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IN SEARCH OF STRANGENESS BY SCATTERING NEUTRINOS OFF NUCLEI*

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Abstract

Understanding the role of strange quarks in the nucleon is a long standing issue in hadron physics. Several approaches to study strangeness have been proposed. Here, we investigate the potential of quasi-elastic neutrino-nucleus scattering at intermediate energies to extract information about the strangeness parameters. To this end, we present a formalism to compute cross sections, describing the target in terms of a relativistic mean-field approach. Final-state interactions are taken into account using a relativistic multiple-scattering Glauber approximation. In order to reduce the troublesome nuclear effects, we introduce cross section ratios. We evaluate the Q^2 dependence of these ratios and study their sensitivity to strangeness.

1 What's strange about the proton?

Over the past century, particle physics has been probing matter at higher and higher energies, enabling us to investigate ever smaller length scales. This has led us to the standard model of particle physics, which describes matter in terms of a limited number of elementary particles and four fundamental forces. Identifying the building blocks of the universe has been a tremendous effort, but is in no way an end-point, for it is equally interesting to understand how these constituents give rise to the well-known properties of everyday matter.

The internal structure of the nucleon poses problems that physicists have been struggling with for several decades. It has been established that quarks and gluons make up the nucleon. Measuring and predicting the contribution of each of these components to the nucleon's properties (mass, charge, spin, etc.), however, has proven to be quite a challenge. The great difficulty to provide a satisfactory description of the nucleon's structure stems from the very nature of the strong interaction that holds the nucleon together. Colored particles interact more strongly when they are further apart. This counter-intuitive feature gives rise to the property of confinement. On the other hand one can consider strongly interacting particles as free at asymptotically high energies. Owing to this asymptotic freedom the field equations of the strong force, coined quantum chromodynamics (QCD), are soluble through the use of perturbation theory at sufficiently high energies. It is beyond doubt that QCD provides the correct framework to understand the nucleon in terms of its fundamental constituents. Unfortunately the QCD coupling constant is larger than unity at the energy scale at which quarks are bound inside hadrons, rendering perturbative solutions unworkable. By considering the QCD field equations on a discrete space-time lattice, solutions in the non-perturbative regime can be obtained. This, however, comes at a huge computational cost. Furthermore, it remains to be seen if lattice QCD results can provide us with true insight in the nucleon's inner workings. Therefore, we appeal to phenomenological models that consider the nucleon as a composite of three effective constituent quarks, each comprising a valence quark surrounded by a cloud of sea quarks and gluons. There exist a large number of such constituent quark models, with a varying number of assumptions and simplifications, whose predictions need to be compared to experimental data.

Model	Reference	g_A^s
Lattice QCD	PRL,75:2092	-0.105
	PRL,75:2096	-0.121
Skyrme	PLB,206:309	-0.180

Table 1: An inexhaustive list of model predictions of the axial strangeness parameter g_A^s.

The role of sea quarks in the nucleon is one of the more challenging aspects to grasp for any quark model. Consequently, pinning down the contribution of strange quarks, being the lightest non-valence quarks, to the nucleon's properties serves as a good testing ground for nucleon structure models. The significance of strangeness in the nucleon can be effectively expressed by means of parameters. The axial strangeness parameter g_A^s (or Δs) accounts for the amount of the nucleon's spin that is carried by the strange quarks. As can be seen in Table 1, model predictions have not converged yet, although all presented models seem to point at a negative value for g_A^s. The vector strangeness parameters r_s^2 and μ_s are a measure for the contribution of strangeness to the mean quadratic charge radius and the magnetic moment of the nucleon, respectively. As shown in Table 2, hadron models make widely different predictions for r_s^2 and μ_s. In what follows, we will turn our attention to possible ways of measuring these strangeness parameters.

Model	Reference	$\mu_s(\mu_N)$	$r_s^2(\text{fm}^2)$
VMD	PLB,229:275	-0.310	0.160
KΛ	Z.Phys.C,61:433	-0.350	-0.007
NJL	hep-ph/9506344	-0.450	-0.170
CQS (K)	PRD,65:014016	0.115	-0.095

Table 2: An inexhaustive list of model predictions of the vector strangeness parameters μ_s and r_s^2.

