure.

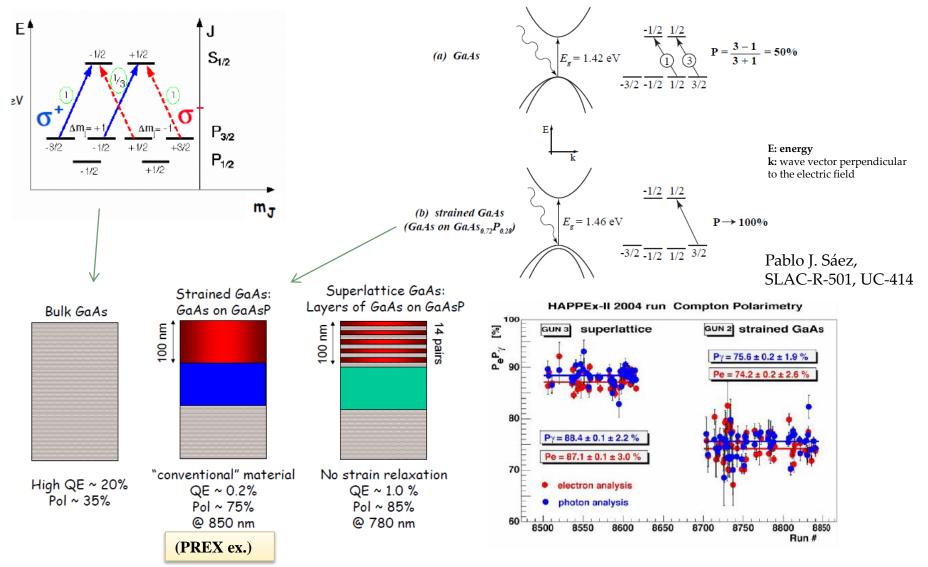
Synchronized with the 60 Hz line frequency.

Signal transmission by fiber-optic cable: suppression of the ground noise and cross talk.

 2×10^7 window quadruplets were recorded in PREX.

Pol. Electron Source (strained GaAs)

Photo-cathode, optical pumping



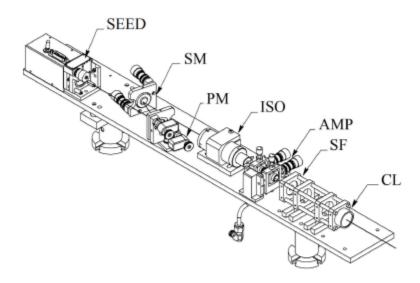


FIG. 6. The MOPA gain-switched diode seed laser and diode amplifier system: SM, steering mirror; PM, picomotor; ISO, optical isolator; AMP, single pass diode amplifier; SF, spatial filter; CL, cylindrical lens.

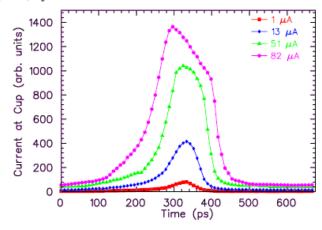
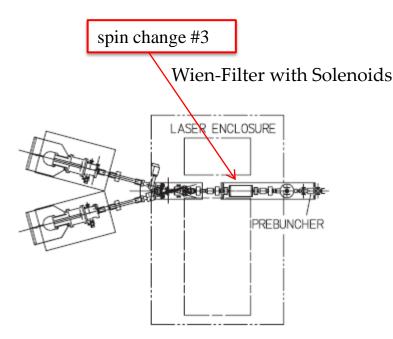


FIG. 7. (Color) Electron bunch length plots at the chopper slits at four different beam currents, obtained from a bulk GaAs cathode in the first polarized electron source. The observed bunch lengthening at higher current led to the installation of a 1497 MHz prebuncher between the gun and the injector chopper.



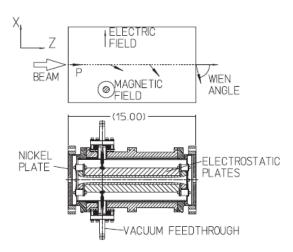


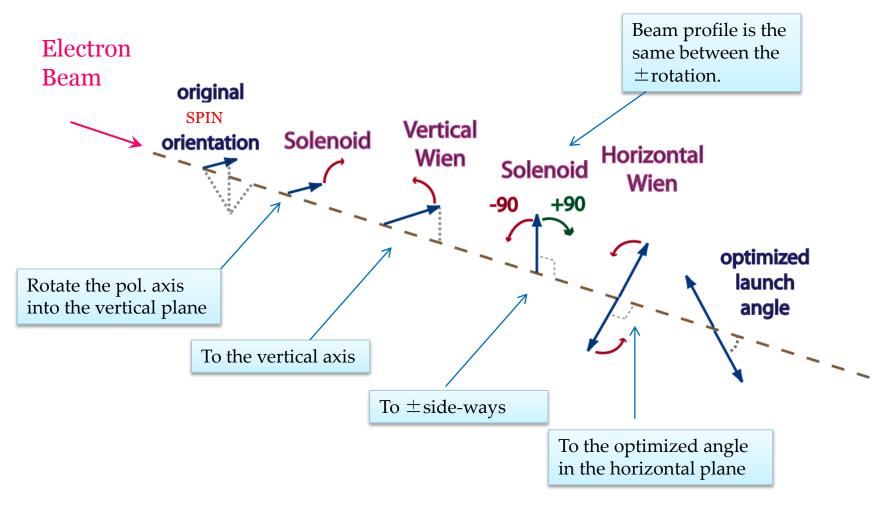
FIG. 4. The Wien filter spin manipulator used with CEBAF's second and third polarized electron sources. The magnet is not shown in the cutaway view.

Double Wien Filter

Crossed E & B fields to rotate the spin

- Two Wien Spin Manipulators in series
- Solenoid rotates spin +/-90 degrees (spin rotation as B but focus as B²).

Flips spin without moving the beam!



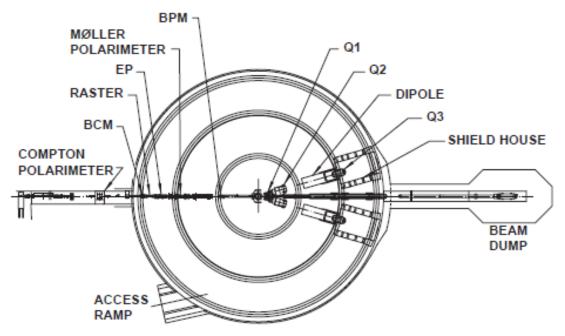


Fig. 18. Schematic layout of Hall A, indicating the location of the Compton and the Møller polarimeters, the raster, the EP energy measurement system, the beam current monitors (BCM) and the beam position monitors (BPM) upstream of the target. Also indicated are the locations of the components of one of the high-resolution spectrometers (Q1, Q2, dipole, Q3 and shield house) and of the beam dump and the truck access ramp.

