The Lead Radius Experiment PREX

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Abstract. The proposed PREX experiment at Jefferson Lab will measure the parity-violating electroweak asymmetry in the elastic scattering of polarized electrons at an energy of 850 MeV and a scattering angle of 6° . Since the Z_0 boson couples mainly to neutrons, this asymmetry provides a clean measurement of R_n with a projected experimental precision of $\pm 1\%$. In addition to being a fundamental test of nuclear theory, 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.

PACS. 20.10.Gv Mass and neutron distributions – 25.30.Bf Elastic electron scattering – 11.30.Er Parity Violation

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2 Introduction

In a heavy nucleus like ^{208}Pb the difference between the neutron radius R_n and the proton radius R_p is believed to be several percent. This neutron skin has not been well established experimentally in stable nuclei. We plan to measure the neutron charge radius R_n (i.e. the RMS radius of neutrons in a nucleus) in a clean and model independent way analogous to the classic measurements[1] of the proton radius R_p and with unprecedented accuracy as suggested originally by Donnelly, Dubach, and Sick[2].

The experiment measures the parity violating asymmetry in elastic scattering $A = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$. This asymmetry arises due to the interference of the Z^0 boson amplitude of the weak neutral interaction with the photon amplitude. The asymmetry is sensitive mainly to the neutron radius R_n because the weak charge of the neutron is much larger than that of the proton. In PWIA, the relationship between the asymmetry and the neutron form factor is given by equation (1)

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

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. Thus A_{LR} is approximately proportional to the ratio of neutron to proton form factors. In the above we used PWIA to illustrate. To achieve 1% accuracy requires corrections for Coulomb distortions, which have been calculated by Horowitz[4].

3 Physics Impact and Interpretation

It is remarkable that a single measurement of R_n with 1% accuracy can have such a broad impact on several areas of physics, including neutron star formation and structure[5], atomic parity violation[6,7], nuclear theory[3], and heavy ion collisions[8].

From a theoretical perspective, the difference between our proposed measurement of R_n and the well-measured proton radius R_p is determined by fundamental parameters of bulk nuclear matter called the symmetry energy S_ν and the density dependence of the symmetry energy S'_ν . These parameters are important for other phenomena involving nuclear matter, such as heavy ion collisions. Today, perhaps the most important application is the field of supernovae and the properties of neutron stars. The proposed measurement of R_n to 1% will provide the best determination of the S_ν and S'_ν at the density of ordinary nuclear matter. This will provide vital input to the dynamics of stellar explosions and thus have implications for our understanding of how the heavy elements in our world were produced.

The relevant part of the energy of nuclear matter of density n and ratio x of protons to neutrons may be writ-

ten

$$E(n, x) = E(n, x = 1/2) + S_\nu(n)(1 - 2x^2).$$

The connection between $S_\nu(n_0)$, where n_0 is the density of Pb, our measurement, and R_n is shown by Furnstahl[9] within the context of realistic nuclear calculations. The model dependence of the relations is small compared to our required sensitivity.

The importance of the symmetry energy S_ν for the formation and structure of neutron stars is given in several review articles[10,11]. A good introduction for the non-specialist by Lattimer and Prakash[12] appeared in Science. Neutron stars are giant nuclei ~ 13 km in diameter, fascinating objects for which astronomical data are rapidly improving. Data on neutron stars include radii, masses, luminosity, temperature, and cooling rates [13]. In addition to their intrinsic interest as newly explored natural phenomena, these stars provide “laboratories” to understand the nature of extremely dense matter. For example, do collapsed stars form “exotic” phases of matter, e.g. strange stars or quark stars ?

A precise measurement of R_n provides a calibration of the equation of state (pressure versus density) of neutron rich nuclear matter, which is an important input for calculating the structure of neutron stars[5]. To rule in or out possible exotic phases of dense matter one needs to combine the high density measurements of neutron stars with low density precision measurements of R_n in nuclei. R_n also has implications for the crust thickness because the transition density for the liquid-solid phase transition depends sensitively on the neutron skin of ^{208}Pb [5]. The proton fraction of neutron rich matter in beta equilibrium depends on the symmetry energy, which is calibrated by R_n . A large symmetry energy favors more protons, and if the proton fraction is high enough then the following “URCA” process can cool neutron stars $n \rightarrow p + e^- + \bar{\nu}_e$; $p + e^- \rightarrow n + \nu_e$ where the $\nu_e, \bar{\nu}_e$ carry off energy. URCA cooling might explain recent Chandra observations of the neutron star 3C58, a remnant of the supernova seen in the year 1186 that appears to be unexpectedly cold[13]. A neutron skin larger than about 0.2 fm may imply that URCA cooling is possible, while a smaller skin implies it is probably not possible[14].

