The possibility to determine the axial strange form factor of the nucleon from neutrino scattering experiments is studied. The existing experimental information is reviewed and several related observables which could be measured in the near future at new neutrino facilities are studied in detail. Elastic scattering from \( S = T = 0 \) nuclei is also briefly considered.

1. Introduction

The determination of the strange quark contribution to the nucleonic axial and vector weak currents has raised large and continuous interest in theoretical and experimental physics, especially after the measurements of the polarised structure function \( g_1^p \) of the proton, which indicated a non–zero contribution of the strange quark to the proton spin.

In recent years, intermediate energy physics has been mainly focused on parity violating electron scattering and on the strange vector current, while the strange contribution to the nucleon axial current has been widely investigated only at higher energies.

The measurement of the structure function \( g_1^p(x) \) in polarised deep inelastic scattering can be used to determine the one nucleon matrix elements of the axial quark current \(^1\)

\[
\langle p, s | \bar{q} \gamma^\alpha \gamma^5 q | p, s \rangle = 2M s^\alpha q^\alpha A.
\]  

This can be obtained by combining the QCD sum rule \( \Gamma_1^p = \int_0^1 dx g_1^p(x) \),
which in the naive quark parton model has the following flavour structure

$$\Gamma_1^p = \frac{1}{2} \left( \frac{4}{9} g_A^u + \frac{1}{9} g_A^d + \frac{1}{9} g_A^s \right),$$

with the relations

$$g_A = g_A^u - g_A^d,$$

based on the isotopic $SU(2)$ invariance of strong interactions, and

$$3F - D = g_A^u + g_A^d - 2g_A^s,$$

based on the $SU(3)_f$ symmetry. Here the axial constant $g_A = 1.2573 \pm 0.0028$ is obtained from neutron beta decay, while the constants $F$ and $D$ come from the measurements of semileptonic decays of hyperons.

Despite the continuous improvements in both experimental accuracy and theoretical calculations, the determination of the values of $g_A^u,d,s$ is still subject to several strong assumptions, such as the small $x$ extrapolation of $g_1^p(x)$, the QCD corrections used to relate its first moment $\Gamma_1^p$ to the constants $g_A^q$ and the $SU(3)_f$ invariance assumed in eq. (4).

It is therefore interesting to look for alternative methods for measuring $g_A^s$, which do not rely on these same assumptions.

It has long been recognised that neutrino scattering 2 can be a powerful tool for this investigation, but up to now the poor precision of the experimental data has not allowed the extraction, from them, of unambiguous results.

However, due to the large interest in neutrino physics raised by the recent results on neutrino oscillations, new neutrino facilities are being constructed, which could reach the required experimental accuracy for using neutrino scattering processes as a precise probe of $g_A^s$.

In this contribution, after presenting the relevant formalism for the description of neutrino scattering, we will review the existing information on the nucleon strange form factors obtained from these processes and we will explore the possibility to obtain new, definite measurements of $g_A^s$ in the near future. Since the main focus here is on the strangeness content of the nucleon, we will mostly consider scattering processes on free nucleons; a detailed analysis of nuclear structure effects can be found elsewhere 1.

A short discussion of elastic neutrino scattering on $S = T = 0$ nuclei will be also presented.

2. Formalism

Let us consider the neutral current (NC) processes

$$\nu_\mu (\overline{\nu}_\mu) + N \rightarrow \nu_\mu (\overline{\nu}_\mu) + N.$$
In the Standard Model and considering the contributions of $u$, $d$ and $s$ quarks only, the weak nuclear current involved in these processes can be written in the form:

$$J^\text{NC}_\alpha = V^\text{NC}_\alpha + A^\text{NC}_\alpha$$

$$= V^3_\alpha - 2\sin^2(\theta_W)J^{em}_\alpha - \frac{1}{2}V^s_\alpha + \frac{1}{2}A^s_\alpha,$$

where the isovector polar and axial vector currents are given by

$$V^3_\alpha = \frac{1}{2} \left\{ \overline{U}\gamma_\alpha U - \overline{D}\gamma_\alpha D \right\}$$

$$A^3_\alpha = \frac{1}{2} \left\{ \overline{U}\gamma_\alpha \gamma_5 U - \overline{D}\gamma_\alpha \gamma_5 D \right\}, \quad (7)$$