Thin-Wire Beam Position Monitor (BPM)

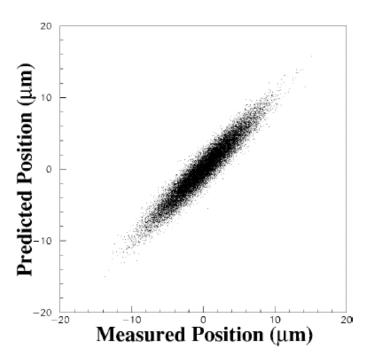


FIG. 5. Window-to-window beam jitter as measured by a BPM is plotted along the x axis. On the y axis is plotted the beam position as predicted by nearby BPMs. The residuals are smaller than 1 μ m.

 ΔX ~1 μ m 1-10 μ m fluctuation in $\sigma(\Delta X)$

5 BPMs are placed in the beam line recorded in every 1Hz [34] J. Alcorn et al., NIMA522,294(2004)

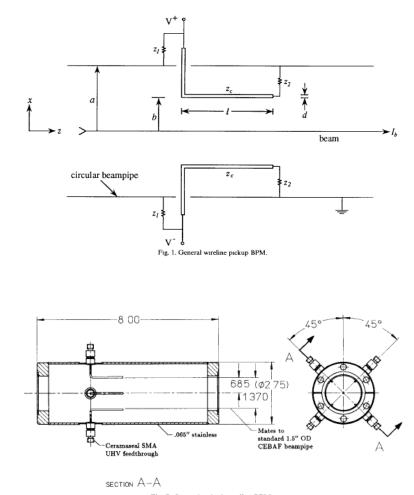


Fig. 7. Open-circuited wireline BPM.

W. Barry., NIMA301_407(1991)

Beam Current Monitor (BCM)

Two RF cavity monitors (non-destructive)

stainless steel, cylindrical, high-Q (3000) wave guide (1.497 GHz)

high-precision 16bit ADC, non-linearity < 0.1%

Precision: 4×10^{-5} at 100 µA for a 30 msec beam window

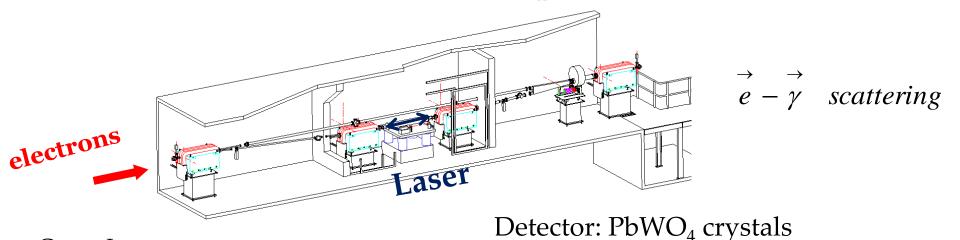
"Unser monitor" for absolute beam current not important for HAPPEX (and PREX)

toroidal Paramagnetic Current Transformer (PCT) sensitive to the DC component of the magnetic field generated by the beam current around the beam pipe

see https://www.jlab.org/div_dept/admin/publications/papers/01/ACT01-12.pdf

[34] J. Alcorn et al., NIMA522,294(2004)

Beam Polarimeter (Compton Polarimeter)



Green Laser (increased sensitivity at low E) Integrating Method (removes some systematics of analyzing power)

Upgrade for 1% accuracy at 1 GeV Events

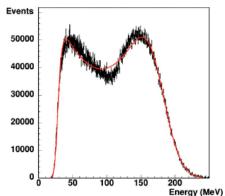
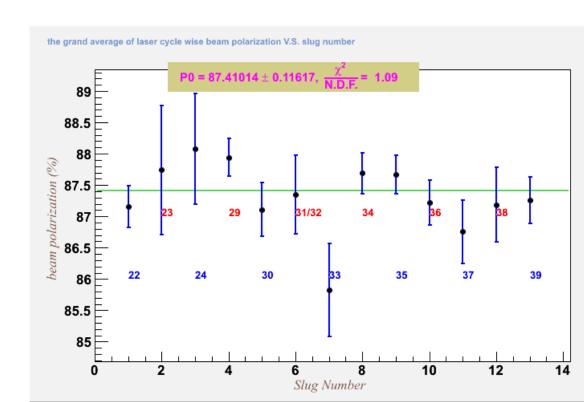


FIG. 13. (Color online) Compton spectrum as measured by the photon calorimeter. The curve is a fit of the Compton cross section convoluted with a Gaussian resolution of the calorimeter [see Eq. (20)].





Upgraded for PREX

Moller Polarimeter

$$\stackrel{\rightarrow}{e} - \stackrel{\rightarrow}{e}$$
 scattering

Superconducting Magnet from Hall C
Saturated Iron Foil Targets (at 4 T)

1 % Accuracy in Polarization

$$A_m^{\text{exp}} = \sum_{i=X,Y,Z} (A_{mi}^{\text{th}} \cdot P_i^{\text{targ}} \cdot P_i^{\text{beam}}), \qquad (17)$$

$$A_{mZ}^{\text{th}} = -\frac{\sin^2 \theta_{\text{c.m.}} (7 + \cos^2 \theta_{\text{c.m.}})}{(3 + \cos^2 \theta_{\text{c.m.}})^2}.$$
 (18)

