University of Massachusetts - Amherst
ScholarWorks@UMass Amherst

Physics Department Faculty Publication Series | Physics

2001

Neutrinos and the standard model

BR Holstein
holstein@physics.umass.edu

Follow this and additional works at: http://scholarworks.umass.edu/physics_faculty_pubs

Part of the Physical Sciences and Mathematics Commons

Holstein, BR, "Neutrinos and the standard model" (2001). *Physics Department Faculty Publication Series.* Paper 301.
http://scholarworks.umass.edu/physics_faculty_pubs/301

This Article is brought to you for free and open access by the Physics at ScholarWorks@UMass Amherst. It has been accepted for inclusion in Physics Department Faculty Publication Series by an authorized administrator of ScholarWorks@UMass Amherst. For more information, please contact scholarworks@library.umass.edu.

arXiv:hep-ph/0010098v1 10 Oct 2000

Neutrinos and the Standard Model

Barry R. Holstein
Department of Physics-LGRT
University of Massachusetts
Amherst, MA 01003

February 1, 2008

Abstract

Since their "discovery" by Pauli in 1930, neutrinos have played a key part in confirmation of the structure of the standard model of strong and electroweak interactions. After reviewing ways in which this has been manifested in the past, we discuss areas in which neutrinos continue to play this role.

1 Introduction

The neutrino is a particle whose impact on contemporary physics far outweighs its (possible) negligible mass. Indeed even the layman has long been fascinated by a particle which is (essentially) massless, chargeless, and which can pass through the earth without interaction—*cf.* the poem by John Updike written nearly four decades ago (allegedly when he became bored during a Harvard physics lecture)[1].

Neutrinos they are very small
They have no charge and have no mass
And do not interact at all.....

At this meeting, we will be hearing from many experts on contemporary aspects of neutrinos, especially having to do with their role in astrophysics and cosmology. I shall not attempt to compete with these experts, but rather will discuss ways in which the neutrino has impacted and continues to affect our understanding of the structure of the standard model. After a brief historical introduction, I will emphasize ways in which the neutrino has affected the evolution of standard model structure even from the beginning and then will mention areas of contemporary physics wherein the neutrino continues to play a key role.

2 Neutrino History

The "discovery" of the neutrino is quite different from that of its sibling leptons in that its existence was inferred nearly three decades before its actual experimental confirmation. Indeed it was Pauli who in 1930 postulated the existence of a light neutral particle inside the nucleus—"not larger than 0.01 proton masses"—and called by him the "neutron," in order to explain why nuclear beta decay was observed to have a continuous (three-body) rather than discrete (two-body) electron energy spectrum[2]. This issue of the spectrum was so troublesome at the time that no less an authority than Niels Bohr had speculated that it might be necessary to abandon the idea of energy conservation, except in a statistical sense, when considering subatomic processes such as beta decay[3]. Of course, there was a serious problem with Pauli's suggestion, in that a quick uncertainty principle estimate shows that

a particle this light has a position uncertainty $\Delta x \sim 1/m_\nu \sim 400$ A and could not therefore be confined within the nuclear volume. This problem was solved by Fermi, who renamed this particle the "neutrino" and proposed his famous field theory of beta decay

$$\mathcal{H}_w = \frac{G_F}{\sqrt{2}} \psi_p^\dagger \mathcal{O}_\mu \psi_n \psi_e^\dagger \mathcal{O}^\mu \psi_\nu + h.c. \tag{1}$$

wherein this particle does not exist inside the nucleus but rather is created as a byproduct of the decay itself[4]. The one unknown constant G_F can be determined from the neutron lifetime via

$$\begin{aligned} \Gamma_n &= \left(\frac{G_F}{\sqrt{2}}\right)^2 \int \frac{d^3p_e}{(2\pi)^3} \frac{d^3p_\nu}{(2\pi)^3} 2\pi\delta(M_n - M_p - E_e - E_\nu)|\mathcal{M}_w|^2 \\ &= \frac{G_F^2}{4\pi^3} \int_{m_e}^{M_n - M_p} dE_e E_e p_e (M_n - M_p - E_e)^2 |\mathcal{M}_w|^2 \\ &\simeq 4.59 \times 10^{-19} \mathrm{GeV}^5 G_F^2 |\mathcal{M}_w|^2 = 887 \pm 2\,\mathrm{sec} \end{aligned} \tag{2}$$

