

Flux-integrated semiexclusive cross sections for charged-current quasielastic and neutral-current elastic neutrino scattering off ^{40}Ar and a sterile neutrino oscillation study

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 (Received 18 January 2023; accepted 16 March 2023; published 10 April 2023)

Flux-integrated semiexclusive differential cross sections for charged-current quasielastic and neutral-current elastic neutrino scattering on argon are analyzed. The cross sections are calculated using the relativistic distorted-wave impulse approximation with values of the nucleon axial mass $M_A = 1$ GeV and 1.2 GeV. The elastic scattering cross sections are also computed for different strange quark contributions to the neutral-current axial form factor. The flux-integrated differential cross sections as functions of reconstructed neutrino energy are evaluated for the far detector of the SBN experiment. The effects of the short baseline neutrino oscillations are taken into account in a $3 + 1$ framework. We found that cross sections depend on oscillation parameters and the ratio of the measured and predicted cross sections can be used in a sterile neutrino oscillation study.

DOI: [10.1103/PhysRevD.107.073001](https://doi.org/10.1103/PhysRevD.107.073001)

I. INTRODUCTION

Neutrino neutral current elastic (NCE) scattering off nuclei can give information about the structure of the hadronic weak neutral current (NC) and on the strange quark contribution to the nucleon spin. In contrast, purely isovector charged-current (CC) processes do not depend on the strange form factors. Therefore the CC and NC processes give complementary information on nuclear effects in neutrino-nucleus scattering.

The weak neutral current of the nucleon may be parametrized in terms of two vector and one axial-vector form factors. An additional induced pseudoscalar form factor is presented. The axial-vector form factor may be split into nonstrange and strange contributions. The latter is proportional to the fraction of the nucleon spin carried by the strange quarks [1,2]. The strange vector form factors were measured in parity-violating electron scattering experiments [3–7]. The combined analysis of these experimental data points to small strangeness of the vector form factors [8,9].

Neutrino induced reactions are sensitive to the strange quark contribution to the NC axial-vector form factor. The strange axial form factor is parametrized as a dipole and uses the same axial mass as applied for the nonstrange form

factor; the strange axial coupling constant at four-momentum transfers squared $Q^2 = 0$ is Δs . A measurement of $\nu(\bar{\nu})$ -proton NCE at Brookhaven National Laboratory (BNL E734) [10] suggested a nonzero value of Δs . However this result suffers strongly from experimental uncertainties due to difficulties in determination of the absolute neutrino flux. The measurement of the neutral-to-charged-current (CC) quasielastic (QE) cross section $R = \text{NCE}/\text{CCQE}$ in neutrino-nucleus scattering was proposed in Ref. [11] to extract information on the strange spin of the proton because much of the systematic uncertainty is canceled by using the ratio. The MiniBooNE experiment measured the flux-integrated NCE differential cross section $d\sigma/dQ^2$ as a function of four-momentum transferred squared Q^2 and the ratio $R = \text{NCE}/\text{CCQE}$ to extract the value Δs [12].

Over the last few decades, a series of anomalous neutrino flavor oscillation measurements [13–17] have been made at short baseline that could be explained by the existence of one more eV-scale neutrinos, the so-called “sterile neutrino” ν_s . The sterile neutrino is addition to 3-flavor model with the three active neutrino $\nu_{\text{active}} = \{\nu_e, \nu_\mu, \nu_\tau\}$ and has no coupling to either the W^\pm or Z^0 bosons. The simplest extension to this 3-flavor model is referred to as the $3 + 1$ model and introduces in addition to massive neutrino ν_1, ν_2, ν_3 a single new mass state, ν_4 , with a corresponding sterile flavor state ν_s . On the other hand neither long-baseline oscillation experiments [18–20], or the SNO experiment with solar neutrinos [21] have found evidence for this sterile neutrino.

Motivated by the need for a resolution to the short baseline anomalies, the Short Baseline Neutrino Program (SBN) using the Booster Neutrino Beam (BNB) at Fermilab was

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proposed [22]. This experiment consists of three liquid argon time projection chambers (LArTPCs) located at the distances of hundreds of meters from BNB targets: a near detector SBND; an intermediate detector MicroBooNE; and a far detector ICARUS. The positions of these detectors optimized for study neutrino oscillation with mass-squared difference $\Delta m_{i4}^2 \sim 1 \text{ eV}^2$, where $i = 1, 2, 3$. Recently the MicroBooNE collaboration presented the result of a measurement of BNB ν_e interactions, to study the excess of low energy interactions observed by the MiniBooNE [14] collaboration. The results are found to be consistent with the nominal ν_e rate expectations from BNB and no excess of ν_e events is observed [23,24].