The contents of the proton was originally revealed in high-energy experiments through unpolarized deep-inelastic lepton scattering off nucleons. When polarizing both beam and target, additional information about the spin contribution of the different quark flavors becomes available. The HERMES collaboration has recently published their latest estimate for the axial strangeness parameter $\Delta s = -0.085 \pm 0.018$ [1]. This result was obtained assuming $SU(3)$ flavor symmetry in hyperon β-decays. Further uncertainties arise from the extrapolation of the measured spin structure function towards vanishing Bjorken x. By conducting experiments at more moderate energies, one wishes to determine the strangeness parameters in a model-independent fashion. Parity-violating electron scattering (PVES) exploits the subtle interference between the electromagnetic and weak interactions in elastic electron-nucleon scattering. PVES is mostly sensitive to the vector strangeness parameters r_s^2 and μ_s. A new analysis of all recent experimental data points to a mildly positive value for μ_s and r_s^2-values consistent with zero [2]. In PVES the axial strangeness parameter g_A^s is accessible as well, although it is kinematically suppressed and veiled by radiative corrections. Neutrino scattering experiments are performed in the same energy regime as PVES and depend on all three strangeness parameters. As neutrinos only interact through the weak force, radiative corrections are not present and thus r_s^s, μ_s and g_A^s can be extracted in a more unambiguous way. The small neutrino-nucleon cross sections, however, necessitates the use of nuclear targets, thereby, inevitably introducing undesired effects by the nuclear medium. By considering ratios of cross sections one hopes to enhance the sensitivity to strangeness and, most of all, reduce the uncertainties related to systematic and nuclear effects. In the eighties, a first attempt to exploit neutrino cross section ratios as a tool to pin down g_A^s was carried out at the Brookhaven National Laboratory [3]. The large systematic error bars on these data prevent one to draw solid conclusions. The proposed FINeSSE experiment plans to improve on this result using a dedicated detector and a high-quality neutrino beam [4]. Other current and planned neutrino experiments, such as Minerνa and BooNE, do not state the study of strangeness as their primary objective, but are well-suited to make a valuable contribution. For an efficient use of neutrino-scattering data in nucleon structure studies, a detailed theoretical study of neutrino-nucleus interactions is mandatory.

2 Describing neutrino-nucleus interactions

In view of current and future neutrino scattering experiments, we wish to describe neutrino-nucleus cross sections in the medium-energy regime. For incoming neutrino energies ranging from 100 MeV up to 1 GeV, quasi-elastic (QE) scattering with one-nucleon knockout is considered to dominate the total cross-section strength. Here, we will only highlight the essential features of the formalism we employed to calculate QE cross sections. A full derivation can be found in [5] and [6]. Neutrino scattering processes are either neutral-current (NC)

$$\begin{aligned} \nu + A &\longrightarrow \nu + (A-1) + N\,, \\ \overline{\nu} + A &\longrightarrow \overline{\nu} + (A-1) + N\,, \end{aligned}$$

or charged-current (CC) reactions

$$\begin{aligned} \nu + A &\longrightarrow l^- + (A-1) + p\,, \\ \overline{\nu} + A &\longrightarrow l^+ + (A-1) + n\,, \end{aligned}$$

mediated by a Z- or a $W^{\pm}$-boson respectively. The target nucleus is denoted as A and the recoiling nucleus by $(A-1)$. The outgoing charged lepton is represented as $l^{\pm}$ and N stands for the ejected nucleon (proton p or neutron n). The one-fold differential cross section as a function of the transferred four-momentum Q^2 is proportional to

$$\frac{d\sigma}{dQ^2} \propto \int d\Omega_l \int d\Omega_N \left(v_L R_L + v_T R_T + h v_{T'} R_{T'} \right). \tag{1}$$

For clarity, we have omitted a number of kinematic prefactors. In the above expression, the integral over the solid angle of the outgoing lepton $\Omega_l(\theta_l, \phi_l)$ and nucleon $\Omega_N(\theta_N, \phi_N)$ needs to be evaluated numerically. In Eq. 1, h denotes the helicity of the incoming neutrino, while v_L, v_T and $v_{T'}$ are the longitudinal, transverse and interference kinematic prefactors and R_L, R_T and $R_{T'}$ the corresponding structure functions. The latter hold all information about the hadronic vertex and are constructed from the nuclear current matrix elements $\langle \mathcal{J}^\mu \rangle$. Assuming that the incoming neutrino interacts with a single nucleon (impulse approximation), the nuclear many-body current operator can be replaced by a sum of one-body current operators