$J^{em}_\alpha$ is the electromagnetic current and the strange currents $V^s_\alpha$ and $A^s_\alpha$ are defined as

$$V^s_\alpha = \overline{s}\gamma_\alpha s$$

$$A^s_\alpha = \overline{s}\gamma_\alpha \gamma_5 s. \quad (8)$$

Complementary to the NC processes (5) are the Charged Current (CC) reactions

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\overline{\nu}_\mu + p \rightarrow \mu^+ + n, \quad (9)$$

with the corresponding currents $J^\text{CC}_\alpha = V_{ud}\overline{U}\gamma_\alpha (1 + \gamma_5)D$ and $(J^\text{CC}_\alpha)^\dagger$, $V_{ud}$ being the $ud$ Cabibbo–Kobayashi–Maskawa matrix element.

The cross sections for the processes (5) depend on the matrix elements of the weak neutral current (6), taken between one nucleon states of initial and final momentum $p$ and $p'$, respectively. Their nucleon structure content can be parameterised in terms of three NC form factors, according to

$$p(n)\langle p'|V^\text{NC}_\alpha|p(n)\rangle = \overline{u}(p') \left[ \gamma_\alpha F_1^{NC;p(n)}(Q^2) + \frac{i}{2M}\sigma_{\alpha\beta}q^\beta F_2^{NC;p(n)}(Q^2) \right] u(p)$$

$$p(n)\langle p'|A^\text{NC}_\alpha|p(n)\rangle = \overline{u}(p')\gamma_\alpha\gamma_5 G_A^{NC;p(n)}(Q^2) u(p), \quad (10)$$

where $q$ is the four-momentum transfer and $Q^2 = -q^2$.

Using eq. (6), the form factors $F_{1,2}^{NC;p(n)}$ can be written in the following form:

$$F_{1,2}^{NC;p(n)}(Q^2) = \pm \frac{1}{2} \left[ F_{1,2}^p(Q^2) - F_{1,2}^n(Q^2) \right] - 2\sin^2(\theta_W)F_{1,2}(Q^2) - \frac{1}{2}F_{1,2}^s(Q^2), \quad (11)$$
where $F^{p(n)}_{1,2}$ are the proton (neutron) Pauli and Dirac electromagnetic form factors and the plus and minus sign refer to the proton and neutron, respectively. Equivalently, NC Sachs form factors can be used, whose expressions are, correspondingly:

$$G^{NC:p(n)}_{E,M}(Q^2) = \pm \frac{1}{2} \left[ G^p_{E,M}(Q^2) - G^n_{E,M}(Q^2) \right] - 2 \sin^2(\theta_W) G^{p(n)}_{E,M}(Q^2) - \frac{1}{2} G^{s}_{E,M}(Q^2).$$  \(12\)

Moreover, using the isotopic invariance of strong interactions, the one nucleon NC axial matrix elements can be written as

$$G^{NC:p(n)}_{A}(Q^2) = \pm \frac{1}{2} G_{A}(Q^2) - \frac{1}{2} G^{s}_{A}(Q^2),$$  \(13\)

where, again, the plus (minus) sign refers to the proton (neutron), and $G_{A}(Q^2)$ is the usual CC axial form factor, measured in the processes (9).

From eqs. (11)–(13) we can see that the NC nucleon current can be expressed in terms of known (electromagnetic and CC) form factors, plus unknown contributions coming from strange quarks. In particular the neutrino–nucleon cross sections turn out to be very sensitive to the NC axial form factor and thus, in combination with the measurement of the strange vector form factors $F^{s}_{1,2}$ (or $G^{s}_{E,M}$) from parity violating electron scattering, their measurement can be used to extract $G^{s}_{A}$.