which yields $G_F \simeq 10^{-5} M_p^2$. This was all very convincing and Bohr soon became a believer, acknowledging "Finally, it may be remarked that the grounds for serious doubts as regards the strict validity of the conservation laws in the problem of the emission of β-rays from atomic nuclei are now largely removed by the suggestive agreement between the rapidly increasing experimental evidence regarding β-ray phenomena and the consequences of the neutrino hypothesis of Pauli so remarkably developed in Fermi's theory"[5].

This is all well and good but it is one thing to postulate the existence of the neutrino and quite another thing to actually detect it. The problem lies in the size of the weak coupling inferred from beta decay. One can easily calculate a resulting neutrino scattering cross section as

$$\begin{aligned} \sigma_\nu &= \left(\frac{G_F}{\sqrt{2}}\right)^2 \int \frac{d^3p_e}{(2\pi)^3} 2\pi\delta(M_p + E_{\bar{\nu}} - M_n - E_e)|\mathcal{M}_w|^2 \\ &\sim \frac{G_F^2}{2\pi} p_e E_e |\mathcal{M}_w|^2 \sim 10^{-44}\mathrm{cm}^2 \ \text{ at } \ E_{\bar{\nu}} = 1\,\mathrm{MeV} \end{aligned} \tag{3}$$

The mean free path passing through a medium of earthlike density is then expected to be

$$\Delta x \sim 1/(\rho\sigma_\nu) \sim 10^{21} \text{ cm} \tag{4}$$

or 10^{10} earth radii!! The solution to this problem, of course, is to get lots of neutrinos, many target nuclei, or better yet *both*! One of the original ideas conceived by Cowan and Reines to this problem of getting many neutrinos on target was to set off a nuclear bomb near an underground detector[6]. They soon had a more realistic thought, however, and decided to place the detector near a reactor. After original work at the Hanford site, they moved their base of operations to Savannah River and in 1956 were able to announce the unambiguous discovery of the neutrino via the reaction $\bar{\nu}_e + p \rightarrow n + e^+$[7].

In retrospect, this discovery took place in the middle of a tremendous amount of seminal work, which led within a decade to the picture which we now call the standard model of weak and electromagnetic interactions. This included

i) Suggestion of parity violation by Lee and Yang[8] and its subsequent experimental confirmation[9];

ii) Postulation of the V-A structure of the weak current by Feynman and Gell-Mann[10] and its confirmation;

iii) Development of the quark model by Gell-Mann and Zweig[11];

iv) Proposal of quark mixing by Cabibbo[12];

v) Discovery of the standard electroweak model by Weinberg and Salam[13].

By 1967 then we already had what has become one of the most successful theories in modern physics. In this picture the neutrino plays a pivotal role and has at least three fundamental aspects which have been subjected to extensive experimental tests:

i) Chirality: Because of the $1 + \gamma_5$ structure of the weak interaction, the neutrino (antineutrino) must be purely left-handed (right-handed).

ii) Dirac Character: The neutrino is predicted of Dirac character, possessing a distinct antiparticle, rather then a Majorana particle which is its own antiparticle.

iii) Mass: The neutrino is massless, implying that there is no lepton analog to the CKM mixing occuring in the charged weak current.

Each of these predictions has been studied over the years and we now have a sizable data base of experimental evidence involving each issue. I will summarize each in turn:

2.1 Chirality

The prediction of definite chirality was first studied by Goldhaber, Grodzins, and Sunyar in 1958 via electron capture on ^{152}Eu to an excited state of ^{152}Sm followed by its subsequent radiative decay to the ground state[14]. By studying those photons which are emitted opposite to the direction of the outgoing neutrinos one can show that the photon and neutrino helicities must be identical. Thus one can study the neutrino helicity by measuring that of the photon. When this was done the authors announced that "our result seems compatible with ... 100% negative helicity of neutrinos emitted in orbital e^- capture," although they did not really quantify this assertion.