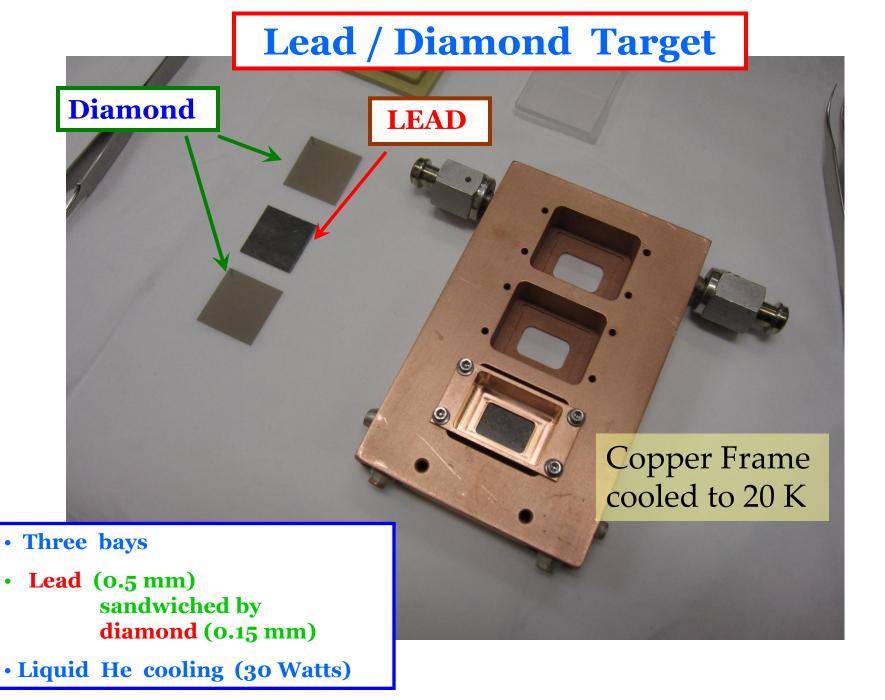
ferromagnetic foil

$$P^{targ} = 7.95 \pm 0.24 \%$$
 at 24 mT

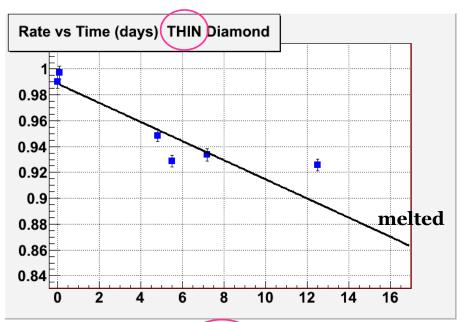
$$75^{\circ} < \theta_{\rm c.m.} < 105^{\circ}$$

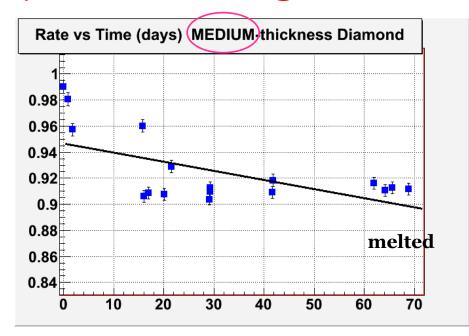
$$-5^{\circ} < \varphi_{c.m.} < 5^{\circ}$$

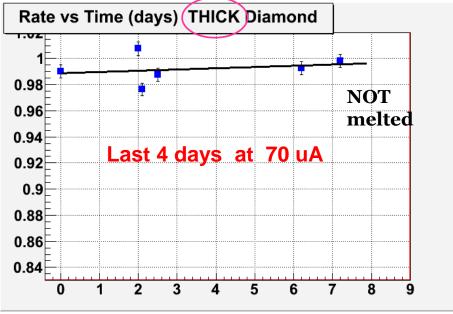
The values are before PREX meas. [34] J. Alcorn et al., NIMA522, 294(2004)



Performance of Lead / Diamond Targets







Targets with thin diamond backing (4.5 % background) degraded fastest.

Thick diamond (8%) ran well and did not melt at 70 uA.

→ Solution: Run with 10 targets.

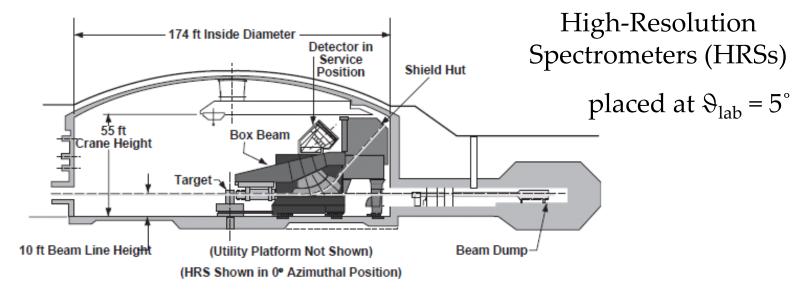


Fig. 2. Schematic cross section of Hall A with one of the HRS spectrometers in the (fictitious) 0° position.

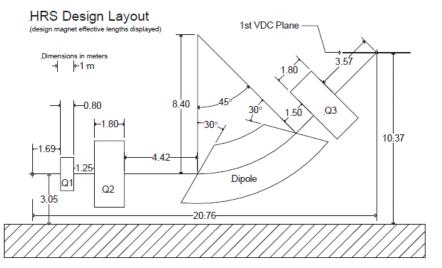


Fig. 5. Schematic layout of a HRS device, showing the geometrical configuration of the three quadrupole and the dip shown is the location of the first VDC tracking detector.

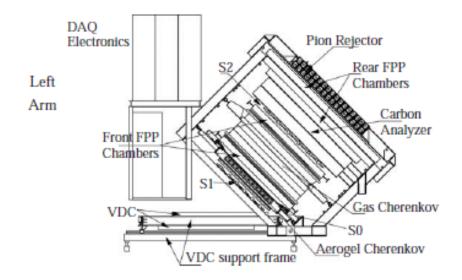
Main design characteristics of the Hall A high resolution spectrometers; the resolution values are for the FWHM

Configuration	QQD _n Q vertical bend
Bending angle	45°
Optical length	23.4 m
Momentum range	$0.3-4.0~{ m GeV}/c$
Momentum acceptance	$-4.5\% < \delta p/p < +4.5\%$
Momentum resolution	1×10^{-4}
Dispersion at the focus (D)	12.4 m
Radial linear magnification (M)	-2.5
D/M	5.0
Angular range	
HRS-L	12.5-150°
HRS-R	12.5–130°
Angular acceptance	
Horizontal	\pm 30 mrad
Vertical	\pm 60 mrad
Angular resolution	
Horizontal	0.5 mrad
Vertical	1.0 mrad
Solid angle at $\delta p/p = 0$, $y_0 = 0$	6 msr
Transverse length acceptance	\pm 5 cm
Transverse position resolution	1 mm 4()

[34] J. Alcorn et al., NIMA522, 294(2004)

