Neutron knockout in neutral-current neutrino-oxygen interactions

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The ongoing and future searches for diffuse supernova neutrinos and sterile neutrinos carried out with large water-Cherenkov detectors require a precise determination of the backgrounds, especially those involving γ rays. Of great importance, in this context, is the process of neutron knockout through neutral-current (NC) scattering of atmospheric neutrinos on oxygen. Nuclear reinteractions of the produced neutron may in fact lead to the production of γ rays of energies high enough to mimic the processes of interest. In this Letter, we focus on the kinematical range suitable for simulations of atmospheric-neutrino interactions and provide the neutron-knockout cross sections computed using the formalism based on realistic nuclear spectral function. The role of the strange-quark contribution to the NC axial form factor is also analyzed. Based on the available experimental information, we give an estimate of the associated uncertainty.

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The detection of the antineutrino burst from the 1987A core-collapse supernova in the Large Magellanic Cloud by three independent experiments [1-3] marked the dawn of a new era in observational astronomy. That measurement, totaling 24 events, was feasible owing to not-too far distance from the collapsing star and to the extreme nature of supernova explosions. While the gravitational energy released in the act of collapse is $\sim$200–300 times higher than that produced by the Sun over its entire lifetime, $\sim$99% of it is radiated over a timescale of a few tens of seconds in the form of immense flux of low-energy neutrinos [4].

Supernovae have long been recognized as unique laboratories to study a number of fundamental physics issues [2]. The scarcity of the available data seems, however, to be an insuperable problem, because the frequency of the core-collapse events within our Galaxy is estimated to be 1.9 ± 1.1 per century [2].

On the other hand, during the lifetime of the Milky Way, those phenomena have occurred approximately 100 million times, and the Universe witnesses them at the rate of approximately one per second [2]. All the past core-collapse supernovae have contributed to a diffuse supernova-neutrino (DSN) flux, which is expected to be tiny but continuous in time. Its detection may provide a great deal of information, complementary to that from the future neutrino bursts.

Although its detailed features show some model dependence, it is rather well established that the predicted DSN spectrum has a peak at the value of 4–7 MeV with an exponential drop at higher energy [8]. In the low energy region, $E_\nu \lesssim 8$–12 MeV, the DSN signal is not accessible owing to an overwhelming flux of reactor $\bar{\nu}_e$. On the other hand, in the high energy region, $E_\nu \gtrsim 30$–40 MeV, it is covered by the $\nu$ and $\bar{\nu}$ flux of atmospheric origin [8–10]. Moreover, at $E_\nu \lesssim 16$ (19) MeV, the solar neutrino flux from the $^8$B (hep) chain dominates over the DSN flux. Therefore, in the search for the DSN signal, the energy window $19 \lesssim E_\nu \lesssim 30$ MeV plays a pivotal role, and studies aimed at extending this range towards lower values are of paramount importance.

In this context, water-Cherenkov detectors are of special significance. The recent result of the Super-Kamiokande (SK) Collaboration [11], performed for $E_\nu > 17.3$ MeV, has reached the sensitivity comparable to state-of-the-art theoretical predictions.

While neutrinos and antineutrinos of all flavors are present in the DSN flux, the dominant reaction process at this kinematics is $\bar{\nu}_e$-induced inverse $\beta$ decay of free protons in the water molecule [12],

$$\bar{\nu}_e + p \rightarrow e^+ + n,$$  \hspace{1cm} (1)

with the rate of a few events per year in the 22.5-ton fiducial volume of the SK detector [11].

When this figure is compared to ~2 cosmic-ray muons penetrating the detector every second and ~25 solar-neutrino and atmospheric-(anti)neutrino events identified every day [11], it clearly appears that very good understanding of the backgrounds is a prerequisite for the measurement of the DSN signal and for lowering the minimal neutrino energy accessible in the data analysis. At the current stage, neutrons cannot be detected in SK, and the observation of process (1) relies on the observation of the positron. Because Cherenkov detectors do not distinguish $e^+$’s from $e^-$’s nor, at the energy of interest, from γ rays, their sources give rise to the backgrounds. The most important of them is the process of oxygen spallation induced by an interaction with cosmic-ray muons, which currently determines the low-energy threshold of the analysis [11].

