27
Parity violation

We are now in a position to understand the standard model foundation of the analysis carried out in chapter 16 of parity violation in the process $A(\vec{e}, e')$, where A includes the nucleon. The Feynman rules for the diagrams shown in Fig. 16.1 follow immediately from the lepton currents in Eqs. (26.39) and quark currents in Eqs. (26.54) and (26.55). The result is the S-matrix in Eq. (16.1). The analysis in chapter 16 then leads to the general expression for the parity-violating asymmetry given in Eq. (16.20), where the response functions are defined in terms of matrix elements of the current by Eqs. (16.21, 16.22). One application has already been presented in chapter 16. Here we briefly discuss two others.

The measurement of parity violation in the scattering of longitudinally polarized electrons in deep-inelastic electron scattering from deuterium at SLAC is a classic experiment which played a pivotal role in the establishment of the weak neutral current structure of the standard model [Pr78, Pr79].

The analysis of parity violation in inclusive DIS in the quark–parton model was given in the end of chapter 16. The response functions $W_{1,2}^{\text{int}}$ and W_8^{int} are given in terms of the quark charges and momentum distributions by Eqs. (16.35) and (16.37). The electromagnetic and weak neutral charges of the quarks follow from the discussion in chapter 26; they have already been presented in Table 16.1.

Here we carry out a very simplified calculation of $^2\text{H}(\vec{e}, e')$ in the deep inelastic region [Wa95]. Assume forward angles with $\theta_e \to 0$ as in the SLAC experiment. Assume also that $\sin^2\theta_W \approx 1/4$. It follows from Eqs. (16.2) and (16.20) that the asymmetry is then given by

$$\mathscr{A} = -\frac{Gq^2}{4\pi\alpha\sqrt{2}}\left[\frac{\nu W_2(\nu, q^2)^{\text{int}}}{\nu W_2(\nu, q^2)^{\gamma}}\right] \tag{27.1}$$

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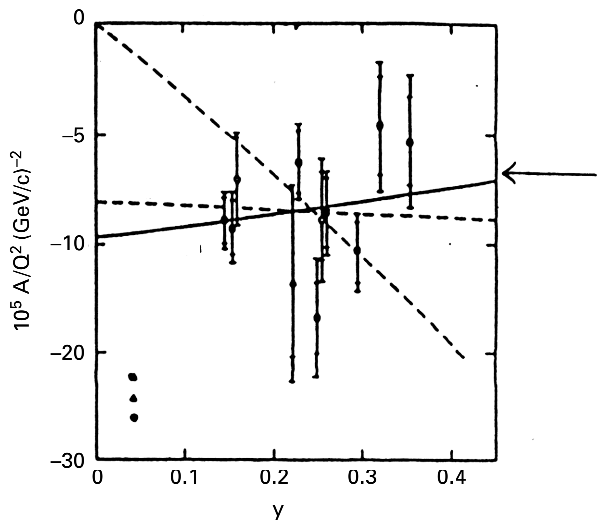

Fig. 27.1. SLAC results for parity-violating asymmetry for scattering of longitudinally polarized electrons from deuterium at forward angles in DIS region [Pr78, Pr79]. Here $y \equiv (E_0 - E')/E_0$. The result in Eq. (27.4) is also shown.

For a nucleon, assume the nuclear domain with just three valence quarks, and assume that the quark distribution functions $f_i(q^2)$ are, in fact, identical for these valence quarks. If this is the case, the required ratio of structure functions reduces simply to a ratio of charges

$$\frac{\nu W_2(\nu, q^2)^{\text{int}}}{\nu W_2(\nu, q^2)^{\gamma}} = \frac{\sum_i 2Q_i^{\gamma} Q_i^{(0)}}{\sum_i (Q_i^{\gamma})^2} \tag{27.2}$$

The target in the initial SLAC experiment was a deuteron, which consists of a very loosely bound neutron and proton. In this case, the cross sections are just an incoherent sum of the cross sections from the nucleon constituents. An incoherent sum of the corresponding structure functions yields

$$\mathscr{A}_{^2\text{H}} = -\frac{Gq^2}{4\pi\alpha\sqrt{2}}\, 2 \left\{ \frac{[\sum_i Q_i^{\gamma} Q_i^{(0)}]_p + [\sum_i Q_i^{\gamma} Q_i^{(0)}]_n}{[\sum_i (Q_i^{\gamma})^2]_p + [\sum_i (Q_i^{\gamma})^2]_n} \right\} \tag{27.3}$$

A proton consists of (uud) and a neutron of (udd) valence quarks. The required charges may now be read off directly from Table 16.1. The result is

$$\mathscr{A}_{^2\text{H}} = -\frac{Gq^2}{2\pi\alpha\sqrt{2}} \frac{2}{5} \tag{27.4}$$

The SLAC results are shown in Fig. 27.1. The simple result in Eq. (27.4) is also indicated. It gives a very nice first explanation of the data. A

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much more sophisticated analysis of the parity-violating DIS process is presented in [Ca78].