The NC interaction can play an important role in oscillation experiments. Because the three active neutrinos couple to Z^0 , the rate of NC events should be unaffected by the 3-flavor neutrino oscillations. Therefore in a sterile search based on the NC interaction, the signal is the disappearance of any active neutrinos creating a deficit in rate of NC events.

To evaluate the oscillation parameters, the probabilities of neutrino oscillations as functions of neutrino energy are measured. The accuracy to which neutrino oscillation parameters can be extracted depends on the ability of experiments to determine the individual energy of detected neutrino. In the few-GeV neutrino energy regime corresponding to the BNB, the quasielastic scattering is the dominant interaction mode and the kinematics of the outgoing lepton or proton are sufficient for determining the neutrino energy.

The semiexclusive reaction $\nu + A \rightarrow \nu + p + B$ is a good signal sample of neutrino NCE scattering off nuclei. The measurements of the proton energy and its angle with respect to direction of the incident neutrino determine the neutrino energy. The LArTPCs provide low tracking thresholds and precise energy and angular resolution for charged particles, improving neutrino energy estimation in NC interactions.

In recent years many theoretical studies have been presented to improve our knowledge on the NCE neutrino-nucleus scattering [25–35]. In the semiexclusive process ($\nu_\mu, \nu_\mu p$) in the neutrino removes a single intact nucleon from the nucleus without producing any additional particles. Understanding the interaction of neutrinos with argon nuclei is of particular importance, since neutrino oscillation experiments such as DUNE [36] and SBN [22] employ neutrino detectors using LArTPCs. Unfortunately the cross section data for the semiexclusive lepton scattering on argon in the relevant energy range are rather scarce. The recent measurement of the $^{40}\text{Ar}(e, e'p)$ cross sections for 2.2 GeV electron [37,38] has enabled the determination of the spectral function of protons in the target nucleus. However, the analysis of data from neutrino scattering experiments requires the availability of the neutron spectral function. Based on the isospin symmetry of nuclear forces one can expect that the proton spectral function obtained

from $\text{Ti}(e, e'p)$ provides information for the neutron spectral function of argon. The reduced cross section of this reaction in terms of a model proton spectral function was measured in Ref. [39]. The flux-integrated differential CCQE-like [40] and NCE [41] cross sections for $\nu_\mu^{40}\text{Ar}$ scattering measured with the MicroBooNE detector also provides information about neutron and proton spectral function in argon. On the other hand, the total uncertainty of the MicroBooNE measured NCE cross sections ranging from 50% to 100% at high energies.

In the first part of this work the flux-integrated differential cross sections of $^{40}\text{Ar}(\nu_\mu, \nu_\mu p)$ interaction are calculated with the relativistic distorted-wave impulse approximation (RDWIA) [42–47], using the BNB. The RDWIA takes into account the nuclear shell structure and final state interaction (FSI) of the ejected nucleon with the residual nucleus. In our approach [48] the effects of the short-range nucleon-nucleon (NN) correlations leading to the appearance of a high-momentum and high-energy distribution in the target are estimated. This approach was successfully applied in Refs. [48–52] for calculation of the quasielastic semi-exclusive and inclusive cross sections for the electron and neutrino scattering on ^{12}C , ^{16}O , ^{40}Ca , and ^{40}Ar nuclei.

In the second part of this article we calculate the flux-integrated differential cross sections for semiexclusive CCQE and NCE scattering as functions of reconstructed with kinematic method neutrino energy. We explore possible application of these cross sections, calculated for the near SBND and far ICARUS detectors, for the sterile neutrino search at SBN. If these cross sections are extracted with good accuracy, this method can be applied to probe sterile neutrino oscillation parameters.

The outline of this paper is the following. In Sec. II we present briefly the formalism for the NCE semiexclusive scattering process and basic aspects of the RDWIA approach. In Sec. III we present the flux-integrated double and single differential cross sections and show how these cross sections can be used to search for sterile neutrino at SBN in context of the 3 + 1 model. Our conclusions are summarized in Sec. IV.

