Weak charge form factor and radius of $^{208}$Pb through parity violation in electron scattering

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We use distorted wave electron scattering calculations to extract the weak charge form factor $F_W(\bar{q})$, the weak charge radius $R_W$, and the point neutron radius $R_n$ of $^{208}$Pb from the Lead Radius Experiment (PREX) parity-violating asymmetry measurement. The form factor is the Fourier transform of the weak charge density at the average momentum transfer $\bar{q} = 0.475$ fm$^{-1}$. We find $F_W(\bar{q}) = 0.204 \pm 0.028$ (exp) $\pm 0.001$ (model). We use the Helm model to infer the weak radius from $F_W(\bar{q})$. We find $R_W = 5.826 \pm 0.181$ (exp) $\pm 0.027$ (model) fm. Here the experimental error includes PREX statistical and systematic errors, while the model error describes the uncertainty in $R_W$ from uncertainties in the surface thickness $\sigma$ of the weak charge density. The weak radius is larger than the charge radius, implying a “weak charge skin” where the surface region is relatively enriched in weak charges compared to (electromagnetic) charges. We extract the point neutron radius $R_n = 5.751 \pm 0.175$ (exp) $\pm 0.026$ (model) $\pm 0.005$ (strange) fm from $R_W$. Here there is only a very small error (strange) from possible strange quark contributions. We find $R_n$ to be slightly smaller than $R_W$ because of the nucleon’s size. Finally, we find a neutron skin thickness of $R_n - R_p = 0.302 \pm 0.175$ (exp) $\pm 0.026$ (model) $\pm 0.005$ (strange) fm, where $R_p$ is the point proton radius.

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Parity-violating elastic electron scattering provides a model-independent probe of neutron densities, because the weak charge of a neutron is much larger than the weak charge of a proton [1]. In the Born approximation, the parity-violating asymmetry $A_{pv}$, the fractional difference in cross sections for positive and negative helicity electrons, is proportional to the weak form factor $F_W$. This is very close to the Fourier transform of the neutron density. Therefore the neutron density can be extracted from an electroweak measurement [1]. However, one must include the effects of Coulomb distortions, which have been accurately calculated [2], if the charge density $\rho_{ch}$ [3] is well known. Many details of a practical parity-violating experiment to measure neutron densities, along with a number of theoretical corrections, were discussed in a long paper [4].

Recently, the Lead Radius Experiment (PREX) measured $A_{pv}$ for 1.06-GeV electrons, scattered by about 5 deg from $^{208}$Pb, and the neutron radius $R_n$ was extracted [5]. To do this, the experimental $A_{pv}$ was compared to a least squares fit of $R_n$ as a function of $A_{pv}$, predicted by seven mean-field models [6] (see also [7]). In the present paper, we provide a more detailed analysis of the measured $A_{pv}$. This analysis provides additional information, such as the weak form factor, and clarifies the (modest) model assumptions necessary to extract $R_n$.

We start with distorted wave calculations of $A_{pv}$ for an electron moving in Coulomb and weak potentials [2]. We use these to extract the weak form factor from the PREX measurement. In the Born approximation, one can determine the weak form factor directly from the measured $A_{pv}$. However,