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Electroweak probe of neutron skins of nuclei☆

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ABSTRACT

We describe a program of elastic electron scattering experiments aimed at direct measurements of the neutral weak form factor of nuclei from which the neutron rms radii of nuclei can be extracted with little theoretical ambiguity. The difference between the neutron and proton rms radii, the neutron skin, is intimately related to the density dependence of the symmetry energy in dense nuclear matter which in turn can be related to neutron star parameters such as mass, radius and mass quadrupole polarizability.

1. Introduction

1.1. Electron scattering and nuclear size

Starting in the late 1940s, the technique of fixed target electron scattering off nuclear targets has been used to probe the structure of subatomic constituents. Since the probe is structureless and the cross-sections are calculable to high accuracy using quantum electrodynamics, elastic electron scattering provides a clean way to measure the size and shapes of nuclei and nucleons. In particular, the differential cross-section for the scattering off electrons off a spin-0 nucleus, neglecting nuclear recoil and in the ultra-relativistic limit, can be written as:

$$\frac{d\sigma}{d\Omega} = \frac{4\pi\alpha^2 Z^2}{Q^4}|F_{ch}(Q)|^2$$

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where Q^2 is the square of the four-momentum transfer and $F_{ch}(Q)$ is the charge form factor, the Fourier transform of the electric charge distribution. A detailed mapping of the charge form factor as a function of Q^2 provides a clean method to extract the radial charge distribution of nuclei. Indeed, electron scattering data are largely responsible for our detailed knowledge of the sizes and shapes of nuclei across the periodic table of the elements.

1.2. Electroweak scattering

In the late 1950s, soon after the discovery of parity-violation and the V–A structure of the weak interaction, Zel'dovich [1] speculated that if there was a neutral analog of the charged weak current then there would be two amplitudes to consider in elastic electron scattering off nuclei that could interfere with each other. Indeed, if one were to measure a parity-violating asymmetry A_{PV} which is defined as the fractional difference in the probability for the elastic scattering with longitudinally polarized right- and left-handed electrons, the interference term would be the dominant term in the numerator whereas the denominator could be simply approximated by the much larger electromagnetic amplitude:

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

where F_W is the weak form factor, G_F is the Fermi constant, α is the fine structure constant and σ_R (σ_L) is the scattering cross-section for incident right-(left-)handed electrons. The first such measurement was carried out in the mid-70s using deep inelastic scattering [2], a critical component of the experimental evidence that validated the SU(2)×U(1) electroweak model of Glashow, Weinberg and Salam [3–5]. We now know that the weak neutral current is mediated by the Z^0 boson. In the case of electrons scattering elastically off a heavy nucleus at low Q^2 and forward angle, the A_{PV} measurement is dominantly sensitive to the weak charge distribution $\rho_W(r)$, the Fourier transform of $F_W(Q^2)$. In the Born approximation, one has

$$\rho_W(r) \simeq (1 - 4\sin^2\theta_W)\rho_p - \rho_n$$

where θ_W is the electroweak mixing angle. The above expression receives small corrections from radiative corrections and the strangeness distribution in the nucleon. Because $\sin^2\theta_W$ is numerically close to 0.25, the weak density's dominant contribution comes from the point neutron density. Thus, the measurement of A_{PV} allows a nearly model-independent extraction of the neutron RMS radius R_n.

1.3. The neutron skin of a heavy nucleus

The neutron skin thickness $\Delta R_{np} \equiv R_n - R_p$ has previously been measured using hadronic probes [6]. However, the extraction of ΔR_{np} from such experimental measurements involves non-perturbative strong interaction physics with large systematic uncertainties [6,7]. Neutron skin measurements across the periodic table are highly sought after because of the lack of experimental constraints on isovector quantities describing nuclei; these are required to comprehensively characterize the properties of nuclear matter. Further, the neutron skin has been shown to be sensitive to the density dependence of the symmetry energy, which is an important parameter to describe dense nuclear matter from neutron rich nuclei to neutron stars.