The gadolinium doping program at SK [12, 14] is specifically designed to overcome the problem of the spallation background. The DSN signal [11] will be identified as a prompt positron detection in coincidence with the delayed 8-MeV γ-ray cascade produced by the neutron capture on the gadolinium nucleus. As a result, the low-
energy threshold of the analysis will be dramatically lowered \cite{11}, down to the region dominated by reactor $\bar{\nu}_e$'s. However, the identification of the signal will require that background events involving neutrons produced through mechanisms other than reaction (11) and leading to $\gamma$-ray emission be under control at quantitative level.

The GEANT-based simulations \cite{13,16} performed for neutrons of energy from 4 MeV to 1 GeV show that their propagation in water can yield cascades of $\gamma$ rays, the spectrum of which is similar to that expected for the DSN signal \cite{11}. It is important to note that neutrons at such kinematics are known to be knocked out from oxygen nuclei by atmospheric neutrinos, of energy extending from a few MeV to arbitrary high values \cite{17,19}.

In this Letter, we discuss neutron production in the aftermath of neutral-current (NC) interactions of both neutrinos and antineutrinos with oxygen. Covering a broad kinematical range, we provide the corresponding cross sections, obtained within the impulse approximation (IA) approach. These results are of immediate relevance to the ongoing DSN program carried out by the SK Collaboration \cite{11}, as well as to the search for sterile neutrinos being conducted in the T2K experiment \cite{16}.

The basic assumption underlying the IA scheme is that nuclear interactions can be seen as the incoherent sum of interactions between the beam particles and individual nucleons. The IA-based framework has proven successful in extensive analyses of the large set of data collected by electron-scattering ($e,e'p$) experiments, in which the knocked-out proton is detected in coincidence with the outgoing electron \cite{20,22}.

We confine our considerations to elastic scattering on quasifree nucleons bound in a nucleus, customarily referred to as quasielastic (QE) scattering.

Note that the final states involving a knocked-out nucleon and no pions may also result from the reaction (12) for the carbon target, such as production of the $\Delta$-resonance subsequently decaying into a nucleon and a $\gamma$ ray. Nevertheless, because the associated cross sections are shown to be lower by two orders of magnitude, those reactions have not been taken into account here.

The process of NC QE interaction is sensitive to the strange content of nucleon. The available experimental evidence \cite{23,24} suggests that the strange contributions to the vector form factors are small and may be neglected in the context of this study.

This is, however, not the case for the strange axial form factor $F_A^s$. In the NC QE axial form factors of proton and neutron, defined as

\[ F_A^p = \frac{1}{2} (F_A + F_A^s), \quad F_A^n = -\frac{1}{2} (F_A - F_A^s), \]

respectively \cite{27}, the dominant term is the the charged-current QE axial form factor $F_A$, while $F_A^s$ introduces the opposite-sign corrections. From this fact it clearly follows that the strange axial form factor plays an important role in our considerations, since it drives the asymmetry between the proton and neutron NC QE cross sections.

It is customary to apply the dipole parametrization of $F_A^s$, by analogy to $F_A$, and to use as a cutoff parameter the same value of the axial mass $M_A$.

\[ F_A^s = \frac{g_A}{(1 + Q^2/M_A^2)^2}, \quad F_A = \frac{g_A}{(1 + Q^2/M_A^2)^2}. \]

This choice is supported by the Brookhaven National Laboratory Experiment 734 (BNL E734), which analyzed proton knockout by (anti)neutrino NC QE interaction using a carbon-dominated target \cite{28}.

