Parity Violating Measurements of Neutron Densities and Nuclear Structure

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Abstract. Parity violating electron nucleus scattering is a clean and powerful tool for measuring the spatial distributions of neutrons in nuclei with unprecedented accuracy. Parity violation arises from the interference of electromagnetic and weak neutral amplitudes, and the $Z^0$ of the Standard Model couples primarily to neutrons at low $Q^2$. Experiments are now feasible at existing facilities. We show that theoretical corrections are either small or well understood, which makes the interpretation clean. A neutron density measurement may have many implications for nuclear structure, atomic parity nonconservation experiments, and the structure of neutron stars.

INTRODUCTION

The size of a heavy nucleus is one of its most basic properties. However, because of a neutron skin of uncertain thickness, the size does not follow from measured charge radii and is relatively poorly known. For example, the root mean square neutron radius in $^{208}\text{Pb}$, $R_n$, is thought to be about 0.25 fm larger than the proton radius $R_p \approx 5.45$ fm. An accurate measurement of $R_n$ would provide the first clean observation of the neutron skin in a stable heavy nucleus. This is thought to be an important feature of all heavy nuclei.

Ground state charge densities have been determined from elastic electron scattering, see for example ref. [1]. Because the densities are both accurate and model independent they have had a great and lasting impact on nuclear physics. They are, quite literally, our modern picture of the nucleus.

In this paper we discuss future parity violating measurements of neutron densities. These purely electro-weak experiments follow in the same tradition and can be both accurate and model independent. Neutron density measurements have implications for nuclear structure, atomic parity nonconservation (PNC) experiments, isovector interactions, the structure of neutron rich radioactive beams, and neutron rich matter in astrophysics. It is remarkable that a single measurement has so many applications in atomic, nuclear and astrophysics.

Donnelly, Dubach and Sick [2] suggested that parity violating electron scattering...
can measure neutron densities. This is because the Z−boson couples primarily to the neutron at low $Q^2$. Therefore one can deduce the weak-charge density and the closely related neutron density from measurements of the parity-violating asymmetry in polarized elastic scattering.

Of course the parity violating asymmetry is very small, of order a part per million. Therefore measurements were very difficult. However, a great deal of experimental progress has been made since the Donnelly et. al. suggestion, and since the early SLAC experiment [3]. This includes the Bates $^{12}$C experiment [4], Mainz $^9$Be experiment [5], SAMPLE [6] and HAPPEX [7]. The relative speed of the HAPPEX result and the very good helicity correlated beam properties of CEBAF show that very accurate parity violation measurements are possible. Parity violation is now an established and powerful tool.

It is important to test the Standard Model at low energies with atomic parity nonconservation (PNC), see for example the Colorado measurement in Cs [8,9]. These experiments can be sensitive to new parity violating interactions such as additional heavy Z−bosons. Furthermore, by comparing atomic PNC to higher $Q^2$ measurements, for example at the Z pole, one can study the momentum dependence of Standard model radiative corrections. However, as the accuracy of atomic PNC experiments improves they will require increasingly precise information on neutron densities [10,11]. This is because the parity violating interaction is proportional to the overlap between electrons and neutrons. In the future the most precise low energy Standard Model test may involve the combination of an atomic PNC measurement and parity violating electron scattering to constrain the neutron density.

There have been many measurements of neutron densities with strongly interacting probes such as pion or proton elastic scattering, see for example ref. [12]. Unfortunately, all such measurements suffer from potentially serious theoretical systematic errors. As a result no hadronic measurement of neutron densities has been generally accepted by the field. Because of the uncertain systematic errors, modern mean field interactions are typically fit without using any neutron density information.

Finally, there is an important complementarity between neutron radius measurements in a finite nucleus and measurements of the neutron radius of a neutron star. Both provide information on the equation of state of dense matter. In a nucleus, $R_n$ is sensitive to the density dependence of the symmetry energy. Likewise the neutron star radius depends also on the density dependence of the symmetry energy at normal and somewhat higher densities. In the future, we expect a number of improving radius measurements for nearby isolated neutron stars such as Geminga [13] and RX J185635-3754 [14].

We now present general considerations for neutron density measurements, discusses possible theoretical corrections and then conclude.
GENERAL CONSIDERATIONS

In this section we illustrate how parity violating electron scattering measures the neutron density and discuss the effects of Coulomb distortions and other corrections. These corrections are either small or well known so the interpretation of a measurement is clean.

**Born Approximation Assymetry**

The effect of the parity-violating part of the weak interaction may be isolated by measuring the parity-violating asymmetry in the cross section for the scattering of left(right) handed electrons. In Born approximation the parity-violating asymmetry is,

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

with \( G_F \) the Fermi constant and \( \theta_W \) the weak mixing angle. The Fourier transform of the proton distribution is \( F_p(Q^2) \) while that of the neutron distribution is \( F_n(Q^2) \) and \( Q^2 \) is the momentum transfer squared. The asymmetry is proportional to \( G_F Q^2/\alpha \) which is just the ratio of \( Z^0 \) to photon propagators. Since \( 1-4\sin^2 \theta_W \) is small and \( F_p(Q^2) \) is known we see that \( A_{LR} \) directly measures \( F_n(Q^2) \). Therefore, \( A_{LR} \) provides a practical method to cleanly measure the neutron form factor and hence \( R_n \).

**Coulomb distortions**

By far the largest known correction to the asymmetry comes from coulomb distortions. By coulomb distortions we mean repeated electromagnetic interactions with the nucleus remaining in its ground state. All of the \( Z \) protons in a nucleus can contribute coherently so distortion corrections are expected to be of order \( Z\alpha/\pi \). This is 20% for \(^{208}\text{Pb}\).

Distortion corrections have been accurately calculated in ref. [16]. Here the Dirac equation was numerically solved for an electron moving in a coulomb and axial-vector weak potentials. From the phase shifts, all of the elastic scattering observables including the asymmetry can be calculated.

Other theoretical corrections from meson exchange currents, parity admixtures in the ground state, dispersion corrections, the neutron electric form factor, strange quarks, the dependence of the extracted radius on the surface shape, etc. are discussed in reference [15]. These are all small. Therefore the interpretation of a parity violating measurement is very clean.
CONCLUSION

With the advent of high quality electron beam facilities such as CEBAF, experiments for accurately measuring the weak density in nuclei through parity violating electron scattering (PVES) are feasible. The measurements are cleanly interpretable, analogous to electromagnetic scattering for measuring the charge distributions in elastic scattering. From parity violating asymmetry measurements in elastic scattering, one can extract the weak charge density in nuclei and from this the neutron density.

By a direct comparison to theory, these measurements test mean field theories and other models of the size and shape of nuclei. They therefore can have a fundamental and lasting impact on nuclear physics. Furthermore, PVES measurements have important implications for atomic parity nonconservation (PNC) experiments. In the future it may be possible to combine atomic PNC experiments and PVES to provide a precise test of the Standard Model at low energies.

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