$$\hat{\mathcal{J}}^\mu = \sum_{k=1}^{A} \hat{J}^\mu(\vec{r}_k), \tag{2}$$

with the sum running over all nucleons in the target nucleus. The one-body current operator describes the coupling of the $Z/W^{\pm}$-boson with the nucleon. Relying on general symmetry principles, Lorentz-covariance and the conserved vector-current (CVC) hypothesis, one can write it in the following general form:

$$\hat{J}^\mu = F_1(Q^2)\gamma^\mu + i\frac{\kappa}{2M_N} F_2(Q^2)\sigma^{\mu\xi} q_\xi + G_A(Q^2)\gamma^\mu\gamma_5 + \frac{1}{2M_N} G_P(Q^2) q^\mu \gamma_5 \,. \tag{3}$$

The vector part comprises the Dirac (F_1) and Pauli (F_2) form factors. The axial part is described by the axial and pseudoscalar form factors G_A and G_P. All information about the structure of the nucleon is absorbed in the weak form factors, which depend solely on the four-momentum transfer Q^2. Within the context of quark models, the various form factors can be linked with nucleon structure parameters such as r_s^2, μ_s and g_A^s. Assuming a dipole shape, we can parametrize the form factors for weak neutral-current processes. The axial form factor becomes

$$G_A^{NC}(Q^2) = \frac{1}{2} \frac{-g_A \tau_3 + g_A^s}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}, \tag{4}$$

with $g_A = 1.262$ and $M_A = 1.032\,\text{GeV}$. The isospin operator τ_3 equals $+1$ for protons and -1 for neutrons. The contribution of the pseudoscalar form factor to neutrino cross sections is proportional to the mass of the scattered lepton and consequently vanishes for NC scattering. Using the CVC hypothesis, one can relate the weak vector form factors with the electromagnetic ones:

$$F_i^{NC}(Q^2) = \left(\frac{1}{2} - \sin^2\theta_W\right)\left(F_{i,p}^{EM} - F_{i,n}^{EM}\right)\tau_3 - \sin^2\theta_W \left(F_{i,p}^{EM} + F_{i,n}^{EM}\right) - \frac{1}{2} F_i^s \ (i = 1, 2)\,, \tag{5}$$

with $\sin^2\theta_W = 0.2224$, the weak mixing angle. In the previous expression, F_i^s represents the strangeness contribution to the vector form factors. We adopt the parametrization based on the three-pole ansatz of Forkel et al. [7]:

$$F_1^s(Q^2) = \frac{1}{6}\frac{-r_s^2 Q^2}{\left(1+\frac{Q^2}{M_1^2}\right)^2}, \quad (6)$$

$$F_2^s(Q^2) = \frac{\mu_s}{\left(1+\frac{Q^2}{M_2^2}\right)^2}, \quad (7)$$

with cut-off parameters $M_1 = 1.30\,\mathrm{GeV}$ and $M_2 = 1.26\,\mathrm{GeV}$. Because of the isovector nature of charged-current reactions, weak CC form factors do not contain a contribution from strange quarks. Their parametrization can be found in [6].

A crucial aspect of our description of QE neutrino-nucleus scattering is the inclusion of nuclear effects. This is achieved by evaluating the appropriate matrix element of the weak current operator. Employing an independent-nucleon model we can write the current matrix elements as

$$\langle J^\mu \rangle = \int d\vec{r}\, \overline{\phi}_F(\vec{r})\, \hat{J}^\mu(\vec{r})\, e^{i\vec{q}\cdot\vec{r}} \phi_B(\vec{r}), \quad (8)$$

with $\hat{J}^\mu$ the weak one-body current operator of Eq. 3. Further, ϕ_B is the mean-field single-particle wave function of the struck nucleon, thus introducing binding effects. The impulse approximation implies that the neutrino scatters off a single nucleon, leaving all other nucleons unaffected. In the relativistic plane-wave impulse approximation (RPWIA) one adopts a relativistic plane-wave for the scattering wave function ϕ_F. It is very likely, however, that the ejected nucleon rescatters off the *spectator* nucleons in the residual nucleus. These final-state interactions (FSI) can be introduced in the formalism by adapting ϕ_F. The calculation of such a scattering wave function is a long-standing issue in nuclear physics. To compute this modified ϕ_F, we adopt a relativistic multiple-scattering Glauber approximation (RMSGA) [8]. Thereby the ejectile is considered as a fast-moving nucleon, scattering elastically off the, temporarily *frozen*, nucleons in the residual nucleus. The successive nucleon-nucleon interactions are described within the eikonal approximation and take experimental nucleon-nucleon scattering data as input. The overall effect of FSI is summarized in a complex phase-factor, which operates on the original relativistic plane-wave. It is obvious that, by setting the Glauber phase equal to one, the RPWIA wave function is retrieved.

