Eur. Phys. J. A **3**, 389–396 (1998)

THE EUROPEAN PHYSICAL JOURNAL A

The role of strange sea quarks on neutrino-nucleus reactions in Superkamiokande and in the supernova r-process

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Received: 30 April 1998 / Revised version: 10 August 1998
Communicated by W. Weise

Abstract. We study the influence of a strange axial vector form factor G_s of the nucleon on the neutrino-induced proton and neutron knockout of ^{16}O. In particular, we calculate how much $G_s \neq 0$ might affect the recently proposed signal for supernova ν_μ and ν_τ neutrinos in the Superkamiokande detector. We discuss whether Superkamiokande might be able to determine the value of G_s in a hypothetical neutrino-beam experiment. Finally we comment on the possible effect $G_s \neq 0$ might have on neutrino-nucleus cross sections in the neutrino-driven wind model for the nuclear r-process.

PACS. 25.30.Pt Neutrino scattering

1 Introduction

In the generally accepted picture the nucleus is built of three valence quarks merged in a sea of quark-antiquark pairs. In particular the role played by strangeness carrying quarks has attracted significant experimental and theoretical attention in the last years [1,2]. While the net strangeness content of the nucleon is zero, the sea of strange quarks can manifest itself in additional components to the conventional vector and axial vector form factors. For example, the axial vector form factor then consists of the well known isovector component, $G_A(Q^2)$, which is responsible for the neutron decay, and an additional isoscalar component $G_s(Q^2)$ introduced by the strange quarks [1,3]; as usual Q^2 defines the momentum transfer to the nucleon. We note that, due to its isoscalar character, G_s only plays a role in processes mediated by the coupling of a Z^0 boson to the nucleon, and therefore charge current reactions are independent of G_s.

Theoretical models place G_s in the range $[-0.2, +0.2]$ [2], and also direct experimental evidence on G_s is rather uncertain so far. The EMC result on the proton spin structure function can be interpreted as implying $G_s = -0.19 \pm 0.08$ [4]. Furthermore, it has been claimed that an AGS neutrino-proton scattering experiment yields $G_s = -0.15 \pm 0.08$ [5]; however, this evidence has been disputed [6].

In [7,8] it has been shown that the ratio R of proton-to-neutron yield in quasielastic scattering of neutrinos from an isoscalar nucleus like ^{12}C is rather sensitive to an (strange quark induced) isoscalar axial vector form factor of the nucleon. Within a Continuum random phase approximation (CRPA) calculation it was found that R depends roughly linearly on $G_s(0)$ (see Fig. 5 of [8]) and is virtually independent of final state interactions and nuclear structure effects. This influence of the strange sea quarks in the nucleon on the ratio R may be illustrated by the following rule of thumb like formula, which is simply obtained by considering axial vector dominance and neglecting final state interactions in neutrino-nucleus scattering:

$$
\begin{aligned}
R = \frac{\sigma(\nu,\nu'p)}{\sigma(\nu,\nu'n)} &\approx \frac{(G_1^p)^2}{(G_1^n)^2} \\
&= \frac{|G_A(0) - G_s(0)|^2}{|G_A(0) + G_s(0)|^2} \approx 1 + 4\frac{G_s(0)}{G_A(0)} \quad . \qquad (1)
\end{aligned}
$$

A positive value for G_s/G_A, like indicated by the EMC experiment, results in constructive (destructive) interference in proton (neutron) knock-out. As an additional bonus, the ratio is independent of the neutrino-flux normalization. Deriving $G_s(0)$ from the measured proton-to-neutron yield in quasielastic neutrino scattering on ^{12}C has been the intention of an experiment performed at LAMPF [9]. We note that, in first order, the presence of a strange form factor $G_s \neq 0$ redistributes the strength between the proton and neutron partial knockout cross sections, but does not change the total cross section $\sigma(\nu,\nu') = \sigma(\nu,\nu'p) + \sigma(\nu,\nu'n)$.

In this paper we want to discuss how $G_s \neq 0$ might affect the cross section for a recently proposed scheme [10] to observe supernova ν_μ, ν_τ neutrinos in water Čerenkov detectors like Superkamiokande. Using the same line of reasoning we will then speculate how, in principle, G_s can also be measured by these detectors. Our discussion is based on the following observation scheme for supernova ν_μ and ν_τ neutrinos [10]. These neutrinos scatter inelastically off ^{16}O in water, basically exciting the giant dipole resonance in ^{16}O at around 20-25 MeV excitation energy. Subsequently the nucleus deexcites by proton or neutron emission with an important branch through particle-bound states in ^{15}N and ^{15}O, respectively. These states decay by γ emissions to the respective ground states. As all excited states in both $A = 15$ nuclei are above the detection threshold of Superkamiokande ($E_{thresh} = 5$ MeV), these γ-decays can be detected. With the same reasoning as above, the presence of an isoscalar component to the axial vector form factor will increase the partial cross section for proton decay, $\sigma(\nu, \nu' p)$, while it will decrease the one for neutron decay, $\sigma(\nu, \nu' n)$. For the following discussion it is important to note that the particle threshold in ^{15}N is at 10.2 MeV, while it is at 7.3 MeV in ^{15}O (see Fig. 1 of [10]). This asymmetry implies that the sum $\sigma(\nu, \nu' p) + \sigma(\nu, \nu' n)$ depends on G_s and that there is a region of γ energies ($E_\gamma > 7.3$ MeV) which uniquely arise from the proton decay route. Adopting a two-step model similar as in [10] – the Continuum random phase approximation to describe the inelastic neutrino scattering processes (^{16}O$(\nu, \nu' p)$, ^{16}O$(\nu, \nu' n)$) and the statistical model to calculate the decay cascades of the excited levels – we will indeed confirm these expectations in Sect. 3. However, first we will briefly describe the model and notations we have used in our study (Sect. 2).