As a second example, consider parity violation in elastic scattering from the nucleon. The single-nucleon matrix element of the weak neutral current in the standard model must have the general form[1]

$$\langle p'|\mathscr{J}_\mu^{(0)}(0)|p\rangle = \frac{i}{\Omega}\bar{u}(p')[F_1^{(0)}\gamma_\mu + F_2^{(0)}\sigma_{\mu\nu}q_\nu + F_A^{(0)}\gamma_5\gamma_\mu - iF_P^{(0)}\gamma_5 q_\mu]u(p) \tag{27.5}$$

The matrix element of the electromagnetic current has the form given in Eqs. (19.6) and (19.7). It is then simply an exercise in Dirac algebra to show that for relativistic electrons the parity-violating asymmetry for $N(\vec{\mathrm{e}},\mathrm{e})N$ is given by [Po87]

$$\begin{aligned}
&\mathscr{A}\left\{[(F_1^\gamma)^2 + q^2(F_2^\gamma)^2]\cos^2\frac{\theta}{2} + \frac{q^2}{2m^2}(G_\mathrm{M}^\gamma)^2\sin^2\frac{\theta}{2}\right\} = \\
&\quad -\frac{Gq^2}{2\pi\alpha\sqrt{2}}\left\{[F_1^{(0)}F_1^\gamma + q^2F_2^{(0)}F_2^\gamma]\cos^2\frac{\theta}{2} + \frac{q^2}{2m^2}G_\mathrm{M}^{(0)}G_\mathrm{M}^\gamma\sin^2\frac{\theta}{2}\right. \\
&\quad \left. -\frac{\sin\theta/2}{m}\sqrt{q^2\cos^2\frac{\theta}{2} + \vec{q}^{\,2}\sin^2\frac{\theta}{2}}\; G_\mathrm{M}^\gamma(1-4\sin^2\theta_W)F_A^{(0)}\right\}
\end{aligned} \tag{27.6}$$

Here the Sachs form factors are defined by

$$\begin{aligned}
G_\mathrm{M} &= F_1 + 2mF_2 \\
G_\mathrm{E} &= F_1 - \frac{q^2}{2m}F_2
\end{aligned} \tag{27.7}$$

The discussion in chapter 26 implies that within the framework of QCD in the nuclear domain of equal mass (u,d) quarks (which implies strong isospin invariance), the form factors appearing in this expression must have the form

$$\begin{aligned}
F_{1,2}^{(0)} &= F_{1,2}^V - 2\sin^2\theta_W F_{1,2}^\gamma \\
F_A^{(0)} &= F_A^V
\end{aligned} \tag{27.8}$$

Here $F_{1,2}^{S,V}$ are obtained from electron scattering and F_A^V from charged current semi-leptonic weak interactions.

In the extended domain of (u,d,s,c) quarks and strong isospin invariance, Eq. (26.67) implies there is an additional isoscalar term in the

[1] Hermiticity of the current again implies that the form factors in this expression are real.

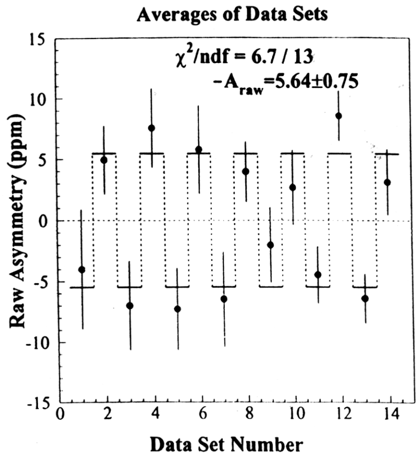

Fig. 27.2. Average value of raw asymmetry (difference/sum) observed with longitudinally polarized electron beam on a proton target for each data set. Odd data sets have the half-wave plate inserted in the laser beam (at the injector) and are expected to have the opposite asymmetry. Note the scale is *parts per million* (ppm). From the HAPPEX experiment at CEBAF [An99].

weak neutral current, so each of the form factors will have an additional isoscalar contribution

$$F_i^{(0)} \to F_i^{(0)} + \delta F_i^S \tag{27.9}$$

A parity-violation experiment to determine the distribution of weak neutral charge in the proton has been carried out at CEBAF. Figure 27.2 shows the measured asymmetry when nothing but the incident photon polarization is reversed at the injector on a macroscopic time scale using a half-wave plate. In the nuclear domain with only the light u and d quarks and their antiquarks, the weak neutral charge distribution should be identical to that of the electromagnetic charge. Any difference must arise from s (heavy) quarks. No difference is found, a result which has profound implications for our understanding of the structure of matter.

In more detail, a measurement of the parity-violating electroweak asymmetry in the elastic scattering of polarized electrons from the proton is presented in [An99]. The kinematic point $[\langle\theta_{\text{lab}}\rangle = 12.3^{\text{o}}$ and $\langle Q^2\rangle = 0.48\,\text{GeV}^2\text{c}^{-2}]$ is chosen to provide sensitivity, at a level that is of theoretical interest, to the strange electric form factor G_{E}^S. The result, $\mathscr{A} = -14.5 \pm 2.2\,\text{ppm}$, is consistent with the electroweak standard model and no additional contributions from the strange quarks. In particular, the measurement implies $G_{\text{E}}^S + 0.39 G_{\text{M}}^S = 0.023 \pm 0.034(\text{stat}) \pm 0.022\,(\text{syst}) \pm 0.026\,(\delta G_{\text{E}}^n)$, where the last uncertainty arises from the estimated uncertainty in the neutron electric form factor.

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