Since that time the chirality issue has been extensively studied. The way one does this is to postulate a form for the charged current weak interaction which includes right-handed components. A typical form for the semileptonic interaction is[15]

$$\mathcal{L} = \frac{G_F \cos\theta}{\sqrt{2}} \left[(V_\mu - \rho A_\mu)(v^\mu - a^\mu) + (xV_\mu + y\rho A_\mu)(v^\mu + a^\mu) \right] \tag{5}$$

where V_μ, A_μ (v^μ, a^μ) are hadronic (leptonic) weak currents respectively. Here $\rho = (1-x)/(1-y)$ with x, y being parameters which characterize the possible existence of right-handed effects. In a minimal left-right model of spontaneous symmetry breaking, we would identify

$$x \simeq \delta - \zeta, \quad y \simeq \delta + \zeta \tag{6}$$

where $\delta = M_1^2/M_2^2$ measures the ratio of (predominantly) left- and right-handed gauge boson masses and ζ is the mixing angle defined via $W_1 = W_L \cos\zeta - W_R \sin\zeta$. The tightest limits on x, y come from precise beta decay studies. Examples include measuring the longitudinal polarization of the electron, which is given by $P_L \simeq \beta(1 - 2y^2)$ or of the asymmetry parameter in the decay of polarized nuclei, which for neutron decay has the form

$$A = 2\frac{g_A(g_A + g_V) - yg_A(yg_A + xg_V)}{g_V^2 + 3g_A^2 + (x^2 g_V^2 + 3y^2 g_A^2)} \tag{7}$$

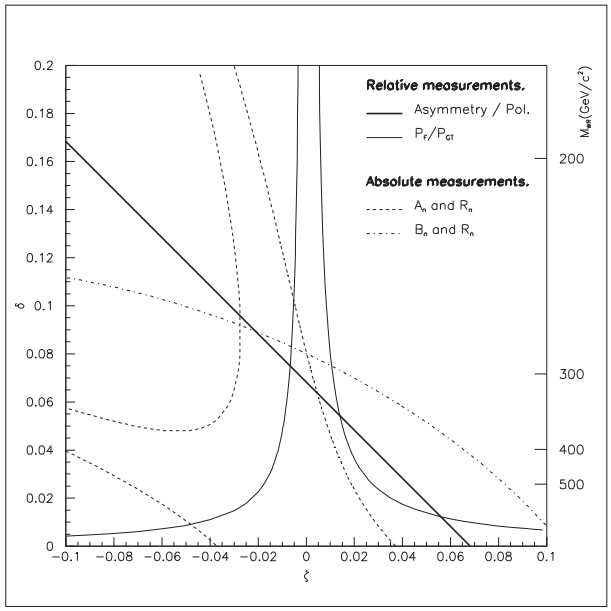

Figure 1: Present experimental limits on right-handed parameters from beta decay experiments.

Over the years a series of careful studies has produced the limits shown in Figure 1, which generally limit x, y at the several percent level[16]. (The reason that generally tenth of a per cent precision in beta decay measurements results in only several percent limits on x, y is due to the feature that left and right handed currents do not interfere, so that any deviations from standard model predictions are quadratic in x, y as can be seen above.)

2.2 Dirac Character

The Dirac character of the neutrino has also been extensively examined, and Frank Avignone has, of course, been extensively involved in such studies. Naively one might think that the issue would already be clear from the feature that while the reaction

$$\nu_e + p \rightarrow n + e^+ \tag{8}$$

does not occur while

$$\nu_e + p \rightarrow p + e^- \tag{9}$$

does. Equivalently the absence of neutrinoless double beta decay

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^- \tag{10}$$

which can occur via sequential beta decay accompanied by the exchange of a virtual neutrino (=antineutrino) would seem to argue strongly against a Majorana character. However, both of these arguments are blunted if the neutrino has definite helicity, as experimentally seems to be the case. Indeed then even if the neutrino has a Majorana character, it has the wrong helicity to bring about the scattering or double beta decay reactions above, so that their experimental absence does not bear on the Dirac vs. Majorana issue. On the other hand, if the neutrino is Majorana and has a small mass, so that helicity is not definite, then neutrinoless double beta decay is possible and it is experiment involving ^{76}Ge which Frank pioneered and has been doing for many years. Just this week a new limit on the Majorana mass of $< m_\mu^M > \leq 0.2$ eV has been announced from such measurements[17].