Position sensitive detectors (VDCs)

only used for calibration purposes



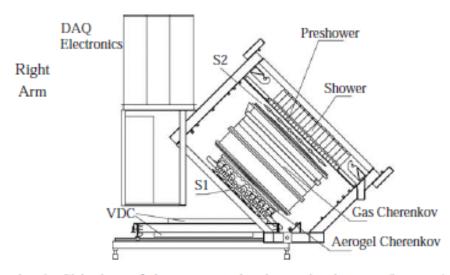
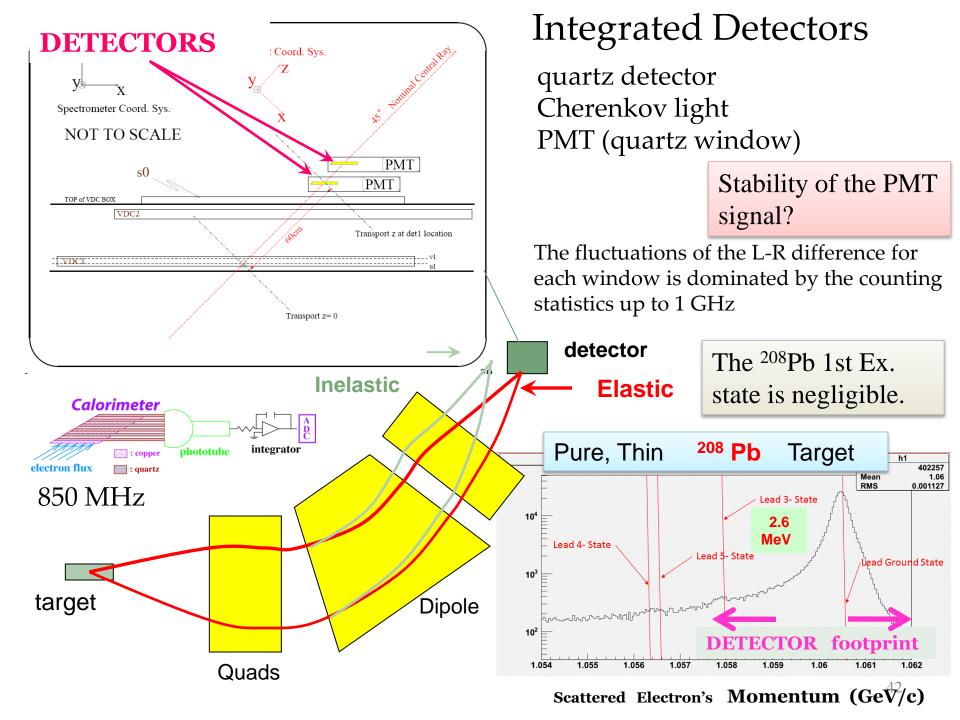
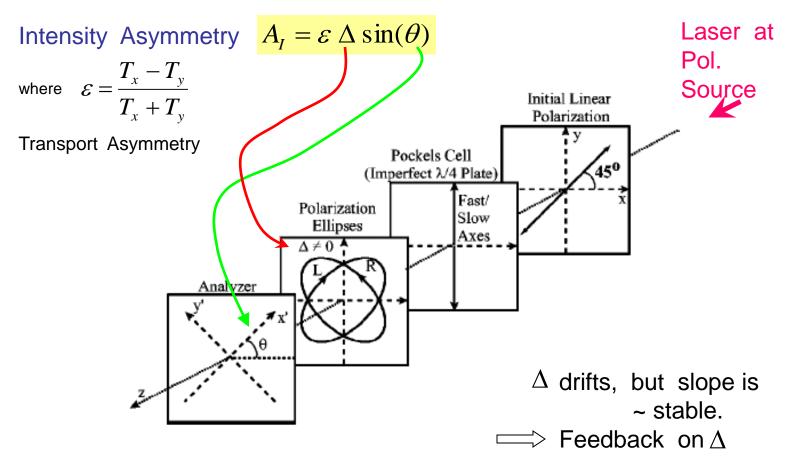


Fig. 8. Sideview of detector stack, shown in the top (bottom) figure for the left (right) (w.r.t. the beam line) HRS device. Individual elements of the detector system are indicated in the configuration used most frequently. Also shown is the position of the data-acquisition (DAQ) electronics and of the VDC support frame.



Important Systematic: PITA Effect

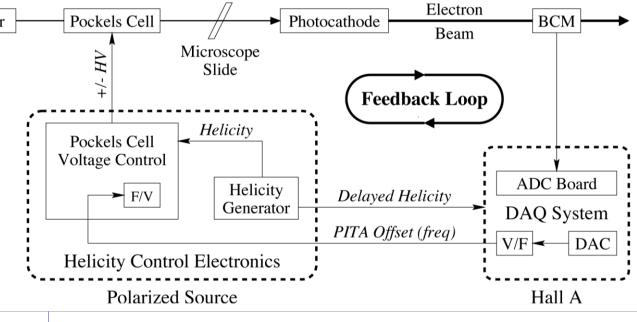
Polarization Induced Transport Asymmetry

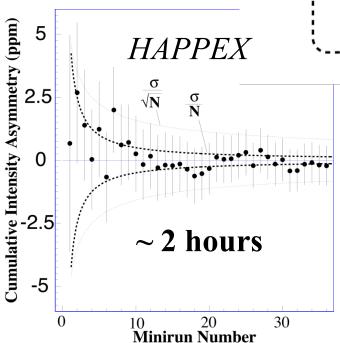


99.99% circular pol. but with 1.4% linear pol. (different orientation) causes intensity asymmetry

Intensity Feedback

Adjustments
for small phase shifts
to make close to
circular polarization





Low jitter and high accuracy allows sub-ppm Cumulative charge asymmetry in ~ 1 hour

In practice, aim for 0.1 ppm over duration of data-taking.

Transverse Polarization

Part I: Left/Right Asymmetry

Transverse Asymmetry

Systematic Error for Parity

$$A_T \approx A_T^0 P_T \sin \phi \rightarrow \delta A = \delta \left(A_T^0 \xi P_T \right)$$
Theory est. (Afanasev)
$$A_T^0 = 5 \pm 1 \quad ppm$$
"Error in"
$$\xi = 1 \text{ off-right}$$

Transverse polarization

$$P_T = P \sin \theta \quad \theta \leq 3^{\circ}$$

HRS-Right HRS-Left

$$\mathcal{S}A = \mathcal{S}\left(A_T^0 \ \xi \ P_T
ight)$$

 ξ = Left-right apparatus asymmetry

Control θ w/ slow feedback on polarized source solenoids.

$$\delta A_T^0 = \pm 1 \ ppm \ \text{measure in } \sim 1 \ \text{hr}$$

Need
$$\xi P_T \ll 10^{-3} \pm 10^{-3}$$
 correction syst. err.