We remark that, for the same reason, an accurate knowledge of the CC axial form factor and of its $Q^2$ dependence is essential to be able to separate $G^{s}_{A}$. Thus, when planning future neutrino experiments it would be important to consider the possibility of performing high precision measurements of CC cross sections as well as NC ones.

Since very little is known about the $Q^2$ dependence of the strange form factors, some assumptions must be done when studying their effects in the cross sections. In the following we will assume, as it is generally done, that the strange form factors have the same $Q^2$ behaviour of the corresponding non–strange ones. In particular a dipole form will be assumed for $G^{s}_{M}$, with cutoff mass $M_{V} = 0.84$ GeV and $G^{s}_{M}(0) = \mu_{s}$, while for $G^{s}_{A}$ the same cutoff mass as for the CC axial form factor $G_{A}$ is used, with $G^{s}_{A}(0) = g_{A}^{s}$.

In terms of NC form factors, the differential cross section for the processes (5) has the following explicit form:

$$\left( \frac{d\sigma}{dQ^2} \right)^{NC}_{\nu(p)} =$$
\[ R_{NC/CC}(Q^2) = \frac{\left( \frac{d\sigma}{dQ^2} \right)_{\nu(\overline{\nu})}^{NC}}{\left( \frac{d\sigma}{dQ^2} \right)_{\nu(\overline{\nu})}^{CC}} \] (15)

and the so-called NC proton over neutron ratio

\[ R_{p/n}^\nu(Q^2) = \frac{\left( \frac{d\sigma}{dQ^2} \right)_{\nu}^{NC}}{\left( \frac{d\sigma}{dQ^2} \right)_{\nu}^{ne}} \]. (16)

The former has been measured (for total cross sections) in the BNL–734 experiment at Brookhaven and is currently being considered for possible future measurements with the NuMi beam at Fermilab; for the latter, a proposal exists for an experiment to be done at Los Alamos, by measuring the ratio of proton and neutron yields for neutrino quasi-elastic scattering on carbon; however some preliminary results seem to indicate that the error bars are too large to provide a precise measurement of \( G_A^\nu \).

Another very interesting quantity is the NC/CC neutrino–antineutrino asymmetry \(^\text{1,7,8}\):

\[ A(Q^2) = \frac{\left( \frac{d\sigma}{dQ^2} \right)_{\nu}^{NC} - \left( \frac{d\sigma}{dQ^2} \right)_{\overline{\nu}}^{NC}}{\left( \frac{d\sigma}{dQ^2} \right)_{\nu}^{CC} - \left( \frac{d\sigma}{dQ^2} \right)_{\overline{\nu}}^{CC}} \] (17)
which, in terms of the single nucleon form factors, reads:

\[ \mathcal{A}_{p(n)} = \frac{1}{4|V_{ud}|^2} \left( \pm 1 - \frac{G_s}{G_A} \right) \left( \pm 1 - 2\sin^2 \theta_W \frac{G_M(p(n))}{G_M^2} - \frac{1}{2} \frac{G_s}{G_M} \right) \]

\[ = \mathcal{A}_{p(n)}^0 \mp \frac{1}{8|V_{ud}|^2} G_M^2 A_{p(n)}^0 \]  

\[ = \mathcal{A}_{p(n)}^0 \mp \frac{1}{8|V_{ud}|^2} G_s \frac{G_A^2}{G_M} \mathcal{A}_{p(n)}^0 \]  

(18)

In the last expression only the linear terms in the strange form factors have been taken into account and

\[ \mathcal{A}_{p(n)}^0 = \frac{1}{4|V_{ud}|^2} \left( 1 \mp 2\sin^2 \theta_W \frac{G_M(p(n))}{G_M^2} \right) \]  

(19)

is the expected asymmetry when all the strange form factors are equal to zero.