Heavy ion reactions[15,16,8], including rare isotope beam experiments anticipated from RIA[17], can also pin down the density dependence of the symmetry energy by probing conditions at neutron densities up to 3 times normal nuclear matter density. A combination of our measurement at sub-nuclear densities and the RIA results will provide useful constraints on nuclear theory.

The impact of an accurate R_n measurement on atomic parity violation (APV) experiments has been analyzed by Pollock *et.al* [3],[7]. Knowledge of R_n at the 1% level is needed for interpreting atomic physics measurements of the Weinberg angle at the level of the Standard Model weak radiative corrections. The most accurate (1% in Q_{weak}) measurement of APV was carried out by Wieman and co-workers in atomic cesium ^{133}Cs [18]. Such low energy experiments provide powerful constraints on the standard

model [19]. More independent tests of APV are needed at the accuracy of the Cesium experiment. An alternative approach which largely cancels the uncertainties due to difficult atomic structure calculations is to measure ratios of APV amplitudes between isotopes [20]. This is being exploited for example in the Berkeley atomic Yb experiment [21]. However, Fortson *et.al.* [22] pointed out that this technique has an enhanced sensitivity to uncertainties in R_n . A recent analysis[6] has emphasized the importance of this experiment on the field.

There have been renewed attempts to obtain R_n from hadronic data. A major effort has been devoted to the analysis of proton scattering [23–26]. Clark and Kerr [25] arrive at the smallest claimed error on R_n , less than 1%. Piekarewicz[23] suggests that the error should be at least 3%. Karataglidis *et al.*[24] suggest that the proton and proposed data are complementary and that both are important. We note that recent data on pion photoproduction from lead and other nuclei [27] have yielded matter radii that are less than the charge radii, implying a *negative* neutron skin in ^{208}Pb .

The physics interpretation of the experiment can be summarized as follows. From the measured asymmetry one may deduce the weak form factor, which is the Fourier transform of the weak charge density at the momentum transfer of the experiment. One must correct for Coulomb distortions, which has been done accurately by Horowitz[4] and others[28]. The weak charge density can be compared directly to theoretical calculations and this will constrain the density dependence of the symmetry energy. The weak density can be directly applied to atomic parity violation because the observables have approximately the same dependence on nuclear shape. From the weak charge density one can also deduce a neutron density at one Q^2 by making small corrections for known nucleon form factors. The uncertainty in these corrections for a realistic experiment have been estimated and are small[3].

Finally from a low Q^2 measurement of the point neutron density one can deduce R_n . This requires knowledge of the surface thickness to about 25% to extract R_n to 1%. The spread in surface thickness among successful mean field models is much less than 25%, hence we can extract R_n with the desired accuracy as shown by Furnstahl[9]. In summary, the physics results of the experiment are the weak charge density, the point neutron density and R_n .

4 Experiment

4.1 Experimental Overview

The ^{208}Pb experiment was proposed for a beam energy of 850 MeV and a 6° scattering angle in Hall A at Jefferson Lab. The two Hall A 3.7 msr spectrometer systems supplemented by septum magnets focus elastically scattered electrons onto total-absorption detectors in their focal planes. A $50\mu\text{A}$, 80% polarized beam with a 30 Hz helicity reversal will scatter from a foil of lead which is sandwiched between sheets of diamond to improve the thermal characteristics. Ratios of detected flux to beam

Table 1. Rate and Asymmetry for ^{208}Pb

Measured Asymmetry (p_e A)	0.51 ppm
Beam Energy	850 MeV
Beam Current	$50\mu\text{A}$
Required Statistical Accuracy	3%
Energy Cut (due to detector)	4 MeV
Detected Rate (ea spectrometer)	860 MHz
Running Time	680 hours

current integrated in the helicity period are formed, and the parity-violating asymmetry in these ratios computed from the helicity-correlated difference divided by the sum: $A = (\sigma_R - \sigma_L) / (\sigma_R + \sigma_L)$, where $\sigma_{R(L)}$ is the ratio for right(*R*) an left(*L*) handed electrons. Separate studies at lower rates are required to measure backgrounds, acceptance, and Q^2 . Polarization is measured once a day by a Møller polarimeter, and monitored continuously with the Compton polarimeter.

Table 1 shows the rates, asymmetries, and running times for the ^{208}Pb parity experiment proposal, the results averaged over the acceptance.