Transverse Polarization

Part II: Up/Down Asymmetry

Vertical misalignment

Systematic Error for Parity

Horizontal polarization e.g. from (g-2)

 $P_T = P \sin \theta$

$$<\cos\phi>\neq0$$
 \rightarrow

$$\delta A = \delta \left(A_T^0 \ P_T < \cos \phi > \right)$$

- Measured in situ using 2-piece detector.
- Study alignment with
- tracking & M.C.
- Wien angle feedback (θ)

Need

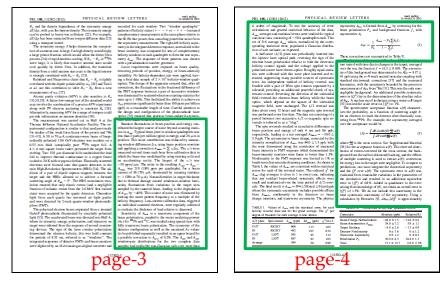
$$P_T < \cos \phi > \ll 10^{-3} \pm 10^{-3}$$

HRS-Right HRS-Left

(Note, beam width is very tiny $\sim 100 \ \mu m$)

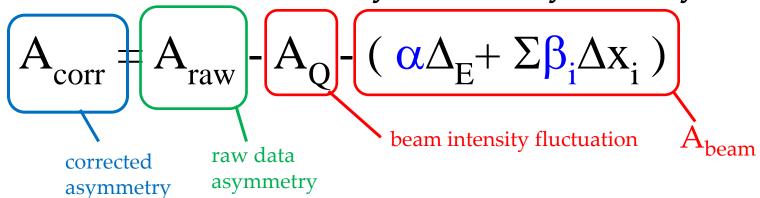
up/down

misalignment



Analysis Details, Calibrations, Corrections

Correction/Uncertainty of the Asymmetry



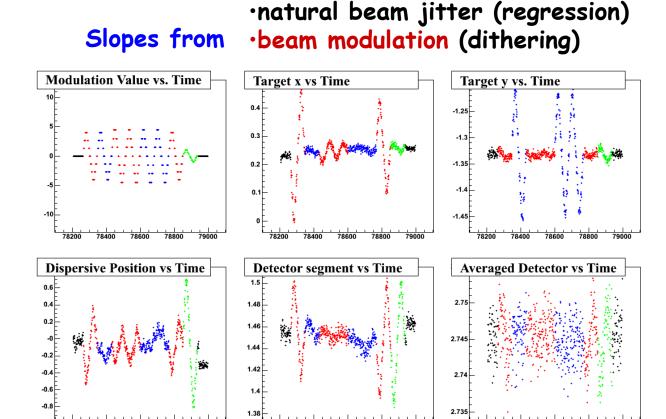
Beam jitter in window quadruplets:

 Δ E/E~2 ppm Δ X~20 µm

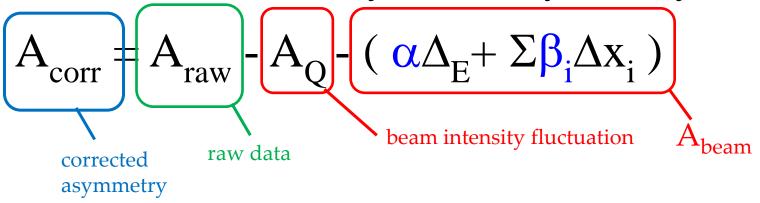


monitored and converted to A and be corrected as A_{beam} .

Coefficients are measured several times each hour with modulation by steering coils and cavity



Correction/Uncertainty of the Asymmetry



$$A_{beam} = -39.0 \pm 5.9 \text{ ppb}$$

$$A_0 = 84.0 \pm 1.3 \text{ ppb}$$

from the text

Why the numbers in Table II are different?



A_{raw} is not written

$$A_{corr} = 594 \pm 50(stat) \pm 9(syst) ppb$$

from A_{beam} , detector non-linearlity, A_Q , and transverse asymmetry

Correction/Uncertainty of the Asymmetry

Spin change

#1 by Pockels cell: for every window (83 msec)

#2 by a λ /2 plate: for every 12 hours

#3 by a solenoid spin rotator: for every few days

With changing the spin by #2 and #3, the same results were obtained within the (statistical) uncertainty

The averaged result:

$$A_{corr} = 594 \pm 50(stat)$$

 $\pm 9(syst) ppb$

TABLE I. Values of A_{∞} and the statistical error, for each helicity reversal state and for the grand average. The χ^2 per degree of freedom for each average is also shown.

$\lambda/2$ plate	Spin rotator	A _{corr} (ppb)	$\delta A_{\rm corr}$ (ppb)	χ^2 /d.o.f.
OUT	RIGHT	606	113	1.03
IN	RIGHT	492	107	0.74
OUT	LEFT	565	95	1.12
IN	LEFT	687	92	1.03
Average		594	50	0.99

Background, Beam Polarization

$$A_{\text{PV}} = \frac{1}{P_b} \frac{A_{\text{corr}} - P_b \sum_{i} A_i f_i}{1 - \sum_{i} f_i}.$$
 (2)

Background from carbon (diamond):

$$f = 6.3 \pm 0.6 \%$$
, $A = 817 \pm 41 ppb$

by cal. using e-N weak neutral isoscalar coupling with corrections [37]

TABLE II. Corrections to A_{PV} and systematic errors.

Correction	Absolute (ppb)	Relative(%)
Beam Charge Normalization	-84.0 ± 1.5	-12.8 ± 0.2
Beam Asymmetries A _{beam}	39.0 ± 7.2	5.9 ± 1.1
Target Backing	-8.8 ± 2.6	-1.3 ± 0.4
Detector Nonlinearity	0 ± 7.6	0 ± 1.2
Transverse Asymmetry	0 ± 1.2	0 ± 0.2
Polarization P_b	70.9 ± 8.3	10.8 ± 1.3
Total	17.1 ± 13.7	$2.6 \pm 2.1\%$

Background, Beam Polarization

Beam Polarization

by Compton polarimeter (continuous)

$$P_b$$
=88.2±0.1±1.0 %

by Moeller polarimeter (9 measurements)

$$P_b = 90.3 \pm 0.1 \pm 1.1 \%$$

Average of the two

$$P_b = 89.2 \pm 1.0 \%$$

TABLE II. Corrections to A_{PV} and systematic errors.