3 Strange effects in neutrino scattering

We wish to examine the influence of strangeness on QE neutrino-nucleus scattering cross sections. As a first step, we investigate the role of the different form factors that have been introduced in the weak current of Eq. 3. In Figure 1, we show the NC proton-knockout cross section off ^{12}C for an incoming neutrino energy of $\epsilon = 1\,\mathrm{GeV}$ as a function of the kinetic energy T_p of the outgoing proton. One immediately notices the overall smallness of the cross section, several orders of magnitude inferior to electron-induced nucleon-knockout cross sections. The dominant role of the axial term is manifest. The Dirac form factor's contribution turns out to be minimal, whereas the terms arising from the Pauli form factor appears to have some, albeit limited, strength. Summing the form-factor contributions in Figure 1 does not reproduce the full cross section, implying a non-negligible impact of the interference terms. Therefore, we expect neutrino-nucleus cross sections to

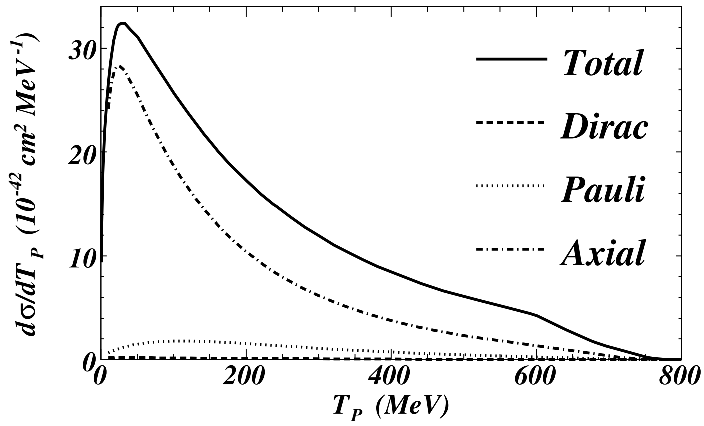

Figure 1: Contribution of weak form factors to the NC proton-knockout cross section for ^{12}C as a function of the outgoing proton's kinetic energy T_p at an incoming energy of $\epsilon = 1\,\text{GeV}$.

be sensitive to the axial strangeness parameter g_A^s, and, to a lesser extent, to the vector strangeness parameters. Figure 2 confirms this. Comparing the RPWIA result without strangeness to the situation with $g_A^s = -0.20$, one notices an enhancement of the NC proton-knockout reaction of about 30%. Non-vanishing vector strangeness parameters, $\mu_s = 0.20$ or $r_s^2 = -0.10$, produce a far less outspoken effect on the cross section. Strange sea quarks appear to have an opposite effect on the neutron-knockout reaction, thereby canceling the overall strangeness impact on the total one-nucleon knockout cross section. Hence, it is essential for neutrino experiments aiming at strangeness, to differentiate between protons and neutrons. Figure 2 proves that strangeness has a sizeable effect on QE neutrino-nucleus scattering, proving it to be a valuable alternative to other experimental methods. Furthermore, it is mostly sensitive to the axial strangeness parameter, making it complementary to PVES. Unfortunately, using nuclei as targets, comes at a cost. The dashed curve in Figure 2 shows the cross section including FSI within the RMSGA. The result is drawn down to proton kinetic energies of 150 MeV, because the Glauber approximation is not valid at low ejectile energies. The lower bound was established by comparing RMSGA calculations with another approximation, valid at lower energies [6]. The influence of final-state interactions is larger than the effect of strangeness, and thus introduces a new source of uncertainties when trying to obtain the strangeness parameters. In the next paragraph, it will be outlined how final-state interactions can be minimized.

4 Divide and conquer

In the study of electroweak interactions with nuclei, it is common practice to consider ratios of cross sections. From an experimental point of view, this is advantageous since systematic errors tend to drop out. In the following, we will show that dividing neutrino cross sections reduces nuclear effects to a large extent and enhances the sensitivity to strangeness.