From the shape analysis of the obtained $Q^2$ distributions, the BNL E734 Collaboration has found that $F_A^s = \frac{1}{2} F_A (1 + \eta)$ with $\eta = 0.12 \pm 0.07$, which translates into the strange axial coupling $g_A^s = -0.15 \pm 0.09$. Rather consistent values of $g_A^s$ have been obtained in the subsequent reanalyses \cite{29,32} of the BNL E734 data.

The axial coupling constant $g_A$ can be precisely extracted from neutron beta-decay measurements. In numerical calculations, we apply the state-of-the-art value $g_A = -1.2701$ \cite{33}.

Both $g_A$ and $g_A^s$ are strictly related to the spin structure of nucleon. In the naive quark model, those quantities have the simple interpretation \cite{27,34,36}

\[ g_A = \Delta d - \Delta u, \quad g_A^s = \Delta s, \]

where $\Delta q$ is the amount of proton spin carried by quarks and antiquarks of flavor $q$ ($q = u, d, s$).

The information on the spin composition of nucleon is accessible in polarized deep-inelastic-scattering (DIS) experiments. From the inclusive data collected using a muon beam and $^{3}$LiD target, the COMPASS Collaboration \cite{37} has recently extracted the value

\[ \Delta s = -0.08 \pm 0.01\text{(stat)} \pm 0.02\text{(syst)}, \]

in excellent agreement with the HERMES result from positron scattering off deuteron \cite{38}. Note that the method of extraction of $\Delta s$ assumes validity of SU(3)$_f$ symmetry in hyperon beta decays. Should SU(3)$_f$ be broken by 20\%, the maximal amount not excluded by the constrains from the KTeV experiment \cite{39,40}, the value of $\Delta s$ would shift by $\pm 0.04$ \cite{37}.

The strange quark contribution to the proton spin can, in principle, be determined more directly from semi-inclusive polarized DIS measurements, in which in addition to the scattered lepton, produced charged pions or kaons are detected \cite{35}. However, the analysis of semi-inclusive data performed by the COMPASS Collaboration \cite{41} leads to the conclusion that $\Delta s$ may be dominated by contributions coming from the kinematic region corresponding to Bjorken $x < 0.004$, not covered by current experiments. This issue is the main source of uncertainty associated with semi-inclusive $\Delta s$ measurements.

When all uncertainties are taken into account, the values of $\Delta s$ obtained from inclusive and semi-inclusive polarized DIS experiments appear to be compatible \cite{42}.
We acknowledge that the value \( g_A^s \) has been also reported from the MiniBooNE experiment \cite{43}, which used the Cherenkov detector filled with mineral oil, CH\(_2\). From the amount of single-proton events in the total NC QE event sample of high kinetic energy, \( g_A^s = +0.08 \pm 0.26 \) has been obtained. Note that while being positive, the MiniBooNE-determined value remains in agreement with other discussed measurements within its uncertainty.

In the IA regime, the nuclear cross sections are factorized. For neutrino NC QE scattering off a nucleus one finds

\[
\sigma_{\nu A} = \sum_{N=p, n} \int d^3p \, d\varepsilon N(p, E) \frac{M}{E_N} \sigma_{\nu N}, \quad (6)
\]

where \( \sigma_{\nu N} \) is the elementary cross section and \( E_N = \sqrt{M^2 + p^2} \) is the struck nucleon’s energy. In the above equation, the information on nuclear structure is contained in the nuclear spectral function, \( P(p, E) \), yielding the probability distribution of removing a nucleon with momentum \( p \) from the nuclear ground state, leaving the residual \((A-1)\)-particle system with excitation energy \( E \).

Accurate estimates of the nuclear cross sections require calculations of the spectral functions based on realistic dynamical models.

Many important features of nuclear structure can be explained within the shell model, based on the assumption that nucleons behave as independent particles subject to a mean field. Within this approach, in the nuclear ground state, the nucleons occupy the \( A \) lowest-energy eigenstates of the Hamiltonian, and the spectral function can be conveniently expressed as

\[
P_N(p, E) = \sum_{\alpha} |\phi_\alpha|^2 \delta(E - E_N^{\alpha}), \quad (7)
\]

where the sum runs over all occupied states and \( \phi_\alpha = \phi_\alpha(p) \) is the momentum-space wave function associated with the \( \alpha \)th eigenstate, belonging to the eigenvalue \( E_N^{\alpha} \).

Nucleon knockout experiments, while confirming the validity of the shell model, have unambiguously shown its limitations. Owing to strong correlations, nucleons are excited to states of higher energy and the occupation of the shell-model states is reduced to values sizably less than one \cite{54, 40}. Moreover, their energy distribution acquires finite widths, reflecting the finite lifetime of single-particle states \cite{17, 48}.

Correlation effects can be accounted for rewriting the spectral function in the form

\[
P_N(p, E) = \sum_{\alpha} n_\alpha |\phi_\alpha|^2 f_\alpha(E - E_N^{\alpha}) + P_{\text{corr}}^N(p, E), \quad (8)
\]

where \( n_\alpha < 1 \), and the function \( f_\alpha(E - E_N^{\alpha}) \) has a width which increases with increasing \( E_N^{\alpha} \). The correlation component \( P_{\text{corr}}^N(p, E) \) is characterized by a distinctive energy dependence. It provides a smooth background, extending to large values of \( |p| \) and \( E \), and does not exhibit the poles associated with the complex energies of single-particle states.

The results of theoretical calculations carried out within highly realistic \textit{ab initio} approaches clearly indicate that the momentum distribution,

\[
n_N(p) = \int d\varepsilon N(p, E), \quad (9)
\]

becomes independent of \( A \) at \(|p| \gtrsim 300 \text{ MeV} \) \cite{22}, and therefore that the correlation component of the spectral function is largely unaffected by surface and shell effects. As a consequence, \( P_{\text{corr}}^N(p, E) \) of a nucleus can be calculated in the local-density approximation (LDA) from the results for uniform nuclear matter \cite{49} of constant density \( \rho \).

\[
P_{\text{corr}}^N(p, E) = \int dR \rho(R) P_{NM, N}^{NM}(\rho, p, E). \quad (10)
\]

In this Letter, we use the realistic spectral function of oxygen obtained by the authors of Ref. \cite{50, 51} in the LDA scheme. It consistently combines the shell structure deduced from experimental \((e, e' p)\) data \cite{44} with the correlation component determined as in Eq. \( (10) \).

The numerical results discussed here can be readily reproduced, employing the elementary NC QE cross section \( \sigma_{\nu N} \) for scattering on an off-shell nucleon explicitly given in our previous article \cite{52}. We apply the state-of-the-art parametrization of the electromagnetic form factors of Refs. \cite{53, 54} and fix the axial mass to the value \( M_A = 1.2 \text{ GeV} \), determined for the oxygen nucleus by the K2K Collaboration \cite{55}. Increasing \( M_A \) with respect to the value extracted from deuterium measurements \cite{56, 57} has been interpreted as an effective way of taking into account multinucleon reaction mechanisms \cite{58}. In our calculations, the strange axial coupling constant is

\[
g_A^s = -0.08 \pm 0.05. \quad (11)
\]

We have estimated the overall uncertainty of \( g_A^s \) adding in quadrature the errors of the COMPASS measurement, see Eq. \( (5) \), and the uncertainty related to possible SU(3)\(_f\) breaking effects \cite{53}. Note that within its uncertainty, the value \( (11) \) is in agreement with a broad class of theoretical predictions \cite{52, 60} and that next-generation measurements should be able to determine the value of \( g_A^s \) with higher precision \cite{51, 52}.

Figure 1 shows the calculated cross sections for neutron knockout induced by neutrino and antineutrino NC QE interaction with the oxygen nucleus. The obtained results exhibit similar energy dependence to that of the total NC QE cross sections, \( \sigma_{\nu\alpha}(\nu) \) and \( \sigma_{\overline{\nu}\alpha}(\overline{\nu}) \). The reason of such behavior is twofold. First, in the IA, underlying our approach, the gross features of the nuclear cross sections follow from the properties of the elementary cross sections. Second, the elementary NC QE cross sections for scattering off proton and neutron are largely similar.