Correction	Absolute (ppb)	Relative(%)
Beam Charge Normalization	-84.0 ± 1.5	-12.8 ± 0.2
Beam Asymmetries A _{beam}	39.0 ± 7.2	5.9 ± 1.1
Target Backing	-8.8 ± 2.6	-1.3 ± 0.4
Detector Nonlinearity	0 ± 7.6	0 ± 1.2
Transverse Asymmetry	0 ± 1.2	0 ± 0.2
Polarization P_b	70.9 ± 8.3	10.8 ± 1.3
Total	17.1 ± 13.7	$2.6 \pm 2.1\%$

Background, Beam Polarization

Result after all the corrections

$$A_{\rm PV}^{\rm Pb} = 656 \pm 60 ({\rm stat}) \pm 14 ({\rm syst}) \ {\rm ppb},$$

Scattering Angle, Acceptance

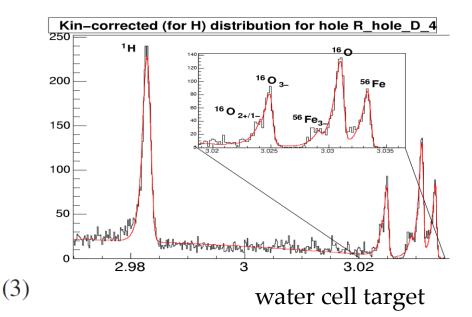
Scattering Angle Calibration

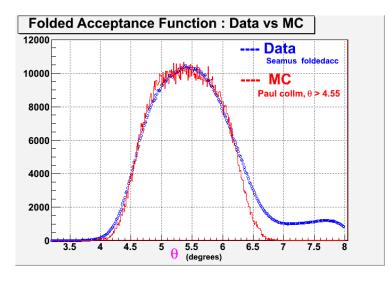
$$\Delta < Q^2 > / < Q^2 > = 1\%$$

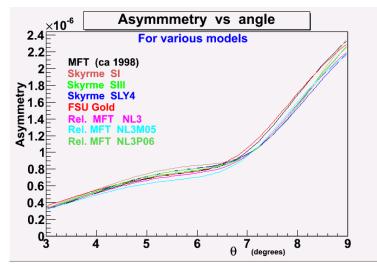
Acceptance Averaging

$$\langle A \rangle = \frac{\int d\theta \sin\theta A(\theta) \frac{d\sigma}{d\Omega} \epsilon(\theta)}{\int d\theta \sin\theta \frac{d\sigma}{d\Omega} \epsilon(\theta)},$$

$$\Delta < Q^2 > / < Q^2 > = 0.8\%$$







Result

Result after all the corrections

$$A_{\rm PV}^{\rm Pb} = 656 \pm 60({\rm stat}) \pm 14({\rm syst}) \ {\rm ppb},$$

$$\langle Q^2 \rangle = 0.00880 \pm 0.00011 \text{ GeV}^2$$

$$q = \langle Q^2 \rangle^{1/2} = 0.475 \pm 0.003 \text{ fm}^{-1}$$

Result

$$R_n = 5.78^{+0.16}_{-0.18}$$

$$R_n - R_p = 0.33^{+0.16}_{-0.18} \text{ fm}$$

In abstract

"provides the first electroweak observation of the neutron skin"

In summary

"A future run is planned which will reduce the quoted uncertainty by a factor of 3 [43], to discriminate between models and allow predictions relevant for the description of neutron stars and parity violation in atomic systems."

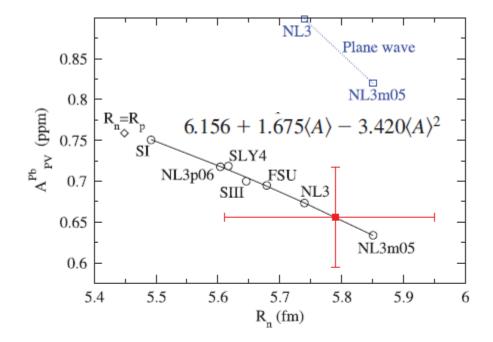


FIG. 1 (color). Result of this experiment (red square) vs neutron point radius R_n in 208Pb. Distorted-wave calculations for seven mean-field neutron densities are circles while the diamond marks the expectation for $R_n = R_p[39]$. References: NL3m05, NL3, and NL3p06 from [11], FSU from [12], SIII from [13], SLY4 from [14], SI from [15]. The blue squares show plane wave impulse approximation results.

No discussion on the impact of the result?

Is this analysis really model independent?



Physicists Measure the Skin of a Nucleus

by Adrian Cho on 2 March 2012

Science Now

• • •

Nailing down such parameters would have equally big implications for the theory of neutron stars, says James Lattimer, a theoretical astrophysicist at Stony Brook University in New York state. "That directly tells you the radius of a neutron star [of a given mass] and a lot of other things like the thickness of its crust, the response of its surface to explosions, et cetera," Lattimer says.

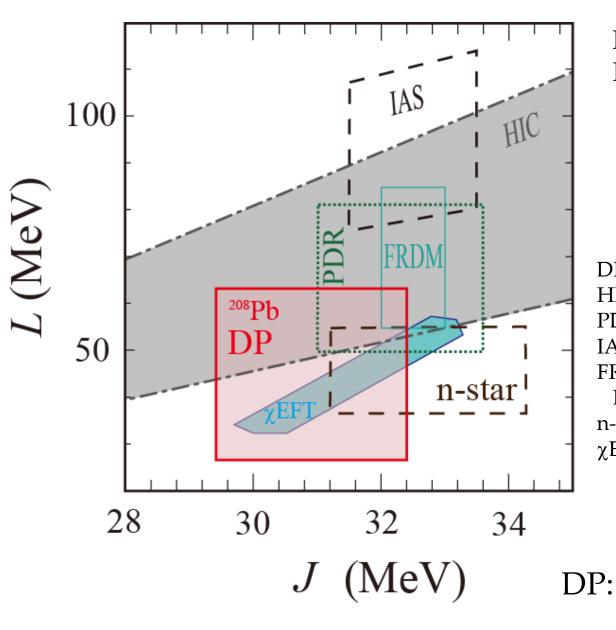
Alas, the uncertainty on the PREX measurement is still too large to pin down the parameters, Lattimer says. "It's a very important experiment and has the potential to constrain theory very nicely, but it's not there yet," he says. JLab's Michaels says the PREX team will run the experiment next year and aims to reduce the uncertainty to one-third its current value. "Then it becomes a very interesting result," he says.