The counteracting influence of strangeness on proton and neutron knockout cross sections can be exploited when selecting ratios that are most suitable for the extraction

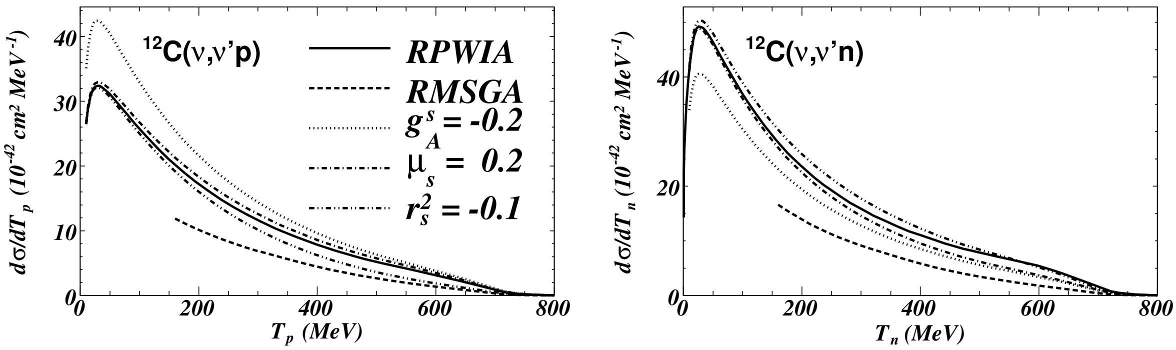

Figure 2: The $^{12}\mathrm{C}(\nu,\nu'p)$ (left) and $^{12}\mathrm{C}(\nu,\nu'n)$ (right) cross section as a function of the outgoing nucleon's kinetic energy T_N at an incoming energy of $\epsilon = 1\,\mathrm{GeV}$. The full line is our RPWIA result. The effect of FSI is illustrated using the RMSGA (dashed). The other curves adopt non-vanishing strangeness parameters: $g_A^s = -0.20$ (dotted), $\mu_s = 0.20$ (dot-dashed) and $r_s^2 = -0.10$ (double dot-dashed).

of information about the role of strange quarks in the nucleon. The ratios

$$R^{\nu}_{p/n}(Q^2) = \frac{\left(\frac{d\sigma}{dQ^2}\right)_{(\nu,\nu'p)}}{\left(\frac{d\sigma}{dQ^2}\right)_{(\nu,\nu'n)}} \quad \text{and} \quad R^{\overline{\nu}}_{p/n}(Q^2) = \frac{\left(\frac{d\sigma}{dQ^2}\right)_{(\overline{\nu},\overline{\nu}'p)}}{\left(\frac{d\sigma}{dQ^2}\right)_{(\overline{\nu},\overline{\nu}'n)}} \,, \tag{9}$$

use the differences in proton and neutron strangeness form factors to maximize the strangeness asymmetry. In Figure 3, both ratios are shown with a number of choices for strangeness parameters. We notice that a non-vanishing axial strangeness parameter induces a quasi-constant enhancement of both ratios. The influence of the vector strangeness parameters is examined by evaluating the proton-to-neutron ratios with the model predictions listed in Table 2, while g_A^s is kept constant at -0.19. The strange vector form factors do not contribute to the ratios at $Q^2 = 0$, yet become increasingly important as the four-momentum transfer rises. The VMD parameters, being the only model to predict a positive value for r_s^2, have the largest impact on the proton-to-neutron ratio.

In neutral-current reactions, the scattered neutrino is not detected, implying that these events need to be tagged by observing the outgoing nucleon. Neutron detection, however, is highly non-trivial, rendering $(\nu,\nu'n)$ events hard to study experimentally. Therefore we replaced the denominator of the proton-to-neutron ratio by a charged-current cross section, yielding

$$R^{\nu}_{NC/CC}(Q^2) = \frac{\left(\frac{d\sigma}{dQ^2}\right)_{(\nu,\nu'p)}}{\left(\frac{d\sigma}{dQ^2}\right)_{(\nu,l^-p)}} \quad \text{and} \quad R^{\overline{\nu}}_{NC/CC}(Q^2) = \frac{\left(\frac{d\sigma}{dQ^2}\right)_{(\overline{\nu},\overline{\nu}'p)}}{\left(\frac{d\sigma}{dQ^2}\right)_{(\overline{\nu},l^+n)}} \,. \tag{10}$$

Because of the isovector nature of charged-current reactions, the denominator is blind to the strangeness content of the nucleon. This obviously reduces the ratio's sensitivity, as can be appreciated in Figure 3. We notice that the NC-to-CC ratio exhibits the same qualitative behavior as the proton-to-neutron ratio, except for the high-Q^2 region, where NC-to-CC ratios seem to diverge. This is caused by the faster fall-off of CC cross sections, because of the reduced phase space brought about by the massive charged lepton in the final state.