2 Brief description of the CRPA and the form factors of the nucleon

The cross section for neutrino and antineutrino scattering of a target nucleus has been derived in [11]. The result is:

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{G_F^2 \epsilon_f^2}{2\pi^2} \frac{4\pi \cos^2 \frac{\theta}{2}}{(2J_i + 1)} \times \left[\sum_{J=0}^{\infty} \sigma_{CL}^J + \sum_{J=1}^{\infty} \sigma_T^J \right] . \quad (2)$$

The partial cross section σ_{CL}^J is defined as ($\kappa = |\boldsymbol{q}|$)

$$\sigma_{CL}^J = \left| \langle J_f \| \tilde{M}_J(\kappa) + \frac{\omega}{|\boldsymbol{q}|} \tilde{L}_J(\kappa) \| J_i \rangle \right|^2 , \quad (3)$$

where $\tilde{M}_J$ and $\tilde{L}_J$ denote the multipole operators for the longitudinal (relative to q) parts of the vector and axial vector four-currents. Similarly, for the transverse cross section one finds

$$\begin{aligned} \sigma_T^J = &\left(+ \frac{Q^2}{2q^2} + \tan^2 \frac{\theta}{2} \right) \times \\ &\left\{ \left| \langle J_f \| \tilde{J}_J^{\mathrm{mag}}(\kappa) \| J_i \rangle \right|^2 + \left| \langle J_f \| \tilde{J}_J^{\mathrm{el}}(\kappa) \| J_i \rangle \right|^2 \right\} \\ &\mp \tan \frac{\theta}{2} \sqrt{\tan^2 \frac{\theta}{2} + \frac{Q^2}{q^2}} \times \\ &2\mathrm{Re} \left(\langle J_f \| \tilde{J}_J^{\mathrm{mag}}(\kappa) \| J_i \rangle \langle J_f \| \tilde{J}_J^{\mathrm{el}}(\kappa) \| J_i \rangle^* \right) . \quad (4) \end{aligned}$$

Here, $\tilde{J}_J^{\mathrm{mag}}$ and $\tilde{J}_J^{\mathrm{el}}$ are the magnetic and electric multipole operators, respectively, containing both vector and axial vector pieces. In (4), the minus sign (plus sign) refers to the neutrino (antineutrino) cross section. Following [11], the various multipole operators introduced in (3,4) are expressed in terms of one-body operators in the nuclear many-body Hilbert space. The evaluation of the cross section then requires the calculation of the reduced matrix elements of these operators between the discrete initial many-body state $|J_i\rangle$ and a final continuum state $|J_f\rangle$ for a fixed energy ω. Noting that inelastic neutrino scattering is predominantly a one-particle-one-hole excitation we adopt the continuum random phase approximation (CRPA) for the description of the initial and final states. For the residual interaction we use the finite-range G-matrix from [12] which has been shown to properly account for charge-exchange effects in the final states [13]. We note that we use the experimental values for the hole energies thus ensuring the exact reproduction of the proton and neutron thresholds in ^{16}O. The CRPA formalism as used in the present study has already been successfully employed in previous studies of electroweak reactions on ^{16}O and other target nuclei [14–16].

The momentum transferred to the nucleus depends on the scattering angle θ of the neutrino and is given by

$$q = |\boldsymbol{q}| = \sqrt{\omega^2 + 4\epsilon_i(\epsilon_i - \omega) \sin^2 \frac{\theta}{2}} . \quad (5)$$

The four-momentum transfer to the nucleus is Q, with $Q^2 = q^2 - \omega^2$. We assume a quasielastic process; i.e., the neutrino interacts only with one nucleon, while the others are viewed as spectators. In this approximation, the momentum transfer 5 is to the struck nucleon.

As usual, the coupling of the nucleon's weak currents to the Z^0 boson is described by form factors. We follow the convention of [8] and thus have for the charge ($j = 1$) and magnetic ($j = 2$) form factors of the proton (p) and neutron (n)

$$\begin{aligned} F_j^z(Q^2) \equiv &\left(\frac{1}{2} - \sin^2 \theta_W \right) \left(F_j^p(Q^2) - F_j^n(Q^2) \right) \tau_3 \\ &- \sin^2 \theta_W \left(F_j^p(Q^2) + F_j^n(Q^2) \right) \\ &- \frac{1}{2} F_j^s(Q^2). \quad (6) \end{aligned}$$

θ_W is the weak mixing angle and F_j^s denote the strange components of the charge and magnetic form factors. As the net strangeness of the nucleon is zero and the reactions we will study involve relatively small values of the momentum transfer Q^2, we set $F_1^s(Q^2) = 0$. The determination of F_2^s is the goal of the SAMPLE experiment at Bates [17]. First results have been reported in [18] ($F_2^s(Q^2 = 0.1$ GeV^2) $= +0.23 \pm 0.37 \pm 0.15 \pm 0.19$ where we have assumed $F_1^s = 0$ to convert the Sachs form factor G_M^s given in [18] into F_2^s), but the large uncertainty clearly restricts the use of this result in the present context. We will explore the potential sensitivity of our results on F_2^s by treating it as a parameter. Finally, the axial vector form factor is given by

$$G_1^z(Q^2) \equiv \frac{-G_A(Q^2)}{2}\tau_3 + \frac{G_s(Q^2)}{2} \; , \qquad (7)$$

The value of $G_A(Q^2=0)$ is known from neutron decay ($G_A(0) = -1.26 \pm 0.004$). The strange contribution G_s will be treated as a parameter in the following. Our adopted form factor values at $Q^2 = 0$ for the proton and neutron are listed in Table 1 of [8]. For the Q^2 dependence we use the standard dipole form with the mass parameters $M = 0.843$ GeV/c^2 and 1.092 GeV/c^2 for the vector and axial vector form factors, respectively. We assume that the strange contributions to the vector and axial vector form factors have the same Q^2 dependence as the respective well known pieces.

