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PREX recent results and future prospects

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Summary. — The PREX experiment at Jefferson Lab has measured the parity-violating electroweak asymmetry in the elastic scattering of polarized electrons from ^{208}Pb at an energy of 1.06 GeV and a scattering angle of 5°. Since the Z_0 boson couples mainly to neutrons, this asymmetry provides a clean measurement of the neutron RMS radius R_n of the lead nucleus. In addition to being a fundamental test of nuclear models, a precise measurement of R_n pins down the density dependence of the symmetry energy of neutron rich nuclear matter, which has impacts on neutron star structure, heavy ion collisions, and atomic parity violation experiments. The asymmetry from the first measurements performed in 2010 is $A_{pv} = 657 \pm 60(\text{stat}) \pm 13(\text{syst})$ ppb at $Q^2 = 0.00906\,\text{GeV}/c$. Prospects for follow-up experiments with ^{208}Pb and ^{48}Ca are discussed.

PACS 21.65.Ef – Symmetry energy.
PACS 21.65.Mn – Equations of state of nuclear matter.
PACS 21.10.Gv – Nucleon distributions and halo features.

1. – Introduction

Historically, electromagnetic scattering has accurately measured the charge distribution of nuclei [1, 2], providing a detailed picture of the atomic nucleus. In contrast, neutron densities are not directly probed by electron scattering because the neutron is uncharged; our knowledge of neutron densities comes primarily from hadron scattering experiments involving for example pions [3], protons [4-6], or antiprotons [7, 8]. However, the interpretation of hadron scattering experiments is model dependent because of uncertainties in the strong interactions.

Parity violating electron scattering provides a model independent probe of neutron densities that is free from most strong interaction uncertainties. The Z^0 boson, which carries the weak force, couples primarily to neutrons. In Born approximation, the parity violating asymmetry A_{pv} is proportional to the weak form factor and hence to the neutron form factor F_n and the RMS radius R_n [9],

$$A_{pv} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right], \tag{1}$$

where G_F is the Fermi constant, $\alpha = \frac{1}{137}$ is the fine structure constant, θ_W is the Weinberg angle, and $F_n(Q^2)$ and $F_p(Q^2)$ are the neutron and proton form factor of the nucleus.

Corrections to the Born approximation from Coulomb distortion effects must be included and have been accurately calculated [10], and other theoretical interpretation issues have been considered in [11]. The Lead Radius Experiment (PREX) measures the parity violating asymmetry A_{pv} for 1.063 GeV electrons scattering from ^{208}Pb at five degrees. This measurement should be sensitive to R_n to 1% (± 0.05 fm).

The neutron radius of ^{208}Pb, R_n, has important implications for astrophysics. Measuring R_n constrains the equation of state (EOS), *i.e.* the pressure as a function of density, of neutron matter. The EOS is very important in astrophysics to determine the structure of neutron stars, for example, the correlation between R_n and the radius of a neutron star r_{NS} [12]. A larger R_n implies a stiffer EOS, with a larger pressure, that will also suggest r_{NS} is larger. Recently there has been great progress in deducing r_{NS} from X-ray observations. Ozel *et al.* find r_{NS} is very small, near 10 km from observations of X-ray bursts [13], while Steiner *et al.* [14] conclude that r_{NS} is near 12 km and predict that $R_n - R_p = 0.15 \pm 0.02$ fm. The high density EOS implied by Ozel *et al.* [15] is soft, suggesting a transition to an exotic phase of QCD. In contrast, the Steiner *et al.* EOS is stiffer, leaving little room for softening due to a phase transition. These results can be tested with a measurement of R_n.

The EOS of neutron matter is closely related to the symmetry energy S. This describes how the energy of nuclear matter rises as one goes away from equal numbers of neutrons and protons. There is a strong correlation between R_n and the density dependence of the symmetry energy $\mathrm{d}S/\mathrm{d}\rho$, with ρ the baryon density. The symmetry energy can be probed in heavy ion collisions [16]. For example, $\mathrm{d}S/\mathrm{d}\rho$ has been extracted from isospin diffusion data [17] using a transport model where projectile and target nuclei with different proton to neutron ratios are collided and one observes how the neutron to proton ratio equilibrates. Often isospin diffusion data is analyzed with transport models, since heavy ion collisions are so complicated. Measuring R_n allows one to extract $\mathrm{d}S/\mathrm{d}\rho$ in a way that is independent of the complex HI dynamics.