Something else physicists will be watching for: The PREX measurement suggests that the neutron skin of lead-208 is twice as thick as more-precise but model-dependent methods indicate. Right now, the PREX result has too much uncertainty to pose a direct challenge to earlier estimates. But if the new value holds up as the uncertainty shrinks, things could get really interesting, Nazarewicz says: "Then, there is something wrong with all theoretical models." There's a possibility to set your skin a-tingling.

Determination of Symmetry Energy 0.49 Non-relativistic models Relativistic models 0.35 δR_{np} Linear fit $\delta R_{np} = 0.101 + 0.00147 L$ PREX 0.30 Skin Thickness 0.25 PES 0.20 0.15 0.10 50 100 150 DP: Dipole Polarizability

L (MeV)

Determination of Symmetry Energy



M.B. Tsang *et al.*, PRC**86**, 015803 (2012).

I. Tews et al., arXiv:1206.0025v1

and this work

DP: Dipole Polarizability HIC: Heavy Ion Collision

PDR: Pygmy Dipole Resonance

IAS: Isobaric Analogue State FRDM: Finite Range Droplet

Model (nuclear mass analysis) n-star: Neutron Star Observation

χΕFT: Chiral Effective Field Theory

Preliminary

 $L=45\pm18 \text{ MeV}$ $J=30.9\pm1.5 \text{ MeV}$

Theoretical Correction by C.J. Horowitz

C.J. Horowitz et al., PRC85,032501(R)(2012)

Firstly Woods-Saxon shape weak density distribution is assumed

$$\rho_W(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]},\tag{2}$$

With fixing a=0.6 fm, R is changed so as to the acceptance average of A

$$\langle A \rangle = \frac{\int d\theta \sin\theta \, \epsilon(\theta) \frac{d\sigma}{d\Omega} A_{pv}}{\int d\theta \sin\theta \, \epsilon(\theta) \frac{d\sigma}{d\Omega}}.$$
 (4)

reproduced the PREX result

$$A_{\rm pv}^{\rm Pb} = 0.656 \pm 0.060 \text{ (stat)} \pm 0.014 \text{ (syst) ppm.}$$
 (5)

Then the *R*=6.982 fm is obtained. With this $\rho_{\rm w}(r)$, and the equation

$$F_W(q) = \frac{1}{Q_W} \int d^3r \frac{\sin qr}{qr} \rho_W(r). \tag{3}$$

 $F_w(q\text{-bar})$ has been determined as $(q\text{-bar} = 0.475 \pm 0.003 \text{ fm}^{-1})$

$$F_W(\bar{q}) = 0.204 \pm 0.028 \text{ (exp)} \pm 0.001 \text{ (mod)}.$$
 (6)

Why can the model dependence be obtained with only change a and fixing?

The model uncertainty (0.001) has been obtained by varying a by ± 0.05 fm.

The range of *a* was obtained from several mean field calculations.

Are the number of model calculations enough to estimate the model dependence?

Helm-model is used to extract the weak-charge radius (R_w).

TABLE I. Least squares fits of Wood Saxon (R, a, see Eq. (2)) or Helm model $(R_0, \sigma, \text{see Eq. (8)})$ parameters to theoretical mean field model weak charge densities.

	Wood Saxon		Helm	
Mean field force	R (fm)	a (fm)	R_0 (fm)	σ (fm)
Skyrme I [8]	6.655	0.564	6.792	0.943
Skyrme III [9]	6.820	0.613	6.976	1.024
Skyrme SLY4 [10]	6.700	0.668	6.888	1.115
FSUGold [11]	6.800	0.618	6.961	1.028
NL3 [12]	6.896	0.623	7.057	1.039
NL3p06 [6]	6.730	0.606	6.886	1.010
NL3m05 [6]	7.082	0.605	7.231	1.012
Average	7	0.61 ± 0.05		1.02 ± 0.09

Helm-model: Gaussian (with σ) is folded with a square uniform distribution with a radius R_0 . The parameter σ represents the surface diffuseness and neutron size.

$$R_W^2 = \frac{3}{5} (R_0^2 + 5\sigma^2). \tag{9}$$

Is this toy-model (Helm-model) enough for the discussion?

 R_w has been determined so that the Helm-model reproduce the $F_w(q$ -bar) result (equation 6). The model dependence has been estimated by varying σ with σ =1.02 \pm 0.09 fm. Again this σ range was estimated from mean-field calculations.

$$R_W = 5.826 \pm 0.181 \text{ (exp)} \pm 0.027 \text{ (mod) fm.}$$
 (10)

Why are the two models, Woods-Saxon shape and Helmmodel, used?

The weak-charge skin has been obtained as

$$R_W - R_{\rm ch} = 0.323 \pm 0.181 \text{ (exp)} \pm 0.027 \text{ (mod) fm.}$$
 (11)

The weak-charge density is expressed as

$$\rho_W(r) = 4 \int d^3r' \left[G_n^Z(|\mathbf{r} - \mathbf{r}'|) \rho_n(r') + G_p^Z(|\mathbf{r} - \mathbf{r}'|) \rho_p(r') \right]. \tag{14}$$

The single proton/neutron weak-charges are described as

$$4G_p^Z = q_p G_E^p + q_n G_E^n - G_E^s, \tag{15}$$

$$4G_n^Z = q_n G_E^p + q_p G_E^n - G_E^s. (16)$$

0.08 0.06 0.04 0.02 0.02 0.02 0.05 r (fm)

FIG. 1. (Color online) Helm model weak charge density $-\rho_W(r)$ of ^{208}Pb that is consistent with the PREX result (solid black line). The brown (gray) error band shows the incoherent sum of experimental and model errors. The red dashed curve is the experimental (electromagnetic) charge density ρ_{ch} and the blue dotted curve shows a sample mean-field result based on the FSUGold interaction [11].