A model-independent measurement of the neutron rms radius R_n to a fractional accuracy of 1% has important implications in many subfields. A number of models based on relativistic mean field theory agree with the world data on nuclear charge distributions and other properties, but predict R_n values between 0.0 and 0.4 fm larger than R_p [8]. There is a strong correlation between R_n and the pressure of neutron matter at ∼2/3rd nuclear density, constraining the equation state EOS (pressure as a function of density) of neutron matter [9]. The correlation between R_n and the radius of a neutron star is also interesting [10]. The EOS of neutron matter is closely related to the symmetry energy S. There is a strong correlation between R_n and the density dependence of the symmetry energy $dS/d\rho$ (ρ is the baryon density) [11]. The symmetry energy S helps determine the composition of a neutron star; the transition density from solid crust to the liquid interior is strongly correlated to $R_n - R_p$ [12]. Very recently, the correlation between neutron skins and the mass quadrupole polarizability of neutron stars extracted from the LIGO neutron star merger has been investigated [13]. Finally, atomic parity violation (APV) measurements are sensitive to R_n [14,15]. A future low energy test of the standard model may involve the combination of a precise APV measurement along with PVES to constrain R_n. Alternatively, measuring APV over a range of isotopes can provide additional information on neutron densities [16].

1.4. The experimental program

The first step in devising the experimental measurement is to choose the appropriate nucleus. One needs sufficient target density to produce high luminosity in a particularly stable nucleus and one must be able to experimentally separate elastically scattered electrons from those that scattered inelastically. One needs to optimize the statistical sensitivity to the neutron skin, which requires choosing a value of Q^2 that is just below the first diffraction minimum, far enough away from the minimum so as to have a sufficiently sizable differential cross-section to make a precision measurement.

By the early 2000s, significant progress had been made with improvements in the technology of parity-violating electron scattering measurements that two measurements could be proposed, one each on ^{208}Pb and ^{48}Ca. An important theoretical ingredient for the optimization was the calculation of the differential cross-section for electron–nucleus scattering including the effects of charge screening manifested as so-called Coulomb distortions [17]. The measurement on ^{208}Pb was proposed in the mid-2000s. The PREX experiment was designed and the first measurement was made in 2010 and published in 2012 [18]. The measurement on ^{48}Ca was proposed and approved in 2013 and the CREX experiment has now been designed and is being constructed. In the following, we describe the experimental technique, report the first experimental result and the immediate plans for more precise measurements.

2. Overview of the experimental technique

The experiments were run at the Thomas Jefferson National Accelerator Facility (JLab) using the high-resolution spectrometers (HRS) [19]. The elastically-scattered electrons are focused onto thin fused silica quartz Cherenkov radiators in their focal planes. The "hardware momentum resolution" of the spectrometer system i.e. the width of the distribution for mono-energetic electrons with no event-by-event corrections, is better than 10^{-3}, so that the elastic electrons populate a region that is otherwise free from contamination from inelastic events.

The polarized electron beam scatters from a target foil, and ratios of detected flux to beam current integrated in the helicity period are formed (so-called "flux integration"), and the parity–violating asymmetry in these ratios computed from the helicity–correlated difference divided by the sum: $A_{PV} = \frac{(\sigma_R - \sigma_L)}{(\sigma_R + \sigma_L)}$, where $\sigma_{R(L)}$ is the ratio for right(R) and left(L) handed electrons. Separate studies at lower rates are required to measure backgrounds, acceptance, and Q^2. Polarization is measured several times a week by a Møller polarimeter, and monitored continuously with the Compton polarimeter.

The experimental techniques are driven by the size of the parity-violating asymmetries, of the order of parts per million (ppm) for the two nuclei under primary consideration namely, ^{208}Pb (PREX) and ^{48}Ca (CREX). To have significant impact on our knowledge of skin thicknesses, A_{PV} must be measured with a precision in the range of 3% or better i.e. statistical and systematic errors must be controlled to 10's of parts per billion (ppb). One thus requires high count rates and low noise to achieve statistical precision as well as a careful regard for potential systematic errors associated with helicity reversal, which must be maintained at the few ppb level.