The symmetry energy S helps determine the composition of a neutron star. A large S, at high density, implies a large proton fraction Y_p that will allow the direct URCA process of rapid neutrino cooling. If $R_n - R_p$ is large, it is likely that massive neutron stars will cool quickly by direct URCA [18]. In addition, the transition density from solid neutron star crust to the liquid interior is strongly correlated with $R_n - R_p$ [19].

Finally, atomic parity violation (APV) is sensitive to R_n [11, 20-22]. A future low energy test of the standard model may involve the combination of a precise APV experiment along with PV electron scattering to constrain R_n.

2. – Results of PREX-I

The PREX-I experiment ran in the Spring of 2010 in Hall A at Jefferson Lab using the High Resolution Spectrometers (HRS) augmented by a new warm-temperature septum magnet to reach a scattering angle of 5°. The beam energy was 1.063 GeV and the beam current was 50–70 μA. The polarized electron beam was produced by photoemission from a GaAs source. The sign of the circular polarization of the laser used for photoemission determined the electron helicity, which was selected at 120 Hz. To avoid noise from the 60 Hz line power cycle, the asymmetry was measured in "quadruplets": 4 helicity states in the patterns RLLR or LRRL, with the polarity of each pattern determined pseudo-randomly. The integrated response of each detector PMT and beam monitor was digitized by a custom, low-noise 18-bit ADC and recorded for each helicity period. Periods of instability in the electron beam trajectory and intensity were removed during offline analysis. No helicity-dependent cuts were applied. The final data sample consisted of 1.94×10^7 quadruplets.

The measured asymmetry was corrected for a false asymmetry A_{beam} induced by helicity-correlated changes in the beam trajectory Δx_i and energy A_E, $A_{beam} = \Sigma_i c_i \Delta x_i$. The factors c_i were measured several times each hour from calibration data in which the beam was modulated by using steering coils and an accelerating cavity. The largest of the c_i was on the order of 50 ppb/nm. This correction removed noise in the measured asymmetry due to beam jitter at the 8.3 ms time scale of about 20 μm in position and 2 ppm in energy. The noise in the resulting $A_{corr} = A_{raw} - A_{beam}$ was about 200 (171) ppm per quadruplet, for running with a beam current of 50 (70) μA. The noise is dominated by counting statistics, corresponding to a rate of about 1 GHz at 70 μA, consistent with rate estimates from low current calibration runs.

A half-wave ($\lambda/2$) plate was periodically inserted into the laser optical path which passively reversed the sign of the electron beam polarization. Roughly equal statistics were thus accumulated with opposite signs for the measured asymmetry, which suppressed many systematic effects. An independent method of helicity reversal was provided by a pair of Wien spin-filters separated by a solenoid near the injector was installed. By reversing the direction of the field in the solenoid, the beam helicity could be reversed. However, the electron beam optics, which depends on the square of the magnetic field, was unchanged. This additional spin flip provides a powerful check for systematic errors. The ($\lambda/2$) reversal was done about every 12 hours and the solenoid reversal was performed every few days. Under the reversals, the absolute values of A_{corr} are consistent within statistical errors.

Averaged over all runs, the $A_{corr} = +593 \pm 51(\text{stat}) \pm 10(\text{syst})$ ppb. Since the differences in the position monitors and beam energy average the entire experiment were only 4 nm and 0.6 ppb, respectively, the average corrections due to systematic helicity-correlated differences in beam parameters were small.

The physics asymmetry A_{pv} is formed from A_{corr} by correcting for the beam polarization P_b, background fractions f_i with asymmetries A_i and finite kinematic acceptance K. The diamond cooling foil contributed $6.6 \pm 0.6\%$ of the measured signal, but because A_{pv} is similar for carbon and lead elastic scattering, the net correction was smaller, $1.6 \pm 0.5\%$. Contributions from inelastic states and re-scattered backgrounds were negligible. The acceptance correction K accounted for the non-linear dependence of the asymmetry with Q^2. A significant systematic error in $\langle Q^2 \rangle$ is in the determination of the absolute scale of the scattering angle θ_{lab}. A nuclear recoil technique with a dedicated calibration run using a water cell target was used to set a scale error on Q^2 of $< 0.2\%$. Nonlinearity in the PMT response was limited to 1% in bench-tests that mimicked running conditions.