At tree level, the weak nucleon charges are

$$q_n = -1$$
$$q_p = 1 - 4\sin^2 \theta_W$$

where ϑ_W is the Weinberg angle., With radiative corrections,

$$q_n = -0.9878$$

$$q_p = 0.0721$$

Then

$$R_n = 5.751 \pm 0.175 \text{ (exp)} \pm 0.026 \text{ (mod)} \pm 0.005 \text{ (str) fm}.$$

$$R_n - R_p = 0.302 \pm 0.175 \text{ (exp)} \pm 0.026 \text{ (mod)}$$

 $\pm 0.005 \text{ (str) fm.}$

This model uncertainty is already larger than the model-dependence of the dipole-polarizability.

(21)

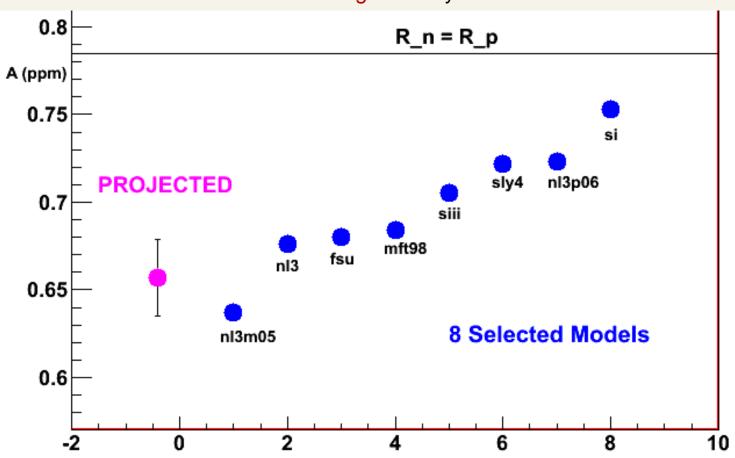
(22)

DP:
$$R_n - R_p = 0.168 \pm 0.022$$
 fm

PREX-II

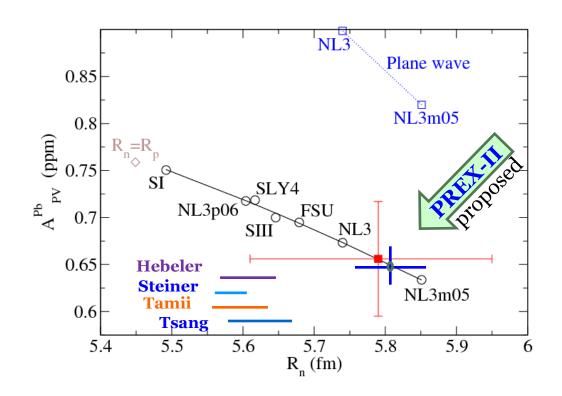
Approved by PAC (Aug 2011)

"A" Rating 35 days to run in 2013 or 2014



Recent R_n Predictions Can Be Tested By PREX at Full Precision

PREX could provide an electroweak complement to R_n predictions from a wide range of physical situations and model dependencies



These can be tested with $\delta(A_{PV})/A_{PV} \sim 3\%$ $\delta(R_n)/R_n \sim 1\%$

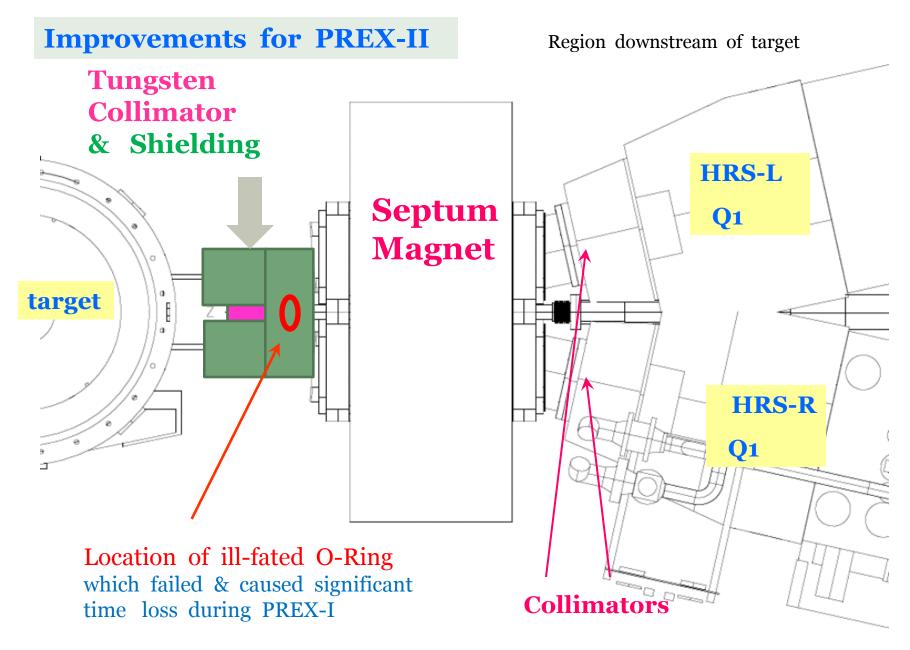
Recent R_n predictions:

Hebeler *et al.* Chiral EFT calculation of neutron matter. Correlation of pressure with neutron skin by Brown. Three-neutron forces!

Steiner *et al.* X-Ray n-star mass and radii observation + Brown correlation. (Ozel *et al* finds softer EOS, would suggest smaller R_n).

Tamii *et al.* Measurement of electric dipole polarizability of ²⁰⁸Pb + model correlation with neutron skin.

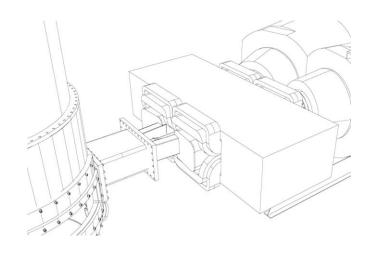
Tsang *et al.* Isospin diffusion in heavy ion collisions, with Brown correlation and quantum molecular dynamics transport model.



→ PREX-II to use all-metal seals



Possible Future PREX Program ?



Each point 30 days

stat. error only

Nucleus	E (GeV)	dR _N / R _N	comment
²⁰⁸ Pb	1	1 %	PREX-II (approved by Jlab PAC, A rating)
⁴⁸ Ca	2.2 (1-pass)	0.4 %	natural 12 GeV exp't will propose @ next PAC
⁴⁸ Ca	2.6	2 %	surface thickness
⁴⁰ Ca	2.2 (1-pass)	0.6 %	basic check of theory
tin isotope	1.8	0.6 %	apply to heavy ion
tin isotope	2.6	1.6 %	surface thickness

Not proposed

Thank you for your attention!