2.3 Neutrino Mass

The issue of whether the neutrino has a mass is clearly a fundamental one. In the standard model the absence of mass is due to Ockham's Razor—*i.e.*, the standard model uses only the *minimal* number of components. Since a right handed neutrino structure is not necessary, the standard model assumes its absence and, as it requires both a left and right handed component in order to generate a mass, the neutrino is predicted to be massless. This prediction is one which has been under experimental scrutiny for many years. (Even Fermi in his original paper suggested examination of this issue by looking at the electron energy dependence of beta decay spectra near the endpoint[4].) Generally most such studies have utilized ^3H due to its low—18.6 KeV—endpoint, since that maximizes the interesting component of the electron spectrum, and such studies have become increasingly precise. An early value by Hamilton, Alford, and Gross placed the upper limit at 250 KeV[18], which in 1972 was lowered to 60 eV by Bergkvist[19]. In 1980 Lubimov announced a nonzero value $14eV \leq m_{\bar{\nu}} \leq 46$ eV, which set off a firestorm of new work[20]. Present experiments do not not find evidence for a nonzero neutrino mass and upper bounds have been place at 9.3 eV by Robertson et al.[21] and at 7.2 eV by Weinheimer et al.[22], so that the Lubimov value has been superceded.

Work continues on such direct mass measurements. Some interesting new ideas have been discussed at this workshop, including use of Rhenium, with an endpoint energy even lower than that of ^3H and the use of bolometric methods to detect the electron.

In is interesting to note in this regard, that in the middle of this intense activity to measure neutrino mass, an event occurred which bears on this issue and which allows a simple limit to be set which is nearly comparable to those obtained from these careful spectral studies—SN1987a, which blazed into the sky on February 27, 1987 and was observed not only optically, but also by neutrino detectors in the US and Japan. If the neutrinos emitted by the supernova were massive, then the velocity would be $v \simeq 1 - m_\nu^2/(2E_\nu^2)$ and the most energetic neutrinos would reach the earth first. It is easy to estimate the time difference as

$$\frac{\delta t}{t} \sim \frac{\delta v}{v} \sim \frac{m_\nu^2}{E_\nu^2}\frac{\delta E_\nu}{E_\nu} \tag{11}$$

and the time gap between the arrival of the high and low energy neutrinos could then be used to measure this mass. Experimentally, the ~ 10 MeV neutrinos arrived over a ~ 10 second time interval after travelling a distance of 165,000 light years from the supernova in the Large Magellanic Cloud but a time-energy correlation was not observed. One can then easily set a limit on the mass—

$$m_\nu \leq E_\nu \left(\frac{\delta t}{t}\frac{E_\nu}{\delta E_\nu}\right)^{\frac{1}{2}} \sim 10\,\mathrm{sec.}\left(\frac{10\,s}{10^{13}\,s}\right)^{\frac{1}{2}} \sim 10\,\mathrm{eV} \tag{12}$$

A more careful analysis sets the upper bound at about 20 eV. It is astounding to me that the relatively trivial analysis given above from an event occurring long before the dawn of civilization is able to set a limit on neutrino mass comparable to that obtained from years of precise experimental studies!

Of course, I have summarized here only the *direct* mass measurements. Simultaneously, a series of experiments involving a search for neutrino mixing has been underway. Such mixing is prohibited in the absence of mass since neutrino identities could just be reassigned. The recent announcements of mixing signals from solar, accelerator, and atmospheric measurements then clearly, if comfirmed, indicates the existence of neutrino mass. Since this will be the subject of many talks during this workshop, I will not here summarize

this data but instead will move on to discuss aspects of neutrino physics which are not as well known, but which have a bearing on contemporary physics issues.

3 Contemporary Issues

Above we have seen how the neutrino has played an essential role in development of the structure of the standard model. In this section, I argue that this is still going on and discuss ways in which neutrino interactions are involved in a number of the central issues in contemprary physics. In this discussion, I will not emphasize some of the more traditional ways in which this is manifested—*e.g.*

i) use of neutrino scattering in order to study the Q^2 evolution of deep inelastic structure functions as a test of perturbative QCD,

ii) use of such deep inelastic structure functions in order to check the validity of various sum rules, such as the Adler sum rule

$$1 = \int_0^1 \frac{dx}{2x}(F_2^{\nu n}(x,q^2) - F_2^{\nu p}(x,q^2)), \tag{13}$$

since these are fairly well known. Instead I will discuss three lesser known applications wherein neutrino studies have a bearing on interesting standard model issues.

3.1 Goldberger-Treiman Discrepancy

One of the important features of QCD is its (broken) chiral symmetry, from which follows the existence of the Goldberger-Treiman (GT) relation, which connects the strong pion-nucleon coupling $g_{\pi NN}$ and the axial coupling $g_A(0)$ measured in neutron beta decay[23],

$$M_N g_A(0) = F_\pi g_{\pi NN}(0) \tag{14}$$

where $F_\pi = 92.3$ MeV is the pion decay constant. One subtlety associated with Eq. 14 is that the pi-nucleon coupling is evaluated *not* at the physical point—$q^2 = m_\pi^2$—but rather at the unphysical value—$q^2 = 0$. In fact when

the physical coupling is used, one expects a *violation* of the GT identity and this is often showcased by quoting the so-called Goldberger-Treiman discrepancy

$$\Delta_\pi = 1 - \frac{g_A(0) M_N}{g_{\pi NN}(m_\pi^2) F_\pi} \tag{15}$$

Strictly speaking the value of Δ_π is given by a chiral counterterm, but in a reasonable model one would expect $g_\pi NN(q^2)$ to vary with q^2 in essentially the same way as its weak analog $g_A(q^2)$. In this way one finds

$$\Delta_\pi = 1 - \frac{g_A(0)}{g_A(m_\pi^2)} = \frac{1}{6} r_A^2 m_\pi^2 \simeq 0.034 \tag{16}$$

where $r_A = 0.65 \pm 0.03$ fm is the axial charge radius measured in charged current neutrino scattering[24].[1]

An alternative approach is to utilize the Dashen-Weinstein relation

$$\Delta_\pi = \frac{\sqrt{3} m_\pi^2 F_K}{2 m_K^2 F_\pi} \left(\frac{g_{\Lambda KN}}{g_{\pi NN}} \Delta_K^\Lambda - \frac{1}{\sqrt{6}} \frac{g_{\Sigma KN}}{g_{\pi NN}} \Delta_K^\Sigma \right) \tag{18}$$

which predicts the pionic GT discrepancy in terms of its kaonic analogs involving Λ and Σ couplings respectively[25]. The original proof of this result argued that it was valid up to terms second order in chiral symmetry breaking. However, recently it has been shown by Goity et al. that in heavy baryon chiral perturbation theory any such difference can arise only at $\mathcal{O}(p^5)$ or higher[26]. Although the strong Λ, Σ couplings are not well determined, the predictions are only weakly dependent upon thse quantities. Thus one finds the relatively robust prediction

$$\Delta_\pi(\text{Dashen} - \text{Weinstein}) = 0.017 \tag{19}$$

in good agreement with that expected from neutrino scattering results.

Now what does experiment say? The problem here is that while the pion decay constant, the nucleon mass, and the weak axial coupling are all well

[1] Here the axial charge radius is defined via

$$g_A(q^2) = g_A(0)(1 + \frac{r_A^2}{6} q^2 + \ldots). \tag{17}$$

known, there is still considerable debate about the value of the size of the pion nucleon coupling constant. A recent analysis of $NN, N\bar{N}, \pi N$ data by the Nijmegen group yields the value $g_{\pi NN}(m_\pi^2) = 13.05 \pm 0.08$[27] and a VPI analysis yields similar results[28]. However, a significantly larger number—$g_{\pi NN}(m_\pi^2) = 13.65 \pm 0.30$—has been found by Bugg and Macleidt[29] and by Loiseau[30]. When these values are used in order to calculate the GT discrepancy, we find

$$\begin{aligned} \Delta_\pi &= 0.014 \pm 0.006 \quad \text{if} \quad g_{\pi NN} = 13.05 \pm 0.08 \\ \Delta_\pi &= 0.056 \pm 0.020 \quad \text{if} \quad g_{\pi NN} = 13.65 \pm 0.30 \end{aligned} \tag{20}$$

The neutrino scattering number Eq. 16 then comes right in the middle, while the Dashen-Weinstein analysis strongly supports the lower value of $g_{\pi NN}$.

3.2 Axial Charge Radius

A second interesting application of neutrino scattering results is associated with confirmation of a prediction of chiral perturbation theory and therefore of QCD. In order to understand this point, we return to the early days of current algebra and PCAC and a low energy theorem derived by Nambu and Schrauner, which argues that the axial charge radius may be obtained via measurement of the isospin odd E_{0+} multipole in threshold electroproduction via[31]

$$E_{0+}^{(-)}(m_\pi = 0, k^2) = \frac{e g_A}{8\pi F_\pi}\left(1 + \frac{k^2}{6} r_A^2 + \frac{k^2}{4M_N^2}(\kappa_V + \frac{1}{2}) + \mathcal{O}(k^3)\right) \tag{21}$$

In this way one has determined the value $r_A = 0.59 \pm 0.05$ fm,[32] differing from the number $r_A = 0.65 \pm 0.03$ fm found via direct neutrino scattering measurements. Although the discrepancy is only at the one sigma level, it is interesting that recent calculations by Bernard, Kaiser, and Meissner in heavy baryon chiral perturbation theory have shown that the old low energy theorem is incorrect and that there exists an additional contribution coming from so-called triangle diagrams, which predicts a difference between the axial charge radius as measured in neutrino scattering and that from electroproduction[33]

$$r_A^2(\text{elec.}) = r_A^2(\text{neu}) - \frac{3}{64F_\pi^2}(\frac{12}{\pi^2} - 1) \tag{22}$$

The 0.046 fm^2 difference predicted from chiral symmetry agrees well in size and sign with that seen experimentally.

3.3 Nucleon Strangeness Content

My final example has to do with the subject of strangeness content of the nucleon, which is one of intense current interest. One of the early studies of such matters is the paper of Donoghue and Nappi[34]. The idea here is that one expects that in the limit of vanishing quark masses the nucleon mass should approach some nonzero value M_0. In the real world, with nonzero quark mass, the nucleon mass is modified to become

$$M_N = M_0 + \sigma_s + \sigma \tag{23}$$

where, defining $\hat{m} = (m_u + m_d)/2$,

$$\sigma_s = \frac{1}{2M_N} < N|m_s \bar{s}s|N >, \quad \sigma = \frac{1}{2M_N} < N|\hat{m}(\bar{u}u + \bar{d}d)|N > \tag{24}$$

are the contributions to the nucleon mass from strange, non-strange quarks respectively. One constraint in this regard comes from study of the hyperon masses, which yields

$$\begin{aligned} \delta &= \frac{\hat{m}}{2M_N} < N|\bar{u}u + \bar{d}d - 2\bar{s}s|N > \\ &= \frac{3}{2}\frac{m_\pi^2}{m_K^2 - m_\pi^2}(M_\Xi - M_\Lambda) \simeq 25MeV \end{aligned} \tag{25}$$

and increases to about 35 MeV when higher order chiral corrections are included. A second constraint comes from analysis of πN scattering, which says that σ can be extracted directly if an isospin even combination of amplitudes could be extrapolated via dispersion relations to the (unphysical) Cheng-Dashen point

$$F_\pi^2 D^{(+)}(s = M_N^2, t = m_\pi^2) = \sigma \tag{26}$$

When this is done the result comes out to be ∼60 MeV, which is lowered to about 45 MeV by higher order chiral corrections. If $< N|\bar{s}s|N >= 0$, as might be expected from a naive valence quark picture, then we would

expect the value coming from the hyperon mass limit and that extracted from πN scattering to agree. The fact that they do not can be explained by postulating the existence of a moderate strange quark matrix element

$$f = \frac{< N|\bar{s}s|N >}{< N|\bar{u}u + \bar{d}d + \bar{s}s|N >} \simeq 0.1 \tag{27}$$

implying $M_0 \simeq 765$ Mev and $\sigma_s \simeq 130$ MeV, which seem quite reasonable. However, recent analyses have suggested a rather larger value of the sigma term, leading to $f \simeq 0.2$, $M_0 \simeq 500$ MeV and $\sigma_s \simeq 375$ MeV, which appear somewhat too large. This problem is ongoing.

In any case it is of interest to study the possibility of a significant strange quark matrix element in other contexts. One quantity which has been extensively studied is the nucleon electromagnetic matrix element, which has the form

$$\begin{aligned} & < N|V_\mu^{em}|N > = < N|\frac{2}{3}\bar{u}\gamma_\mu u - \frac{1}{3}\bar{d}\gamma_\mu d - \frac{1}{3}\bar{s}\gamma_\mu s|N > \\ = \; & \bar{u}(p')\left[\gamma_\mu(F_1^{ns}(q^2) + F_1^s(q^2)) - \frac{i}{2M_N}\sigma_{\mu\nu}q^\nu(F_2^{ns}(q^2) + F_2^s(q^2))\right]u(p) \end{aligned} \tag{28}$$

and one can look for the existence of strange quark pieces $F_1^s(q^2), F_2^s(q^2)$ in parity-violating electron scattering. This has been done in the forward direction by the HAPPEX experiment at JLab[35] and in the backward direction by the SAMPLE experiment at MIT-Bates[36]. The HAPPEX result is consistent with $r_1^s = 0$, while the Bates result seems to indicate a small positive value for μ_s.

Another probe comes from the realm of deep inelastic electron scattering wherein, defining the quark helicity content Δq via

$$\Delta q \sigma_\mu = < p, \sigma|\bar{q}\gamma_\mu\gamma_5 q|p, \sigma > \tag{29}$$

one has the constraint

$$\int_0^1 dx g_1(x) = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right](1 - \frac{\alpha_s(q^2)}{\pi}) \tag{30}$$

When combined with the Bjorken sum rule and its SU(3) generalization

$$\begin{aligned} \Delta u - \Delta d &= g_A(0) = F + D \\ \Delta u + \Delta d - 2\Delta s &= 3F - D \end{aligned} \tag{31}$$

one finds the solution $\Delta u = 0.81$, $\Delta d = -0.42$, $\Delta s = -0.11$, indicating a small negative value for the strange matrix element.

So far, these results have nothing to do with our main focus, which is neutrinos. However, we note that there exists an alternative probe for such a strange matrix element which is accessed via neutral current neutrino scattering. The point here is that the form of the standard model axial current is

$$< N|A_\mu^Z|N >= \frac{1}{2} < N|\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d - \bar{s}\gamma_\mu\gamma_5 s|N > \tag{32}$$

which is purely isovector in the case that the strange matrix element vanishes and can be therefore be exactly predicted from the known charged current axial matrix element. This experiment was performed at BNL and yielded a result[37]

$$\Delta s = -0.15 \pm 0.09 \tag{33}$$

consistent with that found from the deep inelastic sector, but a more precise value is needed.

4 Conclusion

We have argued above that the neutrino has played and continues to play an important role in the development of the standard model. In the past such studies contributed to the now accepted picture of the weak interaction. Present work looks for small deviations from this structure. However, we have also seen how neutrino experiments bear on a number of issues of great interest in contemporary physics and I suspect that neutrino measurements will continue to be exciting far into the new millenium.

Acknowledgement

It is a pleasure to acknowledge the hospitality of University of South Carolina and the organizers of this meeting. This work was supported in part by the National Science Foundation.

References

[1] J. Updike, in **Telephone Poles and Other Poems**, A.A. Knopf, New York (1963).

[2] See, *e.g.* L.M. Brown, Phys. Today **31**, 23 (September 1978).

[3] N. Bohr, Faraday Lecture, J. Chem Soc., 349 (1932).

[4] E. Fermi, Z. Phys. **88**, 161 (1934); see also the translation given by A.L. Wilson, Am. J. Phys. **36**, 1150 (1968).

[5] N. Bohr, Nature **138**, 25 (1936).

[6] See, *ee.g.*, "Celebrating the Neutrino" in Los Alamos Sci. 25, 1-191 (1997).

[7] C.L. Cowan, et al., Science **124**, 103 (1956).

[8] T.D. Lee and C.N. Yang, Phys. Rev. **104**, 254 (1956).

[9] C.S. Wu et al., Phys. Rev. **105**, 1413 (1957).

[10] R.P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).

[11] See, *e.g.* M. Gell-Mann and Y. Ne'eman, **The Eightfold Way**, Benjamin, New York (1964).

[12] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).

[13] S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967).

[14] M. Goldhaber, L. Grodzins, and A. Sunyar, Phys. Rev. **109**, 1015 (1958).

[15] See, *e.g.* B.R. Holstein and S.B. Treiman, Phys. Rev. **D15**, 3472 (1977).

[16] See, *e.g.* J. Deutsch, nucl-th/9901098, to be published in Proc. WEIN98.

[17] Cern Courier, **40**, #1, p.8 (2000).

[18] C.S. Wu, in **Alpha, Beta, and Gamma-Ray Spectroscopy**, ed. K. Siegbahn, North Holland, Amsterdam (1965), Vol. II, p. 1391.

[19] K.-E. Bergkvist, Nucl. Phys. **B39**, 317 (1972).

[20] V.A. Lubimov et al., Phys. Lett. **B94**, 299 (1980).

[21] R.G.H. Robertson et al., Phys. Rev. Lett. **67**, 957 (1991).

[22] Ch. Weinheimer et al., Phys. Lett. **B300**, 210 (1993).

[23] M.L. Goldberger and S.B. Treiman, Phys. Rev. **110**, 354 (1958).

[24] T. Kitagaki et al., Phys. Rev. **D28**, 436 (1983); L. A. Ahrens et al., Phys. Rev. **D35**, 785 (1987) and Phys. Lett. **B202**, 284 (1988).

[25] R. Dashen and M. Weinstein, Phys. Rev. **188**, 2330 (1969).

[26] J. Goity et al., Phys. Lett. **B454**, 115 (1999).

[27] J.J. deSwart, M.C. M. Rentmeester, and R.G.E. Timmermans, Proc. MENU97, TRIUMF Rept. 97-1, 96 (1997).

[28] R.A. Arndt, I.I. Strokovsky, and R.L. Workman, Phys. Rev. **C52**, 2246 (1995).

[29] D.V. Bugg and R. Machleidt, Phys. Rev. **C52**, 1203 (1995).

[30] B. Loiseau et al., πN Newsletter **13**, 117 (1997).

[31] Y. Nambu and E. Lurie, Phys. Rev. **125**, 1429 (1962); Y. Nambu and E. Shrauner, Phys. Rev. **128**, 862 (1962).

[32] A. del Guerra et al., Nucl. Phys. **B107**, 65 (1976); M.G. Olsson, E.T. Osypowski, and E.H. Monsay, Phys. Rev. **D17**, 2938 (1978); S. Choi et al., Phys. Rev. Lett. **71**, 3927 (1993).

[33] V. Bernard, N. Kaiser, and U.-G. Meissner, Phys. Rev. Lett. **69**, 1877 (1992).

[34] J.F. Donoghue and C. Nappi, Phys. Lett. **B168**, 105 (1986).

[35] K.A. Aniol et al. Phys. Rev. Lett. **82**, 1096 (1999).

[36] D.T. Spayde et al, Phys. Rev. Lett. **84**, 1106 (2000).

[37] L.A. Ahrens, Phys. Rev. Lett. **35**, 785 (1987).