Beam polarization was measured using an energy-weighted integrating measurement of the asymmetry in Compton backscattered photons, to be $P_b = 88.20 \pm 1.0\%$. The beam polarization was monitored continuously by the polarimeter over the run, and

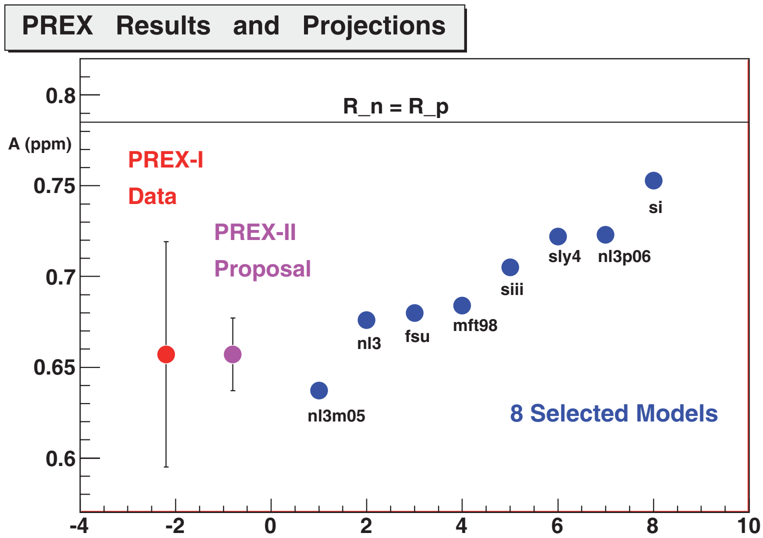

Fig. 1. – The PREX asymmetry for the PREX-I data, the PREX-II projections (new proposal), and 8 selected models. Also shown is the asymmetry for the hypothesis that the neutron radius is the same as the proton radius. References: nl3m05, nl3, and nl3p06 from [23], fsu from [24], mft98 from [25], siii from [26], sly4 from [27], si from [28].

was stable within systematic errors. The Møller polarimeter, which was upgraded to use a superconducting magnet to saturate the ferromagnetic target foil, measured $P_b = 90.32 \pm 1.1\%$ beam polarization. These measurements were averaged to $P_b = 89.2 \pm 1.0\%$, where the uncertainty was taken to be the smallest included in the average.

With all corrections, $A_{pv} = 657 \pm 60(\text{stat}) \pm 13(\text{syst})$ ppb at $Q^2 = 0.00906\,\text{GeV}/c$. The result is consistent with all of the models shown in fig. 1 (refs. [23-28]), but is strongly suggestive that $R_n > R_p$. A journal publication of these results is in preparation.

3. – Future Plans: PREX-II and ^{48}Ca

Clearly, a higher statistical accuracy will be needed to discriminate between the models and to pin down the symmetry energy to a level relevant for neutron stars and atomic parity violation. The summer 2011 PAC at JLab approved a proposal for a follow-up experiment (PREX-II) to reduce the error by a factor of 3. ^{208}Pb remains an attractive target because: 1) Lead is a very well-known nucleus and has a simple structure (doubly-magic). 2) It has the highest separation to the first excited state (2.6 MeV) of any heavy nucleus. Combined with the high momentum resolution of our spectrometers, this separation lends itself well to the flux integration detection technique. 3) ^{208}Pb is thought to have a relatively large value of R_n. 4) Since ^{208}Pb is a heavy nucleus, with a large number of extra neutrons, there should be a relatively clean interpretation of the skin thickness in terms of properties of bulk neutron matter.