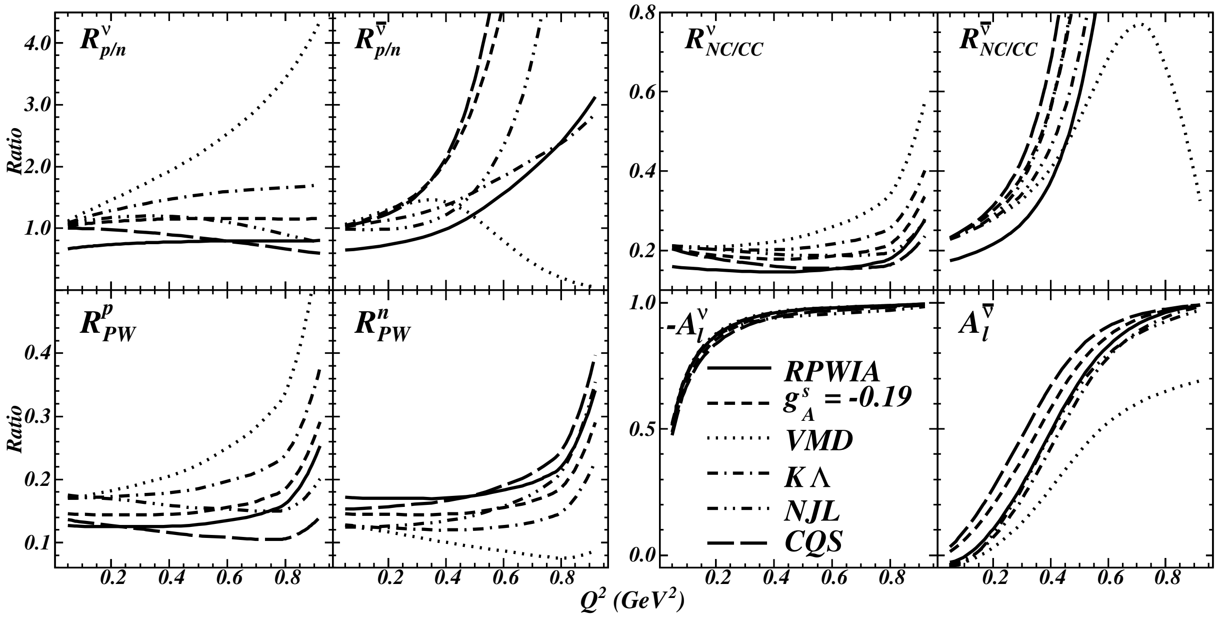

Figure 3: Q^2 dependence of several ratios of (anti)neutrino-induced nucleon-knockout cross sections off ^{12}C at an incoming neutrino energy of 650 MeV. The full line represents the RPWIA result without strangeness. All other curves have $g_A^s = -0.19$. The role of vector strangeness is evaluated using parameters from different hadron models (VMD, KΛ, NJL, CQS), except for the dashed curve which has $r_s^2 = \mu_s = 0$.

Combining neutrino- and antineutrino-induced cross sections, one can define the Paschos-Wolfenstein (PW) relation

$$R^N_{PW}(Q^2) = \frac{\left(\frac{d\sigma}{dQ^2}\right)_{(\nu,\nu' N)} - \left(\frac{d\sigma}{dQ^2}\right)_{(\overline{\nu},\overline{\nu}' N)}}{\left(\frac{d\sigma}{dQ^2}\right)_{(\nu,l^- p)} - \left(\frac{d\sigma}{dQ^2}\right)_{(\overline{\nu},l^+ n)}}, \tag{11}$$

with N being either a proton p or a neutron n. This ratio is used in deep-inelastic scattering to determine the weak mixing angle θ_W and has recently been studied at more moderate energies [9]. In Figure 3, we immediately notice the opposite influence of strangeness on the PW relation for protons and neutrons. The effect of axial strangeness on R^N_{PW} is very much Q^2 independent. Considering the result for the $K\Lambda$ parametrization, which predicts $r_s^2 \approx 0$, we observe that a non-zero value for μ_s also induces a constant offset. The Paschos-Wolfenstein relation is mildly influenced by g_A^s and even more so by vector strangeness. Unfortunately the Paschos-Wolfenstein relation depends heavily on the precise value of $\sin^2\theta_W$ [9], which impairs an accurate measurement of strangeness parameters.