II. THE FORMALISM AND MODEL FOR THE NEUTRAL-CURRENT ELASTIC SCATTERING

In this section we consider the formalism for description of NCE exclusive

$$\nu(k_i) + A(p_A) \rightarrow \nu(k_f) + N(p_x) + B(p_B), \quad (1)$$

scattering off nuclei in the one- Z^0 -boson exchange approximation. Here $k_i = (\varepsilon_i, \mathbf{k}_i)$ and $k_f = (\varepsilon_f, \mathbf{k}_f)$ are the initial and final lepton momenta, $p_A = (\varepsilon_A, \mathbf{p}_A)$, and $p_B = (\varepsilon_B, \mathbf{p}_B)$ are the initial and final target momenta, $p_x = (\varepsilon_x, \mathbf{p}_x)$ is the ejectile nucleon momentum, $q = (\omega, \mathbf{q})$ is the momentum transfer carried by the virtual Z^0 -boson, and

$Q^2 = -q^2 = \mathbf{q}^2 - \omega^2$ is the Z^0 -boson virtuality. As the basic outline follows closely the CC formalism developed in Ref. [48], we present a brief review that focuses on those modifications that arise from the weak neutral current.

A. NCE neutrino-nucleus semiexclusive cross section

In the laboratory frame, the differential cross section for the exclusive (anti-)neutrino NCE scattering, in which only a single discrete state or narrow resonance of the target is excited, can be written as

$$\frac{d^5\sigma^{(nc)}}{d\varepsilon_f d\Omega_f d\Omega_x} = R \frac{|\mathbf{p}_x| \varepsilon_x |\mathbf{k}_f| G^2}{(2\pi)^5 \varepsilon_i} L_{\mu\nu}^{(nc)} W^{\mu\nu(nc)}, \quad (2)$$

where Ω_f is the solid angle for the lepton momentum, Ω_x is the solid angle for the ejectile nucleon momentum, $G \simeq 1.16639 \times 10^{-11} \text{ MeV}^{-2}$ is the Fermi constant, $L_{\mu\nu}^{(nc)}$ and $W_{\mu\nu}^{(nc)}$ are NC lepton and nuclear tensors, respectively, and R is a recoil factor

$$R = \int d\varepsilon_x \delta(\varepsilon_x + \varepsilon_B - \omega - m_A) = \left| 1 - \frac{\varepsilon_x \mathbf{p}_x \cdot \mathbf{p}_B}{\varepsilon_B \mathbf{p}_x \cdot \mathbf{p}_x} \right|^{-1}.$$

The energy ε_x is the solution to the equation

$$\varepsilon_x + \varepsilon_B - m_A - \omega = 0, \quad (3)$$

where $\varepsilon_B = \sqrt{m_B^2 + \mathbf{p}_B^2}$, $\mathbf{p}_B = \mathbf{q} - \mathbf{p}_x$, $\mathbf{p}_x = \sqrt{\varepsilon_x^2 - m^2}$, and m_A , m_B , and m are masses of the target, recoil nucleus and nucleon, respectively. The missing momentum \mathbf{p}_m and missing energy ε_m are defined by

$$\mathbf{p}_m = \mathbf{p}_x - \mathbf{q} \quad (4a)$$

$$\varepsilon_m = m + m_B - m_A \quad (4b)$$

From Eq. (3) the total energy of the ejected nucleon is given by

$$\varepsilon_x = \omega + m_A - \varepsilon_B \approx \omega + m - (\varepsilon_m + p_m^2/2m_B) \quad (5)$$

$$\begin{aligned} \frac{d^5\sigma^{(nc)}}{d\varepsilon_f d\Omega_f d\Omega_x} = & \frac{|\mathbf{p}_x| \varepsilon_x}{(2\pi)^5} G^2 \boldsymbol{\varepsilon}_f |\mathbf{k}_f| R \{ v_0 R_0^{(nc)} + v_T R_T^{(nc)} + v_{TT} R_{TT}^{(nc)} \cos 2\phi + v_{zz} R_{zz}^{(nc)} + (v_{xz} R_{xz}^{(nc)} - v_{0x} R_{0x}^{(nc)}) \cos \phi - v_{0z} R_{0z}^{(nc)} \\ & + h [v_{yz} (R_{yz}^{(nc)} \sin \phi + R_{yz}^{(nc)} \cos \phi) - v_{0y} (R_{0y}^{(nc)} \sin \phi + R_{0y}^{(nc)} \cos \phi) - v_{xy} R_{xy}^{(nc)}] \}, \end{aligned} \quad (10)$$

where the response functions R_i are suitable combinations of the hadron tensor components $W_{\mu\nu}^{(nc)}$, and the coefficients v_i are calculated for massless neutrino. The exclusive cross section as a function of ε_f and $\cos \theta_f$ can be obtained by integrating the exclusive cross sections Eq. (10) over the azimuthal angle ϕ and missing momentum \mathbf{p}_m

and neglecting the recoil nucleus energy $p_m^2/2m_B$, the nucleon kinetic energy can be written as

$$T_N = \omega - (\varepsilon_m + p_m^2/2m_B) \approx \omega - \varepsilon_m. \quad (6)$$