There is also an interest in performing parity-violating measurements from other nuclei; the consensus on the candidates for a next series of runs are ^{48}Ca, ^{40}Ca, and isotopes of tin: ^{112}Sn, ^{120}Sn, and ^{124}Sn, see ref. [29]. Statistical errors better than 1% appear to be feasible with 30 day runs. The ^{48}Ca measurement is optimized at a beam energy of $\sim 2\,\text{GeV}$, making it an ideal 1-pass experiment for Hall A in the 12 GeV era.

4. – Conclusions

We have measured the elastic parity violating asymmetry in ^{208}Pb to an accuracy of 9% corresponding the an error in R_n of 3%. A follow-up experiment has been proposed and accepted which will reduce the error bar in R_n to 1%. Experiments with other nuclei are possible with this technique.

REFERENCES

[1] de Vries H., de Jager C. W. and de Vries C., *At. Nucl. Data Tables*, **36** (1987) 495.
[2] Frois B. *et al.*, *Phys. Rev. Lett.*, **38** (1977) 152.
[3] Garcia-Recio C., Nieves J. and Oset E., *Nucl. Phys. A*, **547** (1992) 473.
[4] Ray L., Coker W. R. and Hoffmann G. W., *Phys. Rev. C*, **18** (1978) 2641.
[5] Starodubsky V. E. and Hintz N. M., *Phys. Rev. C*, **49** (1994) 2118.
[6] Clark B. C., Kerr L. J. and Hama S., *Phys. Rev. C*, **67** (2003) 054605.
[7] Trzcinska A. *et al.*, *Phys. Rev. Lett.*, **87** (2001) 082501.
[8] Lenske H., *Hyperfine Interact.*, **194** (2009) 277.
[9] Donnelly T. W., Dubach J. and Sick Ingo, *Nucl. Phys. A*, **503** (1989) 589.
[10] Horowitz C. J., *Phys. Rev. C*, **57** (1998) 3430.
[11] Horowitz C. J., Pollock S. J., Souder P. A. and Michaels R., *Phys. Rev. C*, **63** (2001) 025501.
[12] Horowitz C. J. and Piekarewicz J., *Phys. Rev. C*, **64** (2001) 062802.
[13] Ozel Feryal, Baym Gordon and Guver Tolga, arXiv:1002.3153.
[14] Steiner Andrew, M. Lattimer James and F. Brown Edward, arXiv:1005.0811.
[15] Ozel Feryal, Baym Gordon and Guver Tolga, *Phys. Rev. D*, **82** (2010) 101301.
[16] Lynch W. G., Tsang M. B., Zhang Y., Danielewicz P., Famiano M., Li Z. and Steiner A. W., ArXiv:0901.0412.
[17] Tsang M. B., Zhang Yingxun, Danielewicz P., Famiano M., Li Zhuxia, Lynch W. G. and Steiner A. W., *Phys. Rev. Lett.*, **102** (2009) 122701.
[18] Horowitz C. J. and Piekarewicz J., *Phys. Rev. C*, **66** (2002) 055803.
[19] Horowitz C. J. and Piekarewicz J., *Phys. Rev. Lett.*, **86** (2001) 5647.
[20] Pollock S. J., Fortson E. N. and Wilets L., *Phys. Rev. C*, **46** (1992) 2587.
[21] Brown B. A., Derevianko A. and Flambaum V. V., *Phys. Rev. C*, **79** (2009) 035501.
[22] Tsigutkin K., Dounas-Frazer D., Family A., Stalnaker J. E., Yashchuk V. V. and Budker D., arXiv:1001.0587.
[23] Lalazissis G. A., Konig J. and Ring P., *Phys. Rev. C*, **55** (1997) 540.
[24] Todd-Rutel B. G. and Piekarewicz J., *Phys. Rev. Lett.*, **95** (2005) 122501.
[25] Horowitz C. J., private communication.
[26] Beiner M., Flocard H., Van Giai N. and Quentin P., *Nucl. Phys. A*, **238** (1975) 29.
[27] Chabanat E., Bonche P., Haensel P., Meyer J. and Schaeffer R., *Nucl. Phys. A*, **635** (1998) 231.
[28] Vautherin D. and Brink D. M., *Phys. Rev. C*, **5** (1972) 626.
[29] Ban Shufang, Horowitz C. J. and Michaels R., arXiv:1010.3246.