This finishes our description of the ^{16}O$(\nu,\nu' N)$ reactions. In the second step we calculate for each of these excited states with well-defined energy, angular momentum, and parity the branching ratios within the proton and neutron decay channels using the statistical model code SMOKER [19]. As possible final states in the residual nucleus the SMOKER code considers the experimentally known levels supplemented at higher energies by an appropriate level density formula [19]. As decay channels the code generally includes proton, neutron, α and γ emission. If the decay leads to an excited level of the residual nucleus (e.g. to p+$^{15}N^*$), we calculate the branching ratios for the decay of this state in an analogous fashion. Keeping track of the energies of the ejected particles and photons during the cascade, and weighting them with appropriate branching ratios and the corresponding ^{16}O$(\nu,\nu' N)$ cross section, we determine the various particle and photon spectra.

3 Results and Discussion

The ability to observe neutral current induced events in water Čerenkov detectors like Superkamiokande via the scheme sketched in Fig. 1 of [10] depends on the neutrino energy in two competing ways:

1. The inelastic neutrino cross section increases with increasing neutrino energy.
2. The average excitation energy of the ^{16}O nucleus increases with increasing neutrino energy. Thus, for too high neutrino energies the decay of the excited levels will predominantly lead to continuum states in ^{15}N and ^{15}O which in turn will then decay by particle emission rather than γ emission. Thus, these events will not be detected by Superkamiokande as the emitted particles are non-relativistic.

Figure 1 explores the relative importance of these two competing effects. The upper panel confirms the well-known fact that the total ^{16}O(ν,ν') cross section increases with neutrino energy E_ν. We note that, at the higher energies, partial waves higher than those considered in the present calculation ($J \le 9$) will further increase the total cross section. The lower panel of Fig. 1 shows the probability for the total cross section to decay via γ emission, defined as $\bar{\sigma}(\nu,\nu'\gamma) = (\sigma(\nu,\nu' p\gamma) + \sigma(\nu,\nu' n\gamma))/\sigma(\nu,\nu')$ as well as the two individual contribution through the proton and neutron channels. At low E_ν, $\bar{\sigma}(\nu,\nu'\gamma)$ increases as excited states in ^{16}O with a large probability to decay to particle-bound excited states in ^{15}O and ^{15}N are increasingly populated (mainly the giant dipole resonance whose branching to the $J^\pi = (3/2)^-$ states in ^{15}N ($E^* = 6.13$ MeV) and ^{15}O ($E^* = 6.1$ MeV) is known to be large from photodissociation experiments [20]). However, at $E_\nu \approx 75$ MeV a maximum is reached as for larger neutrino energies the decay to particle-unbound final states becomes more important. Note that, due to the reduction of phase space for decay to particle-bound states in the daughter nuclei, the detection scheme for neutral current events, as proposed in [10], is probably not a viable tool for high-energy neutrinos as they will be available at the KEK facility ($E_\nu \approx 1$ GeV).

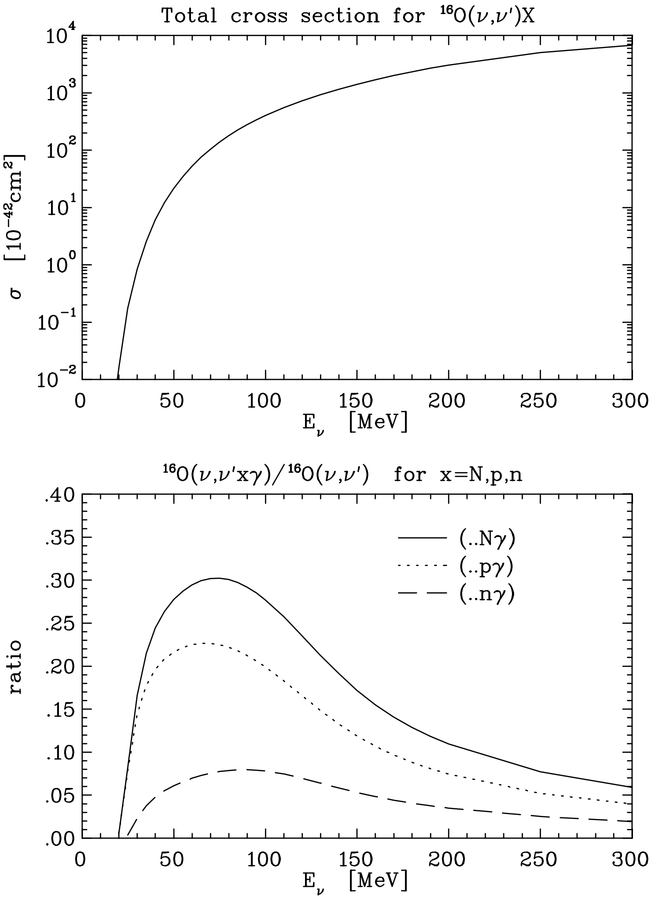

Fig. 1. Upper part: total ^{16}O(ν,ν')X cross section as a function of the neutrino energy E_ν; lower part: probability for γ emission induced by a ^{16}O(ν,ν')X reaction

Let's come back to the theme of this paper. How are the cross sections changed by a potential strange contribution to the nucleon form factors? At first we will set $F_2^s = 0$, which appears to be justified by the SAMPLE result [18]; its effect on the cross sections will be studied below. For the strange component to the axial vector form factor we use $G_s(0) = -0.19$ (the central value of [4]) and $G_s(0) = -0.3$. Supporting our heuristic discussion given