An example of the dependence and sensitivity of the asymmetry (17) on the different strange form factors is shown in fig. 1, where the uncertainty due to electromagnetic form factors has been illustrated by considering two possible parameterisations, labelled here as “our fit” 7 and WT2 9. Although it is not extremely sensitive to the value of \( g_A^s \), the interest of this quantity stems from the fact that, as shown in eq. (18), any deviation from the known reference value \( \mathcal{A}_{p(n)}^0 \) would be a proof of a non-negligible contribution of the strange form factors, independently on the assumptions made for their \( Q^2 \) dependence. In particular, if \( G_s^A \) is known with sufficient accuracy from P–odd electron scattering, it would be possible to extract \( G_s^A \) in a model independent way.

3. The BNL–734 experiment

Up to now the most detailed study of strangeness effects in neutrino–nucleon scattering has been done in the Brookhaven E–734 experiment in 1987 3, using a wide band neutrino beam, with average energies 1.3 and 1.2 GeV for neutrinos and antineutrinos, respectively, and a 170 ton high resolution liquid scintillator target–detector. About 79% of the target protons were bound in carbon and aluminum nuclei and 21% were free protons; Fermi motion and other nuclear effects were taken into account in the analysis of the data, in order to provide “equivalent free” scattering data. From an analysis of the measured, flux averaged, \( \nu p \) and \( \bar{\nu} p \) differential cross sections

\[ \frac{d\sigma}{dQ^2} \|_{\nu(\bar{\nu})} = \frac{\int dE_{\nu(\bar{\nu})} \left( \frac{d\sigma}{dQ^2} \right)^{NC}_{\nu(\bar{\nu})} \Phi_{\nu(\bar{\nu})} \left( E_{\nu(\bar{\nu})} \right)}{\int dE_{\nu(\bar{\nu})} \Phi_{\nu(\bar{\nu})} \left( E_{\nu(\bar{\nu})} \right)} \]  

(20)
an indication for a non zero isoscalar contribution to the axial form factor was found, with $-0.25 \leq G_A^s(0) \leq 0$ at 90\% CL. However, as confirmed by a subsequent and more precise re-analysis, a strong correlation between $G_A^s(0)$ and the dipole cutoff mass $M_A$, employed to describe the $Q^2$-dependence of both $G_A$ and $G_A^s$, was observed, which prevents an unambiguous extraction the axial strange form factor form the BNL data.

The BNL-734 experiment also measured the following ratios of $Q^2$-integrated cross sections:

\[
R_\nu = \frac{\langle \sigma(\nu\mu p \rightarrow \nu\mu p) \rangle}{\langle \sigma(\nu\mu n \rightarrow \mu^- p) \rangle} = 0.153 \pm 0.007 \text{ (stat)} \pm 0.017 \text{ (syst)} \quad (21)
\]

\[
R_\tau = \frac{\langle \sigma(\tau\mu p \rightarrow \tau\mu p) \rangle}{\langle \sigma(\tau\mu n \rightarrow \mu^+ n) \rangle} = 0.218 \pm 0.012 \text{ (stat)} \pm 0.023 \text{ (syst)} \quad (22)
\]
Figure 2. The ratios (21), (22), (23) and the folded asymmetry (24) as functions of \( G_s^A (0) \), for different values of \( G_s^A (0) \), as indicated. The set of curves shown for each of these values correspond to different choices of the strange electric form factor \( G_s^E \).

\[
R = \frac{\langle \sigma (\bar{\nu}_\mu p \to \bar{\nu}_\mu p) \rangle}{\langle \sigma (\nu_\mu p \to \nu_\mu p) \rangle} = 0.302 \pm 0.019 \text{ (stat)} \pm 0.037 \text{ (syst)}. \quad (23)
\]

which were later re-analysed in detail \(^{11}\), in connection with the flux averaged “integrated” neutrino–antineutrino asymmetry derived from the above ratios through the relation

\[
\langle A^I \rangle = \frac{(\sigma)_E^{NC} - (\sigma)_E^{CC}}{(\sigma)_E^{NC} - (\sigma)_E^{CC}} \bigg| \frac{R_{\nu} (1 - R)}{1 - RR_{\nu}/R_{\bar{\nu}}} = 0.136 \pm 0.008 \text{ (stat)} \pm 0.019 \text{ (syst)}. \quad (24)
\]

As illustrated in fig. 2, the combined analysis of the above four quantities seems to exclude large negative values of \( G_s^A \) and to favour a negative value
of $G_M^s$, but, in agreement with the previous findings \cite{10}, the error bars were found to be too large to allow any definite conclusion. The sensitivity of these observables to several other effects was also studied: while nuclear structure effects and uncertainties in the neutrino flux were found to be largely reduced in all of them, the sensitivity of the ratios (21)–(23) to the axial cutoff mass was shown to be still rather relevant. On the contrary, the asymmetry (24) is practically independent of $M_A$.