The uncertainty of the strange axial coupling constant \( (11) \) introduces to our predictions uncertainties represented by the bands in Fig. 1. To provide insight into
their energy dependence, in Fig. 2 we also show the relative uncertainties, defined as

$$\Delta \sigma = \frac{\sigma(g_A^s)}{\sigma(-0.08)} - 1.$$

In the interval $0.2 \leq E_\nu \leq 10$ GeV, the cross section for neutron knockout by neutrino (antineutrino) NC QE scattering decreases by less than 5.71 (7.62)% when the value of $g_A^s$ is fixed to $-0.13$ instead of $-0.08$, and increases by less than 5.90 (8.08)% when $g_A^s = -0.03$.

Unlike the cross sections for neutron knockout, $\sigma_{\text{tot}}(\nu)$ and $\sigma_{\text{tot}}(\bar{\nu})$ exhibit weak dependence on the strange axial form factor. This behavior is easy to understand. In the idealized case of completely isoscalar target, $P_n(p, E) = P_p(p, E)$, the nonvanishing combinations of the form factors are isoscalar-isoscalar, such as $(F_A^s)^2$ and $F_A^s(G_M^p + G_M^N)$, and isovector-isovector, e.g. $(F_A^t)^2$ and $F_A(G_M^p - G_M^N)$, with $G_M^N$ being the nucleon magnetic form factor. However, in view of the relations $g_A^s \ll g_A$ and $(G_M^p + G_M^N) < (G_M^p - G_M^N)$, it clearly appears that the isoscalar-isoscalar contributions are much smaller than the isovector-isovector ones. To a good approximation, that picture applies also to the oxygen nucleus, because the difference between its neutron and proton spectral functions is not large [52], playing important role only at low energy. For example, in the range $0.2 \leq E_\nu \leq 10$ GeV, the total cross section for neutrino (antineutrino) NC QE scattering increases by less than 0.46 (1.57)% when $g_A^s = -0.13$ is applied instead of the value $-0.08$. The somewhat larger dependence of $\sigma_{\text{tot}}(\bar{\nu})$ on the strange axial coupling is a consequence of its large sensitivity to the size of the axial-magnetic term, resulting from the destructive interference between the response functions in the antineutrino cross section [63].

To facilitate use of the results of this Letter, in Supplemental Material [64], we provide them in a tabulated form for energies up to 10 GeV.

Finally, we remark that our approach readily applies to the carbon nucleus [65, 66], the significance of which follows from an extensive use of hydrocarbons in neutrino detectors performing also astrophysical searches [67–69]. In particular, liquid scintillators, while being materials reach in free protons, allow identification of the reaction (1) by the correlated signal from the prompt positron and the delayed 2.2-MeV $\gamma$ ray originating from the neutrino capture on proton. The lack of reliable calculations of the NC cross sections is in fact one of the main sources of the background uncertainty, which is regarded as the most important limitation of experimental searches [69].

In this Letter, we have argued that the formalism based on realistic spectral functions is suitable to carry out accurate calculations of the neutron-knockout cross section in the kinematical regime of atmospheric-neutrino interactions. The numerical results of our work cover a broad energy range, extending to 10 GeV, relevant to Monte Carlo simulations. Using the available experimental information, we have estimated the uncertainty arising from the strange-quark contribution to the NC QE axial form factor, and found it to be smaller than reported elsewhere [65, 71–72]. As a final remark, we want to emphasize that the results of our work are of immediate use in the ongoing searches for diffuse supernova neutrinos and for sterile neutrinos.

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See Ancillary File of the arXiv submission for the cross sections discussed in this Letter given in a tabulated form as a function of energy, calculated for the strange axial coupling constant value of $-0.03$, $-0.08$, and $-0.13$.

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