If we assume the target nucleon to be at rest inside a nucleus we have

$$k_i = k_f \cos \theta_f + p_x \cos \theta_p, \quad (7)$$

where $k_f = |\mathbf{k}_f|$, $p_x = |\mathbf{p}_x|$, and $\cos \theta_f$ and $\cos \theta_p$ are lepton and nucleon scattering angles, respectively. From Eq. (7) it follows that the lepton and nucleon scattering angles are connected by the relation

$$\cos \theta_f = \frac{k_i - p_x \cos \theta_p}{\varepsilon_i - T_N - \varepsilon_m}. \quad (8)$$

The leptonic tensor $L_{\mu\nu}^{(nc)}$ is separated into symmetric and antisymmetric components that are given as in Ref. [48]. Note that the weak lepton NC is conserved for massless neutrino and $q^\mu L_{\mu\nu}^{(nc)} = L_{\mu\nu}^{(nc)} q^\nu = 0$. All the nuclear structure information and FSI effects are contained in the weak NC nuclear tensor $W_{\mu\nu}^{(nc)}$, which is given by the bilinear product of the transition matrix elements of the nuclear NC operator $J_\mu^{(nc)}$ between the initial nucleus state $|A\rangle$ and the final state $|B_f\rangle$ as

$$W_{\mu\nu}^{(nc)} = \sum_f \langle B_f, \mathbf{p}_x | J_\mu^{(nc)} | A \rangle \langle A | J_\nu^{(nc)\dagger} | B_f, \mathbf{p}_x \rangle, \quad (9)$$

where the sum is taken over undetected states.

General expressions for the cross sections of the exclusive and inclusive CCQE neutrino scattering off nucleus are given in Ref. [48] in terms of weak response functions. For calculation of the NCE scattering this expression can be rewritten in the form

$$\left(\frac{d^3\sigma^{(nc)}}{d\varepsilon_f d\Omega_f} \right)_{ex} = \int_0^{2\pi} d\phi \int_{p_{\min}}^{p_{\max}} dp_m \frac{p_m}{p_x |\mathbf{q}|} R_c \times \frac{d^5\sigma^{(nc)}}{d\varepsilon_f d\Omega_f d\Omega_x}, \quad (11)$$

where $p_m = |\mathbf{p}_m|$, $\mathbf{p}_m = \mathbf{p}_x - \mathbf{q}$, and

$$\cos \theta_x = \frac{\mathbf{p}_x^2 + \mathbf{q}^2 - \mathbf{p}_m^2}{2p_x |\mathbf{q}|}, \quad (12a)$$

$$R_c = 1 + \frac{\varepsilon_x}{2p_x^2 \varepsilon_B} (\mathbf{p}_x^2 + \mathbf{q}^2 - \mathbf{p}_m^2). \quad (12b)$$

The integration limits p_{\min} and p_{\max} are given in Ref. [53]. As the outgoing neutrino is undetected the differential cross section Eq. (11) in “the target nucleon at rest” approximation can be rewritten, using Eqs. (6) and (7), as function of p_x and $\cos \theta_p$ as

$$\left(\frac{d^2 \sigma^{(nc)}}{dp_x d \cos \theta_p} \right)_{ex} \approx R_p \left(\frac{d^2 \sigma^{(nc)}}{d\varepsilon_f d \cos \theta_f} \right)_{ex}, \quad (13)$$

where $R_p = p_x^2 / [\varepsilon_x (\varepsilon_i - \omega)]$.

B. Model

We describe the neutrino-nucleon NCE scattering within the RDWIA approach. This formalism is based on the impulse approximation (IA), assuming that the incoming neutrino interacts with only one nucleon (which is subsequently emitted) while the remaining $(A - 1)$ nucleons in the target are spectators. The nuclear current is written as the sum of single-nucleon currents. Then the nuclear matrix element in Eq. (9) takes the form

$$\langle p, B | J^{\mu(nc)} | A \rangle = \int d^3 r \exp(i\mathbf{t} \cdot \mathbf{r}) \bar{\Psi}^{(-)}(\mathbf{p}, \mathbf{r}) \times \Gamma^{\mu(nc)} \Phi(\mathbf{r}), \quad (14)$$

where $\Gamma^{\mu(nc)}$ is the NC vertex function, $\mathbf{t} = \varepsilon_B \mathbf{q} / W$ is the recoil-corrected momentