The ratio of p and n yields in NC neutrino (anti-neutrino) nucleus scattering and strange form-factors of the nucleon.

DOI:10.1016/S0370-2693(98)01043-0

(Article begins on next page)

15 October 1998

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 438 (1998) 9–13

The ratio of p and n yields in NC $\nu(\bar{\nu})$ nucleus scattering and strange form factors of the nucleon

W.M. Alberico [a], M.B. Barbaro [a], S.M. Bilenky [b], J.A. Caballero [c,1], C. Giunti [a], C. Maieron [a], E. Moya de Guerra [c], J.M. Udías [c,2]

[a] *INFN, Sezione di Torino and Dipartimento di Fisica Teorica, Università di Torino, Via P. Giuria 1, 10125 Torino, Italy*
[b] *Joint Institute for Nuclear Research, Dubna, Russia*
[c] *Instituto de Estructura de la Materia, CSIC, Serrano 123, E-28006 Madrid, Spain*

Received 5 January 1998; revised 8 July 1998
Editor: J.-P. Blaizot

Abstract

We calculate the ratio of proton and neutron yields in NC induced $\nu(\bar{\nu})$–nucleus inelastic scattering at neutrino energies of about 1 GeV. We show that this ratio depends very weakly on the nuclear models employed and that in ν and $\bar{\nu}$ cases the ratios have different sensitivity to the axial and vector strange form factors; moreover the ratio of $\bar{\nu}$–nucleus cross sections turns out to be rather sensitive to the electric strange form factor. We demonstrate that measurements of these ratios will allow to get information on the strange form factors of the nucleon in the region $Q^2 \geq 0.4$ GeV^2. © 1998 Published by Elsevier Science B.V. All rights reserved.

PACS: 12.15.mn; 25.30.Pt; 13.60.Hb; 14.20.Dh; 14.65.Bt
Keywords: Neutrino–nucleus scattering; Strange form factors; Nuclear model effects

The determination of the one–nucleon matrix elements of the axial and vector (weak) *strange* currents has become an important challenge both for theory and experiment: after the measurements of the polarized structure function of the proton g_1 in deep inelastic scattering [1,2], the value of the axial strange constant g_A^s has been set to $g_A^s = -0.10 \pm 0.03$ [3], while the value of the strange magnetic form factor of the nucleon has been recently determined at Bates [4] via measurements of the P–odd asymmetry in electron–proton scattering, with the result $G_M^s(0.1\,\mathrm{GeV}^2) = 0.23 \pm 0.37 \pm 0.15 \pm 0.19$. The latter is still affected by large experimental (and theoretical) uncertainties, which are compatible with vanishing magnetic strange form factor; the former seems to indicate a non–zero value of the strange axial constant, but the theoretical analysis of the data leading to the above mentioned result still suffers from some uncertainties and model dependence. Fur-

[1] Permanent address: Dpto. de Física Atómica, Molecular y Nuclear, Universidad de Sevilla, Apdo. 1065, E-41080 Sevilla, Spain.

[2] Present address: Dpto. de Física Atómica, Molecular y Nuclear, Fac. de CC. Físicas, Univ. Complutense de Madrid, Ciudad Universitaria, E-28040 Madrid, Spain.

PII: S0370-2693(98)01043-0

ther progress is thus needed in order to assign a reliable quantitative estimate of the strange form factors of the nucleon.

In previous works [5,6], we have shown that an investigation of elastic and inelastic neutral current (NC) scattering of neutrinos (and antineutrinos) on nucleons and nuclei is an important tool to disentangle the isoscalar strange components of the nucleonic current. In this letter we focus on the ratio between the cross sections of the inelastic production of protons and neutrons in neutrino (antineutrino) processes:

$$\nu_\mu(\bar{\nu}_\mu) + (A,Z) \to \nu_\mu(\bar{\nu}_\mu) + p + (A-1,Z-1), \tag{1}$$

$$\nu_\mu(\bar{\nu}_\mu) + (A,Z) \to \nu_\mu(\bar{\nu}_\mu) + n + (A-1,Z), \tag{2}$$

where (A,Z) is a nucleus with A nucleons and atomic number Z. This ratio has been first suggested as a probe for strange form factors by Garvey et al. [7,8], at rather low incident neutrino energies ($E_\nu \simeq$ 200 MeV), a kinematical condition which is appropriate for LAMPF.

The influence of the nuclear dynamics on this ratio, has been thoroughly discussed in Ref. [9] and [6]. It has been found that at E_ν of the order of 200 MeV the theoretical uncertainties associated, e.g., with the final states interaction (FSI) of the ejected nucleon with the residual nucleus could introduce ambiguities in the determination of the strange axial and magnetic form factors [6]. In our opinion, incident neutrino energies of the order of 1 GeV appear interesting, from the point of view of the determination of the strange form factors of the nucleon, since the nuclear model effects are within percentage range and are well under control. Neutrinos with such energies are available at Brookhaven, KEK, Protvino and probably will be available at Fermilab (see BOONE proposal [10]).

In this letter we calculate the contributions of the axial and vector strange form factors to the ratio of the cross sections of the processes (1) and (2),

$$\mathscr{R}^{\nu(\bar{\nu})}_{p/n} = \frac{(d\sigma/dT_N)_{\nu(\bar{\nu}),p}}{(d\sigma/dT_N)_{\nu(\bar{\nu}),n}}, \tag{3}$$

for incident neutrino energies $E_{\nu(\bar{\nu})} = 1$ GeV and for ^{12}C. In the above T_N is the kinetic energy of the outgoing nucleon. We present here calculations in plane wave impulse approximation (PWIA), within two nuclear models: the relativistic Fermi gas (RFG) and a relativistic shell model (RSM). Calculations in distorted wave impulse approximation (DWIA) are also included for the RSM, with FSI taken into account through a relativistic optical potential (ROP). For details of these models see Refs. [6,11], and references therein.

We also consider the ratio of integrated cross sections,

$$R^{\nu(\bar{\nu})}_{p/n} = \frac{\int dT_N (d\sigma/dT_N)_{\nu(\bar{\nu}),p}}{\int dT_N (d\sigma/dT_N)_{\nu(\bar{\nu}),n}}. \tag{4}$$

In Fig. 1a,b we present the ratio $\mathscr{R}^{\nu}_{p/n}$ (a) and $\mathscr{R}^{\bar{\nu}}_{p/n}$ (b) for incident neutrino energy $E_\nu = 1$ GeV as a function of T_N, at different values of the parameters that characterize the strange form factors. The solid lines correspond to the pure RSM, the dot–dashed lines to the DWIA (RSM + ROP) and the dotted lines to the RFG. The latter almost coincide with the solid ones in Fig. 1a, while small differences are seen in the ratio of $\bar{\nu}$–cross sections (Fig. 1b). Also the effect of FSI appears to be somewhat more relevant in the $\bar{\nu}$ processes, while it is fairly negligible in $\mathscr{R}^{\nu}_{p/n}$.

As already noticed in Ref. [6], at $E_\nu = 1$ GeV the ratio $\mathscr{R}^{\nu}_{p/n}$ is substantially unaffected by the nuclear model description, even by including the distortion of the knocked out nucleon (in spite of the fact that the FSI sizably reduce the separated cross section with respect to the PWIA); moreover $\mathscr{R}^{\nu}_{p/n}$ is fairly constant as a function of the ejected nucleon energy over the whole interval of kinematically allowed T_N values, thus providing a wide range of energy for testing the effects of the strange form factors.

On the contrary $\mathscr{R}^{\bar{\nu}}_{p/n}$ shows a more pronounced dependence upon the energy of the emitted nucleon, stemming from the fact that the $(\bar{\nu},n)$ cross sections decrease faster than the $(\bar{\nu},p)$ ones. As a consequence the range of T_N where the ratio increases appears to be more sensitive to the nuclear model and to FSI (we have partially cut the curves in the large T_N region, the latter being uninteresting for the

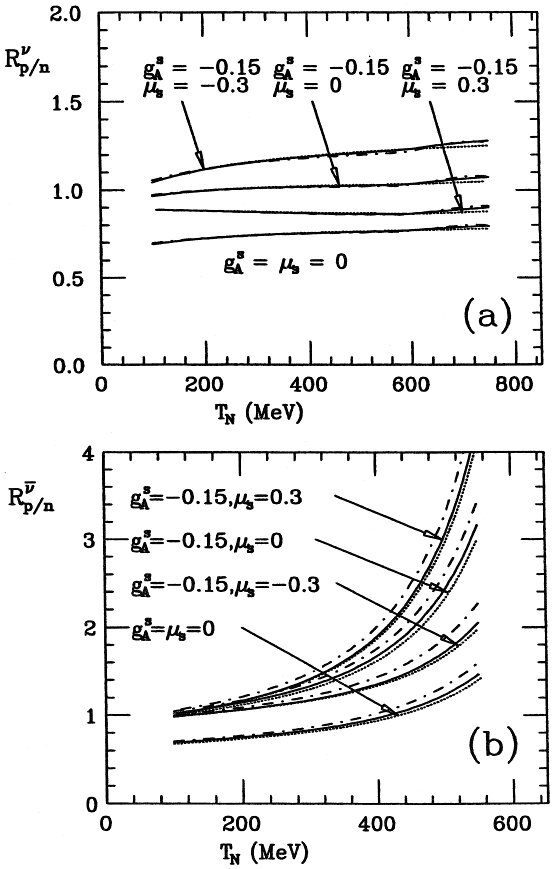

Fig. 1. The ratio $\mathcal{R}^{\nu}_{p/n}$ (a) and $\mathcal{R}^{\bar\nu}_{p/n}$ (b) for NC neutrino processes, versus the kinetic energy of the final nucleon $T_N = T_p = T_n$, at incident energy $E_{\nu(\bar\nu)} = 1$ GeV. The dotted lines correspond to the RFG model, the solid lines to the RSM calculation, the dot–dashed lines include the effect of FSI accounted for by the ROP model. Four different choices of the strangeness parameters are shown, as indicated in the figure.

discussion). If we further restrict to the region where $\mathcal{R}^{\bar\nu}_{p/n}$ remains fairly constant, the sensitivity of the ratio to the nucleonic strangeness is comparable to the one of $\mathcal{R}^{\nu}_{p/n}$.

Models for the strange form factors of the nucleon exist in the low Q^2 limit [13]; a soliton model has been recently employed by Kolbe et al. [12] in a study of the ratio (4) under the LAMPF kinematical conditions. It was shown in Ref. [5] that information on the Q^2 dependence of the strange (axial and magnetic) form factors in the region $Q^2 \gtrsim 0.5\,\text{GeV}^2$ can be obtained from the measurement of the asymmetry of elastic $\nu(\bar\nu)$–proton scattering. To illustrate the size of the effects of strangeness we have adopted here the standard dipole behaviour, both for $G_M^s(Q^2)$ and $F_A^s(Q^2)$, with $G_M^s(0) = \mu_s$ and $F_A^s(0) = g_A^s$, using the same cutoff masses of the non–strange vector (axial) form factors. A stronger decrease of G_M^s and F_A^s at high Q^2 (as suggested by the asymptotic quark counting rule) would indeed reduce the global effects of strangeness, the size of this reduction and the scale where it becomes important being determined by the specific form assumed for the Q^2 dependence: for example a ‘‘Galster-like’’ parameterization as the one used in Ref. [5] would reduce the effects we are considering of about 25%.

The comparison of Figs. 1a and 1b indicates that the interplay between axial and magnetic strangeness is opposite for the ν and $\bar\nu$ ratios. For instance, if g_A^s and μ_s are assumed to have the same (negative) sign (e.g. in our calculation $g_A^s = -0.15$, $\mu_s = -0.3$), their effects on $\mathcal{R}^{\nu}_{p/n}$ have a constructive interference, which enhances the global effect of strangeness, while the opposite occurs for anti–neutrinos. On the contrary, $\mathcal{R}^{\bar\nu}_{p/n}$ is more sensitive than $\mathcal{R}^{\nu}_{p/n}$ to the strange form factors when, e.g., $g_A^s = -0.15$ but $\mu_s = +0.3$.

The interest of considering positive μ_s values stems from the recent measurement of this quantity performed at Bates in parity violating electron scattering on the proton [4]. Though affected by large errors, which give a result still compatible with zero magnetic strangeness, a positive strange magnetic moment of the nucleon is allowed. The value of $G_M^s = +0.23 \pm 0.37 \pm 0.15 \pm 0.19$ at $Q^2 = 0.1$ GeV^2 corresponds to a $\mu_s = 0.30 \pm 0.48 \pm 0.20 \pm 0.25$ if extrapolated down to the origin by using form factors of dipole type (the quoted uncertainties are, respectively, the statistical and systematic errors together with the theoretically estimated radiative corrections [14]).

Thus far we have discussed results obtained for the ratio $\mathcal{R}_{p/n}$ by setting to zero the electric strange form factor, G_E^s: we have included the latter in our calculations, using the form $G_E^s(Q^2) = \rho_s \tau G_D^V(Q^2)$, ρ_s being a constant and $G_D^V(Q^2)$ the usual dipole form factor of the vector currents. We have found that, for rather large values of ρ_s (of the order of ± 2) the ratio $\mathcal{R}_{p/n}$ is appreciably modified, in particular it is enhanced by a negative ρ_s and reduced by a positive one [3]. Moreover we have found that the electric strangeness has a quite different impact on $\mathscr{R}^{\nu}_{p/n}$ and on $\mathscr{R}^{\bar{\nu}}_{p/n}$. In the first case ($\mathscr{R}^{\nu}_{p/n}$) the effect of G_E^s does not exceed 25% of the correction associated to the axial strange form factor, which remains the dominant one, while it can be of the order of 50% of the correction associated with a strange magnetic moment $\mu_s = -0.3$.

Instead, for the ratio obtained with antineutrino beams ($\mathscr{R}^{\bar{\nu}}_{p/n}$), the interference between the electric and magnetic strange form factors appears to be much more important: it turns out that $\mathscr{R}^{\bar{\nu}}_{p/n}$ is even more sensitive to G_E^s than to G_M^s, although, again, the axial strange form factor plays the major role. This introduces a third unknown in the analysis of $\mathscr{R}^{\nu}_{p/n}$ and $\mathscr{R}^{\bar{\nu}}_{p/n}$. However it is worth reminding that it is quite difficult to determine the electric strange form factor in parity violating electron scattering: this component can affect the PV asymmetry by at most 20% at very small scattering angles [16], while it is possible to measure G_M^s, as shown by the SAMPLE experiment and more precise measurements are indeed under way. Thus one can exploit the sensitivity of $\mathscr{R}^{\bar{\nu}}_{p/n}$ to G_E^s precisely to extract the relevant information on the electric strange form factor.

In order to illustrate this point, we present in Fig. 2a,b the ratio (4), where the cross sections have been integrated in the interval 100 MeV $\leq T_N \leq$ 400 MeV (the maximum reliable interval for which the $\bar{\nu}$ ratio is fairly stable versus T_N). The ratio is displayed as a function of μ_s, fixing $g_A^s = 0$ and $g_A^s = -0.15$ and showing, around this last value, the ‘‘band’’ associated with a variation of ρ_s between -2 and $+2$. This band is rather narrow in Fig. 2a, referring to the ratio measurable with neutrino beams, while it is larger in Fig. 2b, referring to the $\bar{\nu}$ case: yet, in this last instance, room enough is left to appreciate different values of g_A^s. Concerning the sensitivity of the integrated ratio to the magnetic strange form factor, one can see that the ν case shows a perceptible slope with increasing μ_s, whereas the $\bar{\nu}$ case appears to be almost independent upon the value of μ_s: this fact favours the extraction of the electric strange form factor [4].

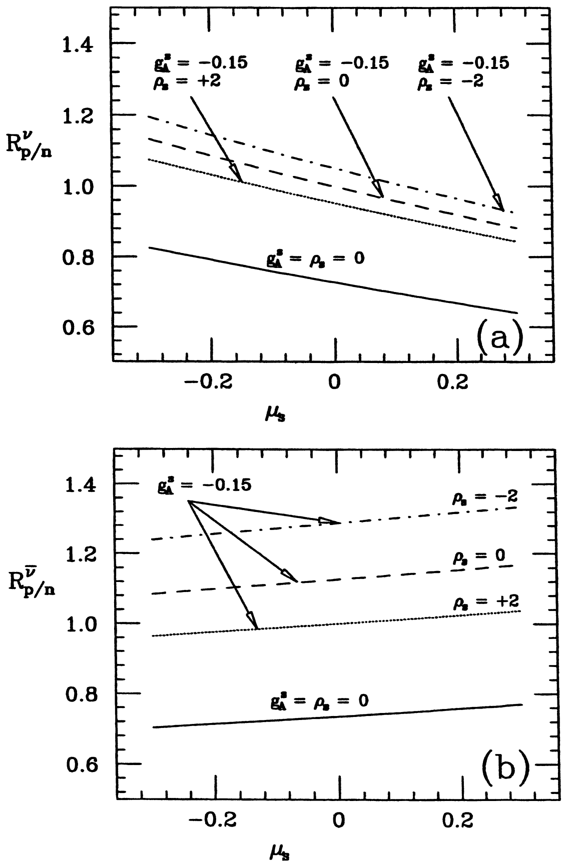

Fig. 2. The ratio $R^{\nu}_{p/n}$ (a) and $R^{\bar{\nu}}_{p/n}$ (b) of the integrated NC neutrino–nucleus cross sections, as a function of μ_s: all curves are evaluated in the RFG. The incident energy is $E_{\nu(\bar{\nu})} = 1$ GeV and the integration limits for the cross sections are $100 \leq T_p \equiv T_n \leq 400$ MeV. The solid line corresponds to $g_A^s = \rho_s = 0$, in the other three curves [both in (a) and in (b)] we have fixed $g_A^s = -0.15$ and chosen ρ_s to be: $\rho_s = 0$ (dashed line), $\rho_s = -2$ (dot–dashed line) and $\rho_s = +2$ (dotted line).

We also recall that the most recent data on the electromagnetic form factors have shown a signifi-

[3] The value $\rho_s = 2$ is compatible with the vector strange form factors employed in fit IV of Garvey et al. [15] in the analysis of $\nu(\bar{\nu})$–p cross sections.

[4] Fig. 2a shows that without strangeness $R^{\nu}_{p/n} \simeq 0.73$. Considering Ref. [8], only the dominant pure axial–vector contribution to the cross sections, one should expect this value to be 1. However, under the kinematical conditions considered here, also the pure vector and especially the vector/axial interference contributions can be important (the pure axial term contributes only about 60% to the νp and 45% to the νn cross sections), giving rise to the above deviation from 1.

cant deviation from the dipole behaviour at $Q^2 \geq 1$ GeV^2. We have investigated the sensitivity of the ratios $\mathscr{R}^{\nu(\bar{\nu})}_{p/n}$ to different parameterizations of the Sach's form factors [17,18], and found that the effect of different forms for G_E and G_M does not exceed $1 \div 2\%$. We have also investigated the sensitivity of the ratios considered here to the axial cutoff M_A. For neutrinos the effect is small (less than 3%) but for antineutrinos a $6 \div 7\%$ variation in M_A can induce an effect as large as $7 \div 8\%$ in $R^{\bar{\nu}}_{p/n}$.

In conclusion we have focussed our analysis on the interplay, in the ratio $\mathscr{R}^{\nu(\bar{\nu})}_{p/n}$, between axial, magnetic and electric strange form factors. The largest effect is associated with the axial strange form factor: the interplay between g_A^s and μ_s crucially depends on their relative sign and turns out to act in opposite ways on $\mathscr{R}^{\nu}_{p/n}$ and $\mathscr{R}^{\bar{\nu}}_{p/n}$. Moreover we have found a strong sensitivity of $\mathscr{R}^{\bar{\nu}}_{p/n}$ to the electric strange form factor. Thus, by assuming that PV electron scattering experiment will support a more precise (than the present one) determination of the magnetic strange form factor, the combined measurement of $\mathscr{R}^{\nu}_{p/n}$ and $\mathscr{R}^{\bar{\nu}}_{p/n}$ could allow a determination of all three strange form factors of the nucleon.

References

[1] D. Adams et al., Phys. Lett. B 329 (1994) 399.
[2] K. Abe et al., Phys. Rev. Lett. 74 (1995) 346.
[3] J. Ellis, M. Karliner, Phys. Lett. B 341 (1995) 397.
[4] B. Mueller et al., SAMPLE Collaboration, Phys. Rev. Lett. 78 (1997) 3824.
[5] W.M. Alberico, S.M. Bilenky, C. Giunti, C. Maieron, Z. für Physik C 70 (1996) 463.
[6] W.M. Alberico, M.B. Barbaro, S.M. Bilenky, J.A. Caballero, C. Giunti, C. Maieron, E. Moya de Guerra, J.M. Udias, Nucl. Phys. A 623 (1997) 471.
[7] G.T. Garvey, S. Krewald, E. Kolbe, K. Langanke, Phys. Lett. B 289 (1992) 249.
[8] G.T. Garvey, E. Kolbe, K. Langanke, S. Krewald, Phys. Rev. C 48 (1993) 1919.
[9] M.B. Barbaro, A. De Pace, T.W. Donnelly, A. Molinari, M.J. Musolf, Phys. Rev. C 54 (1996) 1954.
[10] E. Church et al., nucl-ex/9706011.
[11] J.M. Udías, P. Sarriguren, E. Moya de Guerra, J.A. Caballero, Phys. Rev. C 53 (1996) R1488; C 48 (1993) 2731.
[12] E. Kolbe, S. Krewald, H. Weigel, Z. für Physik A 358 (1997) 445.
[13] See for example H. Forkel et al., Phys. Rev. C 50 (1994) 3108; H.C. Kim, T. Watabe, K. Goeke, Nucl. Phys. A 616 (1997) 606; M. Kirchbach, D. Arenhövel, in Juelich 1994, in: Proceedings, Physics with GeV−particle beams, p. 414, hep-ph/9409293.
[14] M.J. Musolf, B.R. Holstein, Phys. Lett. B 242 (1990) 461.
[15] G.T. Garvey, W.C. Louis, D.H. White, Phys. Rev. C 48 (1993) 761.
[16] T.W. Donnelly, M.J. Musolf, W.M. Alberico, M.B. Barbaro, A. De Pace, A. Molinari, Nucl. Phys. A 541 (1992) 525.
[17] K. Watanabe, H. Takahashi, Phys. Rev. D 51 (1995) 1423.
[18] P.E. Bosted, Phys. Rev. C 51 (1995) 509.