4. Future perspectives at Fermilab

The recent experimental results on neutrino oscillations have motivated the realization of new high intensity neutrino beams \cite{12}, whose energy spectra should be known with accuracies of a few percent. Besides their primary goal to study neutrino physics, these future experiments could be used to obtain new and much more accurate measurements of neutrino cross sections. In particular the NuMi facility is currently under construction at Fermilab \cite{13}. A high intensity, neutrino beam will be available in the next few years, in three possible configurations: a low-energy beam, peaked at 3 GeV and with average energy of about 6 GeV, a medium energy beam with peak and average energies of about 6 and 7 GeV, respectively, and a high energy beam with peak and average energies of about 7 and 11 GeV \cite{14}. The low energy configuration, in particular, looks very promising for accurate studies of neutrino scattering processes. We have explored this possibility by using the expected flux to calculate the ratios (15) and (16) of flux–averaged neutrino cross sections, studying their sensitivity to strange form factors, as well as the effects of other possible theoretical and experimental uncertainties.

The NC/CC ratio for neutrino processes is shown in fig. 3, for different choices of the axial cutoff mass $M_A$ and of the strange axial constant $g_A^s$, as indicated. We have assumed that this ratio could be measured with a 5% accuracy, represented by the small “error band” plotted for each calculated point. We can see that, for the moderate $Q^2$ values represented here, the sensitivity of this ratio to $G_A^s$ is large enough to allow a precise determination of it.

Even if the effects of the strange vector currents in neutrino scattering are usually smaller those of $G_M^s$, they can anyway interfere with the extraction of the latter from the data. We have thus studied the effects of the magnetic form factor $G_M^s$ on the NC/CC ratio, letting $G_M^s(0) = \mu_s$ vary in the rather large range, corresponding to the error bar in the measurement of the SAMPLE collaboration \cite{15}. From the results shown in fig. 4 it is
seen that a large positive value of $G_M^s$ would indeed almost compensate the effects of axial strangeness. This indicates that more precise information on the strange magnetic form factor is needed as an input, in order to study $G_A^s$ with neutrino probes. The effects on the ratio $R_{NC/CC}(Q^2)$ of the electric strange form factor $G_E^s$ and those of the electromagnetic form factors have been found to be very small and are not shown here. Other possible sources of uncertainty in the extraction of $G_A^s$ have been also investigated: nuclear effects were studied, by calculating the same type of ratio for quasi-elastic scattering on carbon nuclei, described within the relativistic Fermi gas, while the sensitivity to the flux-averaging procedure was tested, by comparing the ratio of “folded” cross sections with the same ratio at fixed $E_\nu$, for a few choices of energy values. In both cases no significant effects were found.

Even if antineutrinos will not be immediately available in the low energy NuMi beam, it is interesting to consider the sensitivity to strangeness of
Figure 4. Sensitivity of the neutrino ratio $R_{NC/CC}(Q^2)$ to the strange magnetic form factor.

the corresponding NC/CC ratio, which we have calculated by assuming a $\nu$ beam corresponding to 1% of the NuMi neutrino spectrum. The results of this calculation are shown in fig. 5, where the effects of $g_A^s$ appear to be similar to those for the neutrino case, with a slightly larger sensitivity to $M_A$. Results similar to the case of neutrinos are also obtained for the sensitivity to the vector strange form factors, although in the case of $\nu$ larger effects of the $G_E^s$ are observed, stressing again the importance of obtaining precise complementary results from electron scattering.