Neutrinos are polarized by nature. This feature can be exploited by looking at polarization transfer. Jachowicz *et al.* proposed to consider the longitudinal polarization asymmetries (h_p is the helicity of the ejectile)

$$A_l^{\nu}(Q^2) = \frac{\left(\frac{d\sigma}{dQ^2}\right)^{h_p=+1}_{(\nu,\nu' p)} - \left(\frac{d\sigma}{dQ^2}\right)^{h_p=-1}_{(\nu,\nu' p)}}{\left(\frac{d\sigma}{dQ^2}\right)^{h_p=+1}_{(\nu,\nu' p)} + \left(\frac{d\sigma}{dQ^2}\right)^{h_p=-1}_{(\nu,\nu' p)}} \text{ and } A_l^{\overline{\nu}}(Q^2) = \frac{\left(\frac{d\sigma}{dQ^2}\right)^{h_p=+1}_{(\overline{\nu},\overline{\nu}' p)} - \left(\frac{d\sigma}{dQ^2}\right)^{h_p=-1}_{(\overline{\nu},\overline{\nu}' p)}}{\left(\frac{d\sigma}{dQ^2}\right)^{h_p=+1}_{(\overline{\nu},\overline{\nu}' p)} + \left(\frac{d\sigma}{dQ^2}\right)^{h_p=-1}_{(\overline{\nu},\overline{\nu}' p)}}, \tag{12}$$

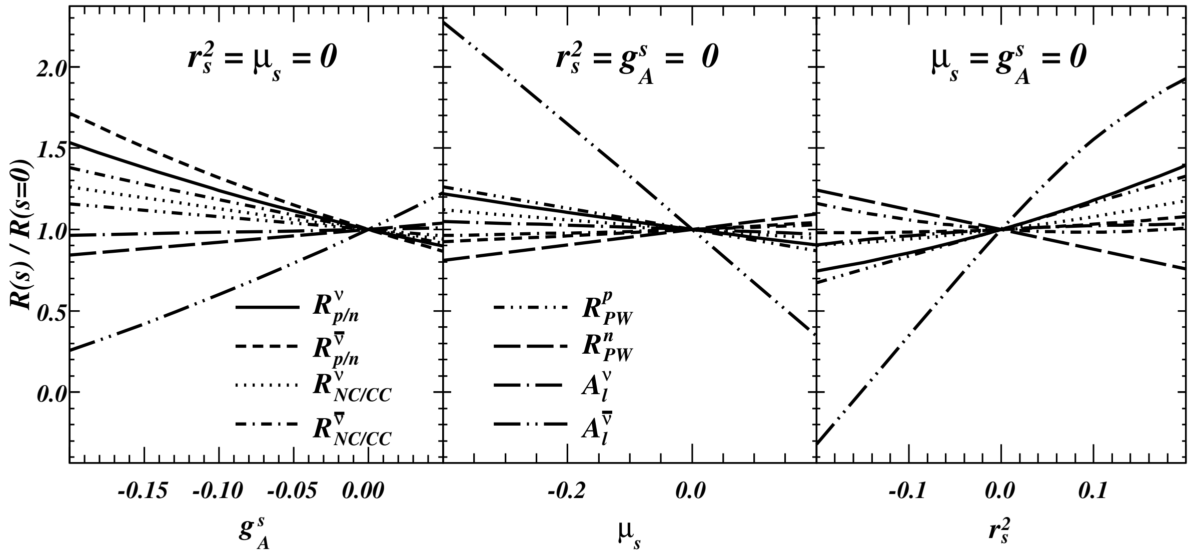

Figure 4: Ratios of integrated QE neutrino-nucleus cross sections normalized to the situation without strangeness as function of g_A^s (left), μ_s (middle) and r_s^2 (right). The incoming neutrinos have an energy of $\epsilon = 1\,\mathrm{GeV}$. The target nucleus is ^{12}C.

as a lever to discriminate neutrino- from antineutrino-induced NC processes at low energies [10]. Furthermore, $A_l^{\overline{\nu}}$ exhibits a strong sensitivity to strangeness [11], as can be appreciated in Figure 3. This contrasts sharply with A_l^{ν}, which is indifferent to strange quarks.

Looking at Figure 3, it is virtually impossible to tell which ratios are most interesting to consider experimentally. Therefore we investigate all previously defined ratios on an equal footing [5]. We introduced ratios to suppress the pernicious effects of final-state interactions. Comparing RPWIA with RMSGA results, we learn that, for all ratios, the influence of FSI is reduced to 1%. In Figure 4, we examine the sensitivity of the various ratios to g_A^s, μ_s and r_s^2. We define ratios of integrated cross sections analogous to Eq. 9-12, e.g.

$$R^{\nu}_{p/n}(s) = \frac{\sigma_{(\nu,\nu' p)}}{\sigma_{(\nu,\nu' n)}}\,, \tag{13}$$

and consider them as function of a set of strangeness parameters $s = (g_A^s, \mu_s, r_s^2)$. Evaluating these *integrated* ratios, normalized to the case without strangeness, as function of one strangeness parameter at a time (the others are kept zero), makes it possible to objectively study the impact of strangeness. On a general note, we notice that ratios with antineutrinos tend to exhibit a larger influence to strangeness than those with neutrinos. The antineutrino-induced helicity asymmetry stands out as the ultimate ratio to probe the strangeness content of the nucleon, being highly sensitive to all three strangeness parameters. The antineutrino-induced proton-to-neutron ratio is the only one that can compete with $A_l^{\overline{\nu}}$ in its g_A^s sensitivity. The vector strangeness parameters, on the other hand, have virtually no impact on $R^{\overline{\nu}}_{p/n}$, making it an interesting observable to try and determine axial strangeness independently of μ_s and r_s^2. Because of the difficulties related to neutron detection, however, the proton-to-neutron ratio is a tedious observable to study experimentally. Likewise, the helicity asymmetry would present quite a challenge, since present neutrino scattering experiments have never considered measuring the spin of nucleons in the final state. The proposed FINeSSE experiment plans to use $R^{\nu}_{NC/CC}$ as a tool to probe the role of strange quarks in the nucleon. The neutrino-induced NC-to-CC ratio turns out to be mildly g_A^s dependent and is only weakly influenced by vector strangeness. FINeSSE would therefore certainly benefit from a run with an antineutrino beam, since $R^{\overline{\nu}}_{NC/CC}$ is far more sensitive to strangeness.

5 Conclusion: when two is better than one

We have studied quasi-elastic neutrino scattering off nuclei with one-nucleon knockout. These processes are shown to be sensitive to axial strangeness and, to a lesser extent, to vector strangeness. The influence of final-state interactions on cross sections renders the extraction of strangeness parameters more difficult. These complications can be avoided by studying cross section ratios. Doing so, the effect of final-state interactions is indeed reduced to approximately 1%. We evaluated the Q^2 dependence of a comprehensive list of ratios and studied their sensitivity to strangeness. We noticed that the effect of vector strangeness parameters is enhanced by the subtle interplay of structure functions in numerator and denominator. Next, we investigated ratios of integrated cross sections. Ratios constructed with antineutrino cross sections turn out to be far more affected by strangeness than their neutrino-induced counterparts. In our model, the longitudinal helicity asymmetry with antineutrinos emerged as the ultimate ratio to assess the strangeness content of the nucleon, whereas the FINeSSE ratio $R^{\nu}_{NC/CC}$ exhibits only a modest strangeness dependence.

In the intermediate-energy regime, two experimental efforts are nowadays brought forward to address the strangeness puzzle. In PVES, being mostly sensitive to vector strangeness, the tininess of the axial strangeness effects hampers the determination of g_A^s. Neutrino scattering, on the other hand, is usually regarded as an excellent probe for axial strangeness, while vector strangeness effects are thought to be small. When we consider ratios of neutrino cross sections, however, the influence of r_s^2 and μ_s becomes remarkably strong. This makes a detailed knowledge of vector strangeness imperative to accurately extract information on axial strangeness. Hence we propose a combined analysis of parity-violating electron scattering and neutrino-induced reactions to disentangle the intricate correlations between vector and axial strangeness and reach a thorough understanding of the role of the strange quarks in the nucleon [12].

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