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Parity violating electron scattering on ^{4}He

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Abstract. In order to isolate the contribution of the nucleon strange electric form factor to the parity-violating asymmetry measured in $^4\text{He}(\mathbf{e}, e')^4\text{He}$ experiments, it is crucial to have a reliable estimate of the magnitude of isospin-symmetry-breaking (ISB) corrections in both the nucleon and ^{4}He. Isospin admixtures in the nucleon are determined in chiral perturbation theory, while those in ^{4}He are derived from nuclear interactions, including explicit ISB terms. At the low momentum transfers of interest in recent measurements reported by the HAPPEX collaboration at Jefferson Lab, it results that both contributions are of comparable magnitude to those associated with strangeness components in the nucleon electric form factor.

One of the challenges of modern hadronic physics is to determine, at a quantitative level, the role that quark-antiquark pairs, and in particular $s\bar{s}$ pairs, play in the structure of the nucleon. Parity-violating (PV) electron scattering from nucleons and nuclei offers the opportunity to investigate this issue experimentally. The PV asymmetry (A_{PV}) arises from interference between the amplitudes due to exchange of photons and Z-bosons, which couple respectively to the electromagnetic (EM) and weak neutral (NC) currents. These currents involve different combinations of quark flavors, and therefore measurements of A_{PV}, in combination with electromagnetic form factor data for the nucleon, allow one to isolate, in principle, the electric and magnetic form factors G_E^s and G_M^s, associated with the strange-quark content of the nucleon.

Experimental determinations of these form factors have been reported recently by the Jefferson Lab HAPPEX [1] and G0 [2] Collaborations, Mainz A4 Collaboration [3], and MIT-Bates SAMPLE Collaboration [4]. These experiments have scattered polarized electrons from either unpolarized protons at forward angles [1–3] or unpolarized protons and deuterons at backward angles [4]. The resulting PV asymmetries are sensitive to different linear combinations of G_E^s and G_M^s as well as the nucleon axial-vector form factor G_A^Z. However, no robust evidence has emerged so far for the presence of strange-quark effects in the nucleon.

Last year, the HAPPEX Collaboration [5,6] at Jefferson Lab reported on measurements of the PV asymmetry in elastic electron scattering from ^{4}He at four-momentum transfers of 0.091 $(\text{GeV/c})^2$ and 0.077 $(\text{GeV/c})^2$. Because of the J^π=0^+ spin-parity assignments of this nucleus, transitions induced by magnetic and axial-vector currents are forbidden, and therefore these measurements can lead to a direct determination of the strangeness electric form factor G_E^s [7,8], provided that isospin symmetry breaking (ISB) effects in both the nucleon and ^{4}He, and relativistic and meson-exchange (collectively denoted with MEC) contributions to the nuclear EM and weak vector charge operators, are negligible. A realistic calculation of these latter contributions [8] found that they are in fact tiny at low momentum transfers.

Recently, we have completed the first realistic calculations of the ISB and here we will discuss their effect on the PV asymmetry (see Ref. [9] for details). The PV asymmetry measured in (e, e') elastic scattering from ^{4}He is given by

$$A_{PV} = \frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}} \left[4\sin^2\theta_W - 2\,\frac{F^{(1)}(q)}{F^{(0)}(q)} - \frac{2\,G_E^{\not{I}} - G_E^s}{(G_E^p + G_E^n)/2} \right] , \tag{1}$$

where G_μ is the Fermi constant as determined from muon decays, and θ_W is the Weinberg mixing angle. The term $G_E^s(Q^2)$ is the strange electric form factor of the nucleon, while the terms $G_E^{\not{I}}$ and $F^{(1)}(q)/F^{(0)}(q)$ are the contributions to A_{PV}, associated with the violation of isospin symmetry at the nucleon and nuclear level, respectively.

The most accurate measurement of A_{PV} has been recently reported at four-momentum transfer of Q^2=0.077 (GeV/c)^2 [6]:

$$A_{PV} = [+6.40 \pm 0.23\ \text{(stat)} \pm 0.12\ \text{(syst)}]\ \text{ppm} , \tag{2}$$

from which one obtains

$$\Gamma \equiv -2\frac{F^{(1)}(q)}{F^{(0)}(q)} - \frac{2\,G_E^{\not{I}} - G_E^s}{(G_E^p + G_E^n)/2} = 0.010 \pm 0.038 \tag{3}$$

at $Q^2 = 0.077\,(\text{GeV/c})^2$. This result is consistent with zero. In the following, we discuss the estimates for the ISB corrections first in the nucleon and then in ^{4}He, respectively $G_E^{\not{I}}(Q^2)$ and $F^{(1)}(q)$, at Q^2=0.077 (GeV/c)^2 (corresponding to q=1.4 fm^{-1}).

For $G_E^{\not{I}}(Q^2)$ we use the estimate obtained in Ref. [10], combining a leading-order calculation in chiral perturbation theory with estimates for low-energy constants using resonance saturation. At the specific kinematical point of interest $Q^2 = 0.077\,(\text{GeV/c})^2$, it results that $G_E^{\not{I}}(Q^2) = -0.0017 \pm 0.0006$, and with

$$G_E^p(Q^2) = 0.799 \text{ and } G_E^n(Q^2) = 0.027$$

[11], we obtain

$$-\frac{2\,G_E^{\not{I}}}{(G_E^p + G_E^n)/2} = 0.008 \pm 0.003 \tag{4}$$

at $Q^2 = 0.077$ (GeV/c)^2.