4.2 Technical Issues

For the ^{208}Pb experiment the asymmetry of 0.5 ppm must be measured to 3% accuracy. Both the absolute error (15 ppb) and the relative accuracy (3%) are challenging to achieve. The main issues affecting the absolute error are the control of false asymmetries associated with helicity correlations in beam parameters such as intensity, energy, and position. The main issues affecting the relative error are the beam polarimetry and measurement of Q^2 . In addition, we need a lead target that can withstand a high beam current.

4.3 Helicity Correlated Systematics

To evaluate the systematic error we need to know the helicity correlated differences as well as our sensitivity to these which are measured online by modulation of the parameters. During the 2005 HAPPEX run we have made tremendous progress in controlling helicity correlated systematics, see fig 1 which shows 1-month averages of ~ 1 nanometer in helicity correlated position differences. This accomplishment is due to a long-term effort to improve the setup of the polarized source and accelerator. For the polarized source we have a well-developed model for controlling the laser systematics, which allows us to minimize helicity correlations in the laser beam used to produce polarized electrons. For the accelerator, progress in understanding the betatron matching has helped achieve maximum dampening of position differences, while improved understanding of beam tuning has provided both excellent signal-to-noise ratios in the Compton polarimeter and

good phase advances along our beamline that permit us to simultaneously have good measurements to the sensitivities of each of the independent beam parameters. For ^{208}Pb we will maintain position differences to less than 1 nm with an accuracy of 0.1 nm averaged over a 1 month run. The charge asymmetry will be maintained to less than 100 ppb with an accuracy of 10 ppb.

4.4 Lead Target Tests

We have built a high power lead target which will be stable at 40 Watt for a $50\mu\text{A}$ beam. Successful beam tests at $80\mu\text{A}$ show that we have a good target design. Recently we have performed low-intensity tests at 1.1 GeV, which is approximately the energy of this proposal. These tests checked the rates, backgrounds, resolution, sensitivity to beam parameters (slopes), and width of asymmetry.

4.5 Noise

The pulse-to-pulse noise in the lead experiment is 140 ppm. All other noises must be small compared to 140 ppm in order for counting statistics to dominate our errors and to keep the running time minimal. It will be important to avoid long cable runs for our detectors, and therefore we have installed a distributed DAQ system during HAPPEX-2, in which the DAQ crates are situated near the detectors. For understanding the noise, beam systematics, and possible target boiling effects, we have implemented a new luminosity monitor which was used during HAPPEX. New 18-bit ADCs are being fabricated at JLab for use in upcoming parity experiments which will improve our pedestal noise.

4.6 Precision Polarimetry

Improvements in polarimetry are of vital importance for the Jefferson Lab parity violation program. For this proposal, the polarization must be measured to 1% preferably, or at least 2%. With a polarization accuracy of 1% (2%) we can extract R_n to 1% (1.2%) respectively. Our plan is to use a combination of upgraded Compton polarimeter and upgraded Møller polarimeter.

The best accuracy obtained so far with the Compton polarimeter is 1.5% total relative error within 40 minutes for a beam energy of 4.5 GeV. We plan to implement a green laser to improve the figure of merit at 850 MeV. This brings the mean asymmetry to 0.65%. At the Compton edge the photon energy is 26 MeV and the associated scattered electron is 6 mm above the primary beam at the location of the electron detector. Assuming the same laser power of 1.5 kW at the Compton interaction point, a 1% statistical accuracy is achieved within 16 hours. The laser and much of the associated optics equipment has been obtained and is undergoing test. In addition to the laser, we plan on using a new crystal for the photon detector.

We will compare Møller to Compton at $5\mu\text{A}$ and 6 GeV to give a clear comparison at the 1% level.

Fig. 1. Helicity correlated beam monitor differences (μm) versus slug number (1 “slug” $\sim$ 1 day of running) for HAPPEX-2. The top four plots are X and Y monitors near the target, and the bottom plot is a monitor in the dispersive section of the magnet ARC leading into the hall, providing a relative energy monitor. The averages over a month of running are $\sim$ 1 nanometer.

5 Summary and Outlook

Measurement of R_n will have a fundamental impact on nuclear physics and its applications to neutron rich matter. The neutron skin is a qualitative feature of heavy nuclei which has never been cleanly observed. These experiments require state-of-the-art control of systematic errors. The technological developments will help drive other facets of the Jefferson Lab parity program, such as Q_{weak} which has similar demands.

The HAPPEX run in 2004 and 2005 have demonstrated excellent control of helicity correlated beam parameters. An upgrade of the Compton polarimeter, necessary to achieve 1% accuracy at 850 MeV, is underway.

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