Table 1. Total and partial cross sections in units of 10^{-42}cm^2 and in percent of the total for a typical supernova neutrino spectrum (T=8 MeV) and averaged over neutrinos and antineutrinos ($\tilde{\nu} := (\nu + \overline{\nu})/2$). Superkamiokande is sensitive to the summed cross section ^{16}O$(\nu,\nu' N\gamma)$=^{16}O$(\nu,\nu' p\gamma)$ + ^{16}O$(\nu,\nu' n\gamma)$

reaction	σ_{tot}	%	σ_{tot}	%	σ_{tot}	%
$G_s(0)$	–0.00		–0.19		–0.30	
^{16}O$(\tilde{\nu},\tilde{\nu}')$X	5.19	100.0	5.41	100.0	5.67	100.0
^{16}O$(\tilde{\nu},\tilde{\nu}' N\gamma)$	1.55	29.9	1.63	30.1	1.72	30.3
^{16}O$(\tilde{\nu},\tilde{\nu}' p\gamma)^{15}$N	1.17	22.5	1.32	24.4	1.43	25.2
^{16}O$(\tilde{\nu},\tilde{\nu}' n\gamma)^{15}$O	0.38	7.3	0.31	5.7	0.29	5.1

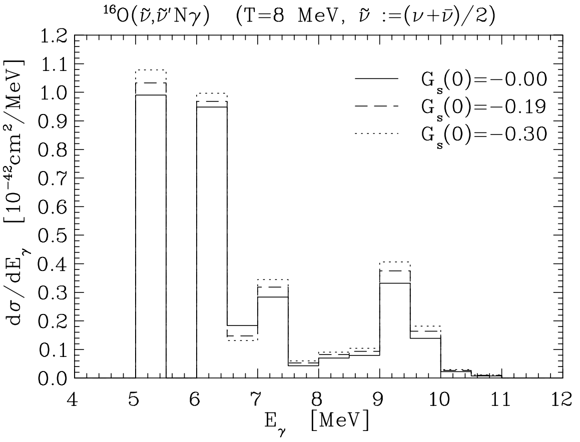

Fig. 2. Sum of partial ^{16}O$(\nu,\nu' p\gamma)$ and ^{16}O$(\nu,\nu' n\gamma)$ cross sections for a typical supernova neutrino spectrum. The cross sections are averaged over neutrinos and antineutrinos

above, for $G_s \neq 0$ the ^{16}O$(\nu,\nu' p\gamma)$ cross section increases due to the constructive interference of the two components in the axial vector form factor, while the ^{16}O$(\nu,\nu' n\gamma)$ cross section decreases. Obviously the cross section ratio ^{16}O$(\nu,\nu' p\gamma)$/^{16}O$(\nu,\nu' n\gamma)$ were a useful quantity to test whether $G_s \neq 0$ (similar to the LSND experiment). Unfortunately the Superkamiokande detector cannot observe protons and neutrons directly nor does its resolution allow to determine the origin of the emitted photons and thus Superkamiokande has currently no ability to distinguish between $(\nu,\nu' p\gamma)$ and $(\nu,\nu' n\gamma)$ events. As a consequence the main sensitivity to the strange axial vector component is lost as Superkamiokande only observes the sum spectrum in which the increase in the proton channel and the decrease in the neutron channel for $G_s \neq 0$ partially cancel.

While this cancellation is bad, if one discusses Superkamiokande as a tool to determine G_s, it is an advantage for the observation of ν_τ and ν_μ supernova neutrinos. Provided supernova ν_μ and ν_τ neutrinos are detected by Superkamiokande, one would like to derive some statements about the neutrino distributions from the observed signals. To see the possible effects of G_s on the detection cross section for supernova ν_μ and ν_τ neutrinos and their antiparticles, we have calculated the partial ^{16}O$(\nu,\nu' p\gamma)$ and ^{16}O$(\nu,\nu' n\gamma)$ cross sections for a typical supernova neutrino spectrum [21] (Fermi-Dirac (FD) distribution with temperature $T = 8$ MeV and chemical potential $\mu = 0$). The results are listed in Table 1 and shown in Fig. 2. If $G_s = -0.19$ the total cross section is increased from 5.2 to 5.4; relatedly the number of events observed by Superkamiokande will also increase by 4%. We note that the sensitivity on F_2^s in the event rate is cancelled due to the opposite sign of the vector-axial vector interference term for neutrinos and antineutrinos; these are expected to have the same distributions for supernova ν_μ and ν_τ neutrinos.

In Table 1/Fig. 2 we have seen that the total ^{16}O$(\nu,\nu N\gamma)$ cross section, despite strong cancellations between the proton and neutron channels, increases slightly if $G_s \neq 0$. This is due to the asymmetry of the proton and neutron thresholds in ^{15,16}O and ^{15}N which favors the $(\nu,\nu' p\gamma)$ over the $(\nu,\nu' n\gamma)$ cross sections. This slight increase in the sum spectrum due to $G_s \neq 0$ is however not a viable scheme to determine G_s. However, we note that Superkamiokande has the ability to resolve the γ spectrum (with a resolution of order 1 MeV). Thus, it can, at least in principle, decide whether the γ event has an energy above $E_\gamma = 7.3$ MeV, the particle threshold in ^{15}O. If so, the γ emission follows a proton decay of an excited state in ^{16}O and, due to our discussion from above, this cross section will be increased if $G_s < 0$. Our expectations are confirmed in Fig. 3, where we have calculated the partial ^{16}O$(\nu,\nu' p\gamma)$ and ^{16}O $(\nu,\nu' n\gamma)$ cross sections (upper and lower part, respectively) for the "optimal" neutrino energy $E_\nu = 75$ MeV (see Fig. 1). We find that the ^{16}O$(\nu,\nu' p\gamma)$ cross section for $E_\gamma > 7.3$ MeV is increased from $9.5 \cdot 10^{-42}$ cm^2 for $G_s = 0$ to $11.1 \cdot 10^{-42}$ cm^2 for $G_s = -0.19$; cross sections for other values of G_s can be obtained by linear interpolation.