Finally, we have considered the proton over neutron ratio (16) of flux averaged neutrino cross sections, in the case of quasi–elastic scattering on $^{12}C$, described within the Fermi gas model (again, no difference is obtained with respect to the corresponding ratio of free nucleon cross sections)\(^a\). The sensitivity of this ratio to $G_A^s$ and $M_A$ as well as to $G_M^s$ is shown in figs. 6

\(^a\)In this case $Q^2$ is to be interpreted as an “equivalent free momentum transfer”, $Q^2 \equiv 2MT_N$, $T_N$ being the outgoing nucleon kinetic energy.
Figure 5. Plot of the ratio $R_{NC/CC}(Q^2)$ antineutrino–proton.

and 7, respectively. We can see that the effects of the axial strange form factor are very large and are not significantly masked by the uncertainty on $M_A$, while, again, the present large error band on $G_s$ would not allow a precise determination of $G_A^s$ from this measurement.

Similar conclusions for all the above considered observables can be drawn when considering the corresponding ratios of $Q^2$-integrated cross sections.

5. Elastic Scattering on $S = T = 0$ nuclei

Before concluding we want to briefly discuss the possibility of using neutrino scattering to study nuclear strange form factors, by measuring the cross sections for the elastic scattering of (anti)neutrinos on $S = T = 0$ nuclei,

$$\nu (\overline{\nu}) + A \rightarrow \nu (\overline{\nu}) + A.$$  (25)
In this case, both the axial current $A_\alpha$ and the isovector part of the polar vector weak neutral current, $V_3\beta(1 - 2\sin^2(\theta_W))$, do not contribute to the cross sections, whose expressions are given by:

$$\frac{d\sigma_\nu}{dQ^2} = \frac{d\sigma_{\nu\nu}}{dQ^2} = \frac{G_F^2}{2\pi} \left( 1 - \frac{p \cdot q}{M_A E} - \frac{Q^2}{4E^2} \right) [F^{NC}(Q^2)]^2.$$  \hspace{1cm} (26)

Here $E$ is the neutrino energy in the laboratory system and $F^{NC}(Q^2)$ is the NC nuclear elastic form factor, which can be expressed in terms of the isoscalar nuclear electromagnetic form factor $F(Q^2)$ and of an unknown strange contribution $F^s(Q^2)$, in the following form:

$$F^{NC}(Q^2) = -2\sin^2 \theta_W F(Q^2) - \frac{1}{2} F^s(Q^2).$$  \hspace{1cm} (27)

The measurement of the elastic cross section (26) requires the detection of the small recoil energy of the final nucleus, and it is thus a very challenging experimental task. However it could provide very important
information on the nuclear strange form factor. In fact, if the electromagnetic form factor $F(Q^2)$ is obtained from a measurement of the cross section for the elastic scattering of unpolarised electrons,

$$\frac{d\sigma_e}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} \left( 1 - \frac{p \cdot q}{M_A E} - \frac{Q^2}{4E^2} \right) \left[ F(Q^2) \right]^2,$$

then $F_s(Q^2)$ could be obtained directly from measured cross sections:

$$F_s(Q^2) = \pm 2F(Q^2) \left\{ \left( \frac{2\sqrt{2\pi\alpha}}{G_F Q^2} \right) \sqrt{\frac{(d\sigma_\nu/dQ^2)}{(d\sigma_e/dQ^2)}} \mp 2\sin^2 \theta_W \right\},$$

and thus in a completely model independent way.

6. Conclusions

In conclusion we believe that neutrino scattering is a very important tool to study strangeness contributions to the structure of the nucleon. New high intensity neutrino beams, available in the near future, and improvements
in the precision of the measurements of the vector strange form factors in polarised electron scattering, could allow a definite determination of the axial strange form factor $G_s^A$. We would like to stress, that, although seldom available, antineutrino beams, would offer the possibility of accessing additional complementary information on the nucleon axial strangeness; in particular the measurement of the NC/CC neutrino–antineutrino asymmetry would provide a model independent method to determine $G_s^A$.

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