One common feature of all measurements of parity-violation in electron scattering is a rapid flipping of the electron beam helicity, allowing a differential measurement between opposing polarization states on a short timescale. The enabling technology for these measurements lies in the semiconductor photo-emission polarized electron source, which allows rapid reversal of the electron polarization while providing high luminosity, high polarization, and a high degree of uniformity between the two beam helicity states. Developments with the polarized source at Jefferson Lab are critical to the success of this program [20].

In the design of a parity experiment, often a compromise must be chosen between maximizing the parity violating signal while having sufficiently high scattering rate and low background. The asymmetry generally increases with Q^2 while the cross section decreases, which leads to an optimum choice of kinematics. For parity-violating neutron density experiments, the optimum kinematics is the point which effectively minimizes the error in the neutron radius R_n. This is equivalent to maximizing the following product, which is the figure-of-merit (FOM) : $\text{FOM} = R \times A^2 \times \epsilon^2$, where R is the scattering rate, A is the asymmetry, $\epsilon = \frac{dA/A}{dR_n/R_n}$ is the sensitivity of the asymmetry for a small change in R_n, dR_n/R_n is a fractional change in R_n and dA/A is a fractional change in A.

Given practical constraints on the solid angle of the HRS, the optimization algorithm favors smaller scattering angles. Using septum magnets we reach $\sim 5^\circ$ scattering angle. Once the angle is fixed, the optimum energy for elastic scattering can be specified. Simulations that are performed to design the experiment include the Coulomb distortions, as well as radiative losses, multiple scattering, and ionization losses in materials, together with a model for the tracking of particle trajectories through the HRS and septum magnets.

The two nuclei of interest for 1%, or better, R_n measurements (^{48}Ca and ^{208}Pb) are equally accessible experimentally and have been very well studied [21–24]. These are doubly-magic and have a simple nuclear structure, making them good candidates for extracting the symmetry energy. Each nucleus has the advantage that it has a large splitting to the first excited state (2.6 MeV for ^{208}Pb and 3.8 MeV for ^{48}Ca), thus lending themselves well to the use of a flux integration technique.

3. PREX

3.1. PREX-I result

Many details of a practical PVES experiment to measure neutron densities were spelled out in [25], and formed the basis of the PREX experiment that took first data in Spring 2010. A 50 to 70 μA CW beam of longitudinally polarized 1 GeV electrons was incident on a 0.55 mm thick isotopically pure ^{208}Pb target. The optimum figure-of-merit requires that A_{PV} be measured with elastically scattered electrons in the range from 4 to 7 degrees, at a rate of more than 1 GHz, spatially separated from inelastic events from the first excited state at 2.6 MeV. The solution is to use a pair of septum magnets that bend the electrons into the acceptance of the high resolution spectrometers, whose minimum angle is 12.5° and whose hardware momentum resolution is 0.1%. The relative flux of the electrons over each 8.33 ms beam window of opposite longitudinal polarization was measured by intercepting the electron trajectories with quartz detectors and directing the resulting Cherenkov light onto photomultiplier tubes and integrating the output using precision 18-bit ADCs. The magnitude of A_{PV} at the requisite low Q^2 of 0.01 (GeV/c)^2 is $\sim$ 700 ppb and a 3% measurement is required in order to determine R_n to 1%.

The PREX design presented several technical challenges that needed to build on previous PVES experiments. The bulk of these issues were resolved during the run, and systematic control at the 10 ppb level and normalization control at the 1.5% level was demonstrated. The important technical achievements were the commissioning of a new room temperature septum magnet, the implementation of a new "double Wien filter" at the front-end of the machine, successful commissioning of a new high power Pb target, and the successful demonstration of the thin quartz integrating detector concept. After correcting the raw detector asymmetry for beam fluctuations, normalizing to the electron beam longitudinal polarization and subtracting background, the PREX-I grand result is [18] $A_{PV} = 657 \pm 60\ (\text{stat}) \pm 13\ (\text{syst})$ ppb. The measured result corresponds to a value for the neutron skin of $R_n - R_p = +0.34^{+0.15}_{-0.17}$ fm. The result demonstrates for the first time that the rms radius of neutrons is larger than that of protons at the 95% C.L.