As mentioned above the KEK neutrino beam has too high neutrino energies for investigating G_s. We therefore hypothetically assume that an experiment can be performed with a neutrino beam with a pion-decay-at-rest (DAR) spectrum, like the ν_e, $\overline{\nu}_\mu$ beam available in the KARMEN experiment [23], or a pion-decay-in-flight (DIF) spectrum, like the ν_μ beam in the LSND experiments [9]. The results for the partial $(\nu,\nu' p\gamma)$ and $(\nu,\nu' n\gamma)$ cross sections are summarized in Table 2 and 3 and are plotted in Fig. 4. Thus $G_s = -0.19$ ($G_s = -0.3$) would increase the $(\nu,\nu' p\gamma)$ cross sections with $E_\gamma > 7.3$ MeV by about 12% (21%) for the DAR and 17% (29%) for the DIF distribu-

Table 2. Total and partial cross sections in units of 10^{-42}cm^2 and in percent of the total for the KARMEN-DAR-spectrum ($\tilde{\nu} := \overline{\nu}_\mu + \nu_e$). The notation is the same as in Table I

reaction	σ_{tot}	%	σ_{tot}	%	σ_{tot}	%
$G_s(0)$	–0.00		–0.19		–0.30	
^{16}O$(\tilde{\nu},\tilde{\nu}')$X	11.75	100.0	12.33	100.0	12.98	100.0
^{16}O$(\tilde{\nu},\tilde{\nu}' N\gamma)$	3.09	26.3	3.35	26.4	3.40	26.2
^{16}O$(\tilde{\nu},\tilde{\nu}' p\gamma)^{15}$N	2.47	21.0	2.72	22.1	2.91	22.4
^{16}O$(\tilde{\nu},\tilde{\nu}' n\gamma)^{15}$O	0.62	5.3	0.53	4.3	0.49	3.8

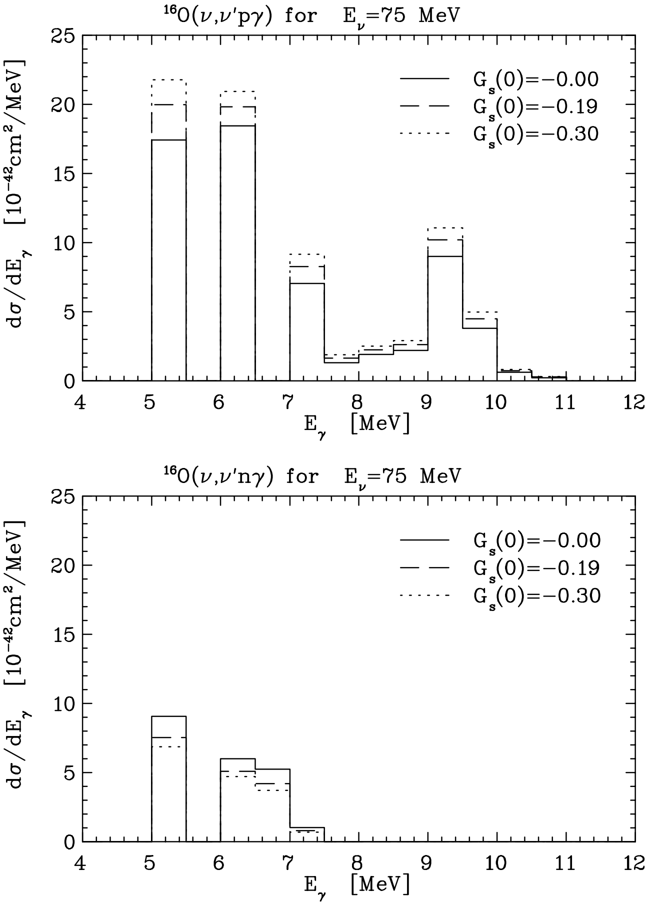

Fig. 3. Upper part: partial $^{16}\mathrm{O}(\nu,\nu' p\gamma)$ cross section for a neutrino energy of $E_\nu = 75$ MeV; lower part: the same for the $^{16}\mathrm{O}(\nu,\nu' n\gamma)$ reaction

Table 3. Total and partial cross sections in units of $10^{-42}\mathrm{cm}^2$ and in percent of the total for the LSND-DIF-spectrum. The notation is the same as in Table I

reaction	σ_{tot}	%	σ_{tot}	%	σ_{tot}	%
$G_s(0)$	−0.00		−0.19		−0.30	
$^{16}\mathrm{O}(\nu_\mu,\nu'_\mu)\mathrm{X}$	739	100.0	750	100.0	770	100.0
$^{16}\mathrm{O}(\nu_\mu,\nu'_\mu N\gamma)$	128	17.3	133	17.7	140	18.2
$^{16}\mathrm{O}(\nu_\mu,\nu'_\mu p\gamma)^{15}\mathrm{N}$	88	11.9	100	13.3	110	14.3
$^{16}\mathrm{O}(\nu_\mu,\nu'_\mu n\gamma)^{15}\mathrm{O}$	40	5.5	33	4.4	30	3.9

tions. However, the absolute values are significantly different for the two distributions. Due to the higher neutrino energies we find $^{16}\mathrm{O}(\nu,\nu' p\gamma; E_\gamma > 7.3\ \mathrm{MeV}) = 32.9\cdot 10^{-42}$ cm^2 for the DIF spectrum and only $0.62\cdot 10^{-42}$ cm^2 for the DAR spectrum.

In Fig. 5 we test the sensitivity of our results on F_2^s. We find that the cross sections are only slightly effected, if F_2^s is indeed as small as indicated by SAMPLE [18]. Furthermore we checked to what extent the $(\nu,\nu' p\gamma)$ and $(\nu,\nu' n\gamma)$ cross sections are affected by our assumption that the strange contributions to the vector and axial vector form factors have the same Q^2 dependence as the respective well known counterparts. For that purpose G_s was fixed at a constant value $G_s(Q^2) \equiv -0.3$, while the standard dipole form for $G_A(Q^2)$ was kept. The resulting cross sections are given by the short-dashed curve in Fig. 5 and, by comparison to the dotted lines, show that the assumed Q^2 dependence of G_s has a much smaller effect than the uncertainties caused by the rather unknown value for F_2^s. This is explained by the fact that the momentum transfer involved in the $^{16}\mathrm{O}(\nu,\nu' N\gamma)$ reactions is mainly low for the moderate neutrino energies considered here. Therefore a dipole form for $G_s(Q^2)$ does not significantly deviate from fixing $G_s(Q^2)$ at the constant value $G_s(Q^2=0)$.

One word about possible background in our hypothetical DAR and DIF experiments at Superkamiokande. The main source for backgrounds are charged-current events (which are insensitive to G_s) and neutrino-electron scattering. The major background source for the detection of supernova ν_μ and ν_τ neutrinos are $\bar{\nu}_e + p \rightarrow n + e^-$ events [22]. Fortunately $\bar{\nu}_e$'s are absent in the DAR and DIF spectra (which allows KARMEN and LSND to search for neutrino oscillations). The ν_μ induced charged current events do not produce a signal in the relevant energy window 5-10 MeV which can be detected by Superkamiokande as for DIF energies the produced muon is non-relativistic and all states in $^{16}\mathrm{F}$ are particle-unbound. For the DIF source, the ν_e spectrum has only $E_\nu < 52$ MeV (as the muon decays at rest) and ν_e induced charged current events with a relativistic electron in the final state are suppressed by about 2 orders of magnitude compared to the ν_μ induced cross sections. For the DAR spectrum, however, the ν_e induced cross sections are compatible in magnitude and will give a smooth background. This background (an additional smooth background will also arise from inelastic neutrino-electron scattering) and the very small cross sections makes a DAR spectrum neutrino beam useless for our hypothetical experiment.

Finally we like to touch on a topic which is only loosely connected to the previous discussion. It has recently been pointed out that neutrino-nucleus reactions might play an important role within the r-process nucleosynthesis, if the site of the r-process is in fact the hot-neutrino bubble above the newly born neutron star in a supernova explosion [24]. In particular, the strong neutrino flux can lead to postprocessing of the r-process matter distribution after freeze-out [25,26]. In this postprocessing neutrino-induced charged and neutral current reactions will excite the very neutron-rich nuclei into the continuum which then will subsequently decay by neutron emission. As after freeze-out the neutron density is not high enough to reassure recapture of neutrons, neutrino-induced spallation affects the r-process abundance distribution, most noticeably at and below the peaks ($A \approx 130$ and 195) associated with the magic neutron numbers $N = 82$ and 126. Following the general picture derived above, $G_s < 0$ will decrease the relevant neutral current cross sections as the particle decay mode for the neutron-rich r-process matter is neutron emission. To estimate these effects, we have calculated the cross section for ν-induced neutron spallation of $^{130}\mathrm{Cd}$ which is a typical progenitor nucleus in the $A = 130$ peak.

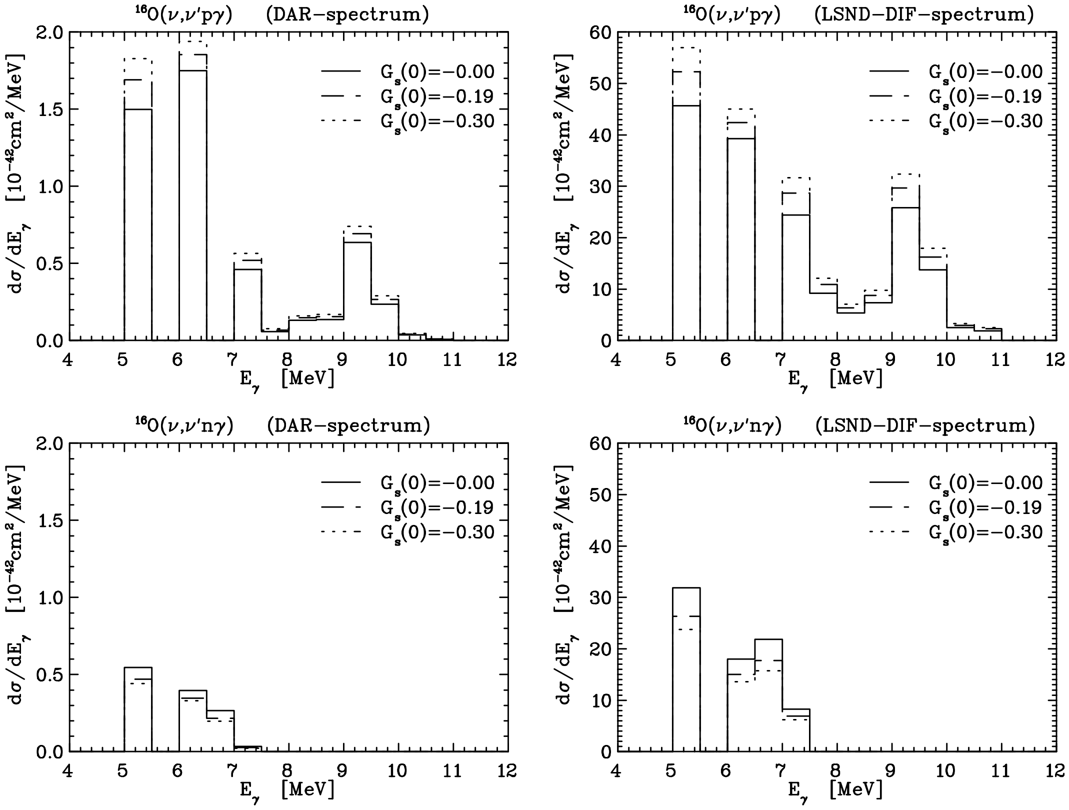

Fig. 4. Sensitivity of the partial ^{16}O$(\nu, \nu' p\gamma)$ (upper parts) and ^{16}O$(\nu, \nu' n\gamma)$ (lower parts) cross sections on the strange quark axial form factor $G_s(0)$ for neutrino spectra from pion-decay-at-rest and pion-decay-in-flight

Table 4. Total cross sections for the ^{130}Cd$(\nu, \nu' n)$ reaction as a function of the strange quark axial form factor $G_s(0)$. The cross sections are given per nucleon in units of 10^{-42}cm^2 and are averaged over neutrinos and antineutrinos

$G_s(0)$	σ_{tot}	%
–0.00	0.92	100
–0.19	0.75	81
–0.30	0.67	73

Again, we assumed a FD neutrino distribution with $T = 8$ MeV and $\mu = 0$ for ν_μ and ν_τ neutrinos and their antiparticles. The cross sections are given in Table 4. In fact, a value $G_s = -0.19$ ($G_s = -0.3$) reduces the ^{130}Cd$(\nu, \nu' n)$ cross section by 19% (27%) compared with the case for $G_s = 0$. Our total cross sections are slightly different than the one quoted in [26] due to differences in the single particle energies in the CRPA calculation. We stress that the ν_e-induced charged current reactions, which are independent of G_s are believed to be more important for the post-processing [26].

4 Summary

Recent research [2] suggests that the sea of strange $s\bar{s}$ quarks gives rise to additional form factors of the nucleon. The strange component of the axial vector form factor, G_s, is an isoscalar, and thus its interference with the conventional isovector form factor, G_A, would give rise to opposite effects in the neutrino-induced proton and neutron spallation off $T = 0$ nuclei. This effect had already been pointed out in [7,8].

Here we study the effect of G_s on the neutrino-induced neutral-current reactions on ^{16}O. The ^{16}O$(\nu, \nu' p)^{15}$N* and ^{16}O$(\nu, \nu' n)^{15}$O* reactions to particle-bound excited levels in the daughter nuclei have recently been suggested [10] as a possible detection scheme for supernova ν_μ and ν_τ neutrinos in Superkamiokande, which might observe the γ's of the decays in ^{15}N and ^{15}O. If $G_s < 0$, as suggested by recent experiments [4,5], this will increase the ^{16}O$(\nu, \nu' p)^{15}$N* cross sections due to constructive interference of the two components in the axial vector form factor, while it decreases the ^{16}O$(\nu, \nu' n)^{15}$O* cross sections (here the two components interfere destructively). As Superkamiokande will only observe the sum spectrum of the two channels, the effect of G_s is largely cancelled. The remaining sensitivity (of order a few percent increase in the total cross section) is caused by the asymmetry between the proton- and neutron-thresholds in ^{15}O and ^{15}N, and in ^{16}O. This asymmetry favors the proton decay channels and consequently the event rate for supernova ν_μ and ν_τ neutrinos in Superkamiokande (which is proportional to the sum of proton and neutron decay channels) goes slightly up if $G_s < 0$. We note that the dependence of

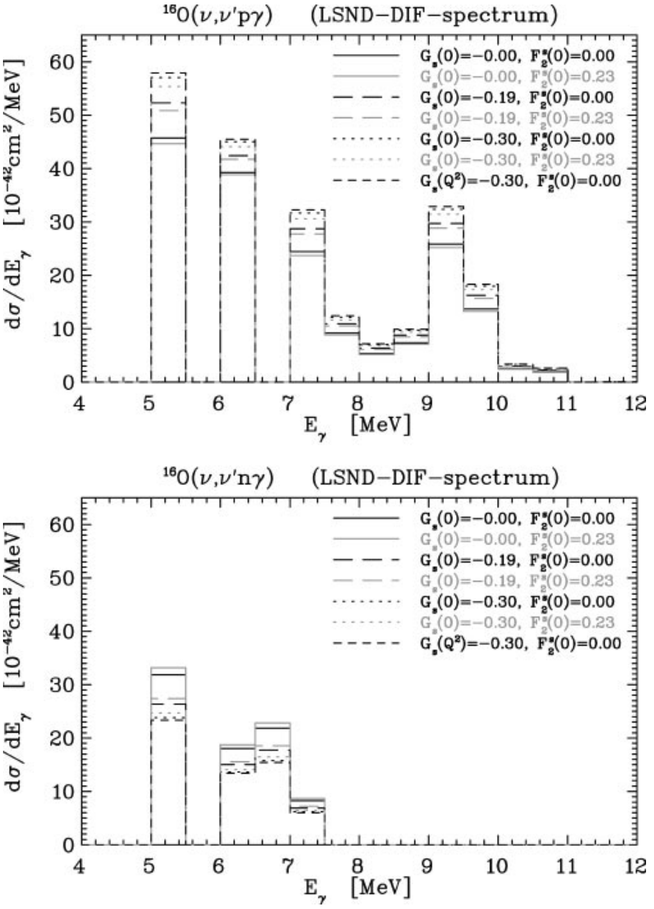

Fig. 5. Sensitivity of the partial ^{16}O$(\nu,\nu'p\gamma)$ (upper parts) and ^{16}O$(\nu,\nu'n\gamma)$ (lower parts) cross sections on the strange magnetic form factor F_2^s and on the assumed Q^2 dependence of G_s for the LSND-decay-in-flight neutrino spectrum

the event rate on the strange vector form factor F_2^s is cancelled, as supernova models predict the same distributions and amounts for ν_μ and ν_τ neutrinos and their antiparticles.

As the detection rate for neutrinos via the scheme of [10] depends, at least slightly, on G_s, Superkamiokande could in principle been used to determine the strange axial vector form factor. As the particle threshold in ^{15}O is at 7.3 MeV, γ-rays in the energy window $E_\gamma = 7.3 - 10.2$ MeV follow a proton-decay of excited states in ^{16}O. Due to the constructive interference of the two components in the axial vector form factor, the cross section for this range of γ rays increases if $G_s < 0$. In first order this increase is linear in G_s. If G_s is as large as indicated by the EMC experiment, this corresponds to a rise of about 20%. Of course, the determination of G_s from a measurement of the ^{16}O$(\nu,\nu'p\gamma; E_\gamma > 7.3\text{MeV})$ cross sections requires a rather precise knowledge of the nuclear structure involved. The precision offered by the current CRPA approach surely does not suffice. However, up-to-date large-scale shell model calculations might be capable of handling this challenge, in particular if the experimental cross sections could be binned into various ranges for E_γ.

Of course, the determination of G_s by Superkamiokande requires the availability of a neutrino beam. The detection of supernova neutrinos - even if we are fortunate enough to observe neutrinos from a nearby supernova - is not useful as the neutrino spectrum is not sufficiently well known. On the contrary, the detection of the neutrinos will be used to learn something about the spectrum. From phase space considerations one might conclude that a hypothetical experiment to determine G_s at Superkamiokande might want to use neutrinos in the energy range $E_\nu = 50 - 300$ MeV. This is too low for the beam in future available from KEK, but coincides roughly with the pion-in-flight-decay neutrino beam available at LSND. For completeness we have calculated the relevant cross sections for this neutrino distribution and confirmed the expected increase if $G_s < 0$.

Finally we have calculated the neutrino-induced neutron-spallation of ^{130}Cd which is a typical nucleus on the r-process path at the waiting point due to the magic neutron number $N = 82$. We find that the neutron spallation cross section is decreased if $G_s < 0$. For the EMC result for G_s the decrease is by roughly 20%. Such an effect would ultimatively have to be taken into account if the neutrino-driven wind model is indeed the site of the nuclear r-process. Currently, however, astrophysical and nuclear structure uncertainties in the simulation of the r-process are larger than those introduced by the uncertain knowledge of G_s.

References

1. R. L. Jaffe and A. Manohar, Nucl. Phys. **B337**, 509 (1990)
2. M.J. Musolf, T.W. Donnelly, J. Dubach, S.J. Pollock, S. Kowalski and E.J. Beise, Phys. Rep. **239**, 1 (1994)
3. E. J. Beise and R. D. McKeown, Comm. Nucl. Part. Phys. **20**, 105 (1991)
4. EMC Coll., J. Ashman *et al.*, Nucl. Phys. **B328**, 1 (1989)
5. L. A. Ahrens *et al.*, Phys. Rev. **D35**, 785 (1987)
6. G. T. Garvey, W. C. Louis, and D. H. White, Phys. Rev. C**48**, 761 (1993)
7. G. T. Garvey, S. Krewald, E. Kolbe, and K. Langanke, Phys. Lett. **B289**, 249 (1992)
8. G. Garvey, E. Kolbe, K. Langanke and S. Krewald, Phys. Rev. C**48**, 1919 (1993)
9. W. C. Louis (LSND Collab.), spokesman, LAMPF proposal 1173; M. Albert et al., Phys. Rev. C**51**, 1065 (1995)
10. K. Langanke, P. Vogel and E. Kolbe, Phys. Rev. Lett. **76**, 2629 (1996)
11. J. D. Walecka, in *Muon Physics*, eds. V. W. Hughes and C. S. Wu (Academic Press, New York, 1975) p. 113
12. K. Nakayama, S. Drożdż, S. Krewald, and J. Speth, Nucl. Phys. **470**, 573 (1987)
13. M. Buballa, S. Drożdż, S. Krewald, and A. Szczurek, Phys. Rev. **C44**, 810 (1991)
14. E. Kolbe, K. Langanke, S. Krewald, and F. K. Thielemann, Nucl. Phys. **A540**, 599 (1992)
15. E. Kolbe, K. Langanke and S. Krewald, Phys. Rev. C**49**, 1122 (1994)

16. E. Kolbe, K. Langanke and P.Vogel, Nucl. Phys. A**613**, 382 (1996)
17. R.D. McKeown, Phys. Lett. **B219** (1989) 140; D.H. Beck, Phys. Rev. **D39**, 3248 (1989)
18. B. Müller et al., Phys. Rev. Lett. **78**, 3824 (1997)
19. J.J. Cowan, F.-K. Thielemann and J.W. Truran, Phys. Rep. **208**, 599 (1991)
20. F. Ajzenberg-Selove, Nucl. Phys. A**523**, 1 (1991).
21. S.E. Woosley, D.H. Hartmann, R.D. Hoffman and W.C. Haxton, Astrophys. J. **356**, 272 (1990)
22. Y. Totsuka, Rep. Progr. Phys. **55**, 229 (1992)
23. G. Drexlin et. al., Karmen collaboration, Proc. of Neutrino Workshop, Heidelberg 1987, eds. B. Povh and V. Klapdor (Springer, Heidelberg, 1987) p. 147; Phys. Lett. B**267**, 321 (1991)
24. S.E. Woosley, J.R. Wilson, G.J. Mathews, R.D. Hoffman and B.S. Meyer, Astrophys. J. **433**, 229 (1994)
25. W.C. Haxton, K. Langanke, Y.-Z. Qian and P. Vogel, Phys. Rev. Lett. **78**, 2694 (1997)
26. Y.-Z. Qian, W.C. Haxton, K. Langanke and P. Vogel, Phys. Rev. C**55**, 1532 (1997)