We now turn to $F^{(0)}(q)$ and $F^{(1)}(q)$, the isoscalar and isovector form factors of ^{4}He, respectively. The form factor $F^{(1)}(q)$ is very small because ^{4}He is predominantly an isospin $T = 0$ state, but it contains also tiny $T = 1$ and 2 components. We have computed such components using a variety of Hamiltonian models, in order to have an estimate of the model dependence. We have considered: i) the AV18 NN potential [12]; ii) the AV18 plus Urbana-IX 3N potential [13] (AV18/UIX); iii) the CD Bonn [14] NN plus Urbana-IXb 3N potentials (CDBonn/UIXb); and iv) the chiral N3LO [15] NN potential (N3LO). The Urbana UIXb 3N potential is a slightly modified version of the Urbana UIX (in the UIXb, the parameter U_0 of the central repulsive term has been reduced by the factor 0.812), designed to reproduce, when used in combination with the CD Bonn potential, the experimental binding energy of ^{3}H.

The form factors $F^{(0)}(q)$ and $F^{(1)}(q)$ calculated with the AV18/UIX Hamiltonian model, are displayed in Fig. 1, where the effect of inclusion of meson-exchange contributions (MEC) is also shown. The dashed curves are the calculations including only the one-body operators, while the solid curves have been obtained including the relativistic one-body and MEC [8] in the electromagnetic charge operators. The experimental data are from Refs. [16]. From the figure it is evident that for $q \leq 1.5$ fm^{-1}, the effect of MEC in both $F^{(0)}(q)$ and $F^{(1)}(q)$ is negligible.

In the inset of Fig. 1, we also show the the model dependence of the ratio $|F^{(1)}(q)/F^{(0)}(q)|$ (all calculations include MEC). The various Hamiltonian models give predictions quite close to each other; the remaining differences reflect the different percentages of the T=1 component in the ^{4}He wave function.

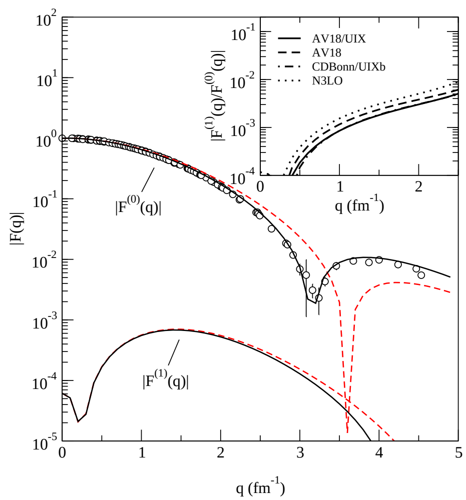

Fig. 1. The $F^{(0)}(q)$ and $F^{(1)}(q)$ form factors for the AV18/UIX Hamiltonian model. The $F^{(0)}(q)$ is compared with the experimental ^{4}He charge form factor [16]. The dashed curves are the calculations including only one-body operators. The solid curves include also MEC. The ratio $|F^{(1)}(q)/F^{(0)}(q)|$ (all calculations include MEC) is shown in the inset for the four Hamiltonian models considered in this paper.

The calculated ratios $F^{(1)}(q)/F^{(0)}(q)$ at Q^2=0.077 (GeV/c)^2 are of the order of -0.002. The value corresponding to the N3LO is somewhat larger than for the other models, as can be seen in Fig. 1, reflecting the larger percentage of T=1 admixtures predicted by the N3LO potential. The inclusion of 3N potentials tends to decrease the magnitude of $F^{(1)}/F^{(0)}$, and relativistic and MEC are, at this value of Q^2, negligible.

Therefore, at Q^2=0.077 (GeV/c)^2, both contributions $F^{(1)}/F^{(0)}$ and G_E^{γ} are found of the same order of magnitude as the central value of Γ in Eq. (3). Using in this equation the value $F^{(1)}/F^{(0)} \approx -0.00157$ obtained with the Hamiltonian models including 3N potentials, and the chiral result for $G_E^{\gamma} = -0.0017 \pm 0.0006$, one would obtain $G_E^s\left[Q^2 = 0.077\,(\mathrm{GeV/c})^2\right] = -0.001 \pm 0.016$ thus suggesting that the value of Γ is almost entirely due to isospin admixtures. Of course, the experimental error on Γ is still too large to allow us to draw a more definite conclusion. A recent estimate of G_E^s using lattice QCD input obtains [17] $G_E^s(0.1\ (\mathrm{GeV/c})^2) = +0.001 \pm 0.004 \pm 0.003$. An increase of the experimental accuracy of one order of magnitude would be necessary in order to be sensitive to G_E^s at low values of Q^2. Indeed, if the lattice QCD prediction above is confirmed, the present data would suggest that the leading correction to the PV asymmetry is from isospin admixtures in the nucleon and/or ^{4}He.

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