3.2. PREX-II

While the PREX-I run was a technical success [18], only about 15% of the total statistics required for a 1% R_n determination was accumulated. A follow-up 25 PAC day run (PREX-II) was approved soon after and designated as one of the high impact measurements to be carried out in the early 12 GeV physics program. The run has been scheduled for summer 2019 with the aim of the achieving the projected uncertainties envisioned in the original PREX proposal namely a determination of R_n to ± 0.06 fm

4. CREX

The ^{48}Ca Radius Experiment CREX has been approved by the JLab Program Advisory Committee and scheduled to run in late Fall 2019. CREX aims to measure the neutron skin thickness of ^{48}Ca to an accuracy of 0.02 fm. A measurement this precise will have significant impact on nuclear theory, providing unique experimental input to help bridge ab-initio theoretical approaches based on nucleon–nucleon and three-nucleon forces, and nuclear density functional theory (DFT) based on energy density functionals (EDFs). Together with the PREX-II measurement, CREX will provide unique input in such diverse areas as neutron star structure, heavy ion collisions and atomic parity violation [26].

EDFs used in DFT calculations are assumed to have a convenient form in terms of local nucleonic densities and are optimized to reproduce many nuclear observables [27,28], but isovector field characteristics differ [29,30], resulting in significant variations in predictions for neutron skins. As our most precise information comes from electromagnetic probes, experimental information on neutron densities and other isovector properties has been lacking. ^{48}Ca provides an important bridge between light and heavy nuclei and will serve as an anchor point in extrapolating isovector nuclear characteristics across the periodic table. Remarkably, models are unable to agree on whether ^{48}Ca or ^{208}Pb has the larger neutron skin!

State-of-the-art coupled cluster calculations using chiral nucleon–nucleon interactions and augmented by three-nucleon forces are becoming available [31]. The neutron density and skin are very sensitive to three-nucleon forces, particularly the poorly constrained three-neutron force. With recent theoretical advances in microscopic many-body methods combined with ideas from effective field theory and renormalization group techniques, realistic ab-initio calculations for medium mass nuclei are becoming possible. Indeed, neutron and weak charge distributions of ^{48}Ca were calculated and predicts that the neutron skin of this nucleus is significantly smaller than previously thought [32]. In contrast, a very recent nonlocal dispersive-optical-model analysis of neutrons and protons in ^{48}Ca predicts a much more sizable neutron skin [33]. The projected uncertainty of CREX is small enough that it should settle the issue of which approach works better for a medium mass nucleus.

5. Current status and future plans

A unified team of dedicated PREX and CREX collaboration members are currently planning, designing and constructing the apparatus for the upcoming PREX and CREX runs. Installation is scheduled to begin in late March 2019. PREX commissioning will commence in mid-June 2019 and the run will last about two months. After a break, CREX is scheduled to begin data collection in mid-November and run until April 2020. It is anticipated that the analysis of the data will take approximately one year, so final results can be expected to be released in early 2021.

Looking beyond PREX-II and CREX, there are ideas to pursue an even more precise measurement of R_n in ^{208}Pb at the new Mainz MESA facility [34]. It might also be possible to make additional Q^2 measurements on ^{48}Ca using the same apparatus [35], providing insight into possible substructure in the neutron distribution in medium mass nuclei.

6. Conclusions

We have described an experimental program to provide theoretically clean and quantitatively precise new information on the neutron RMS radii of nuclei using the technique of parity-violating electron scattering. Apart from the fundamental nuclear physics motivation for such measurements to understand the isovector components of the nuclear ground state, they are particularly relevant in the exciting new era of gravitational wave detectors with its direct connections to mass quadrupole polarizability of neutron stars. Precise new measurements of the neutron RMS radii of ^{208}Pb and ^{48}Ca will be released by early 2021 and there are investigations for even more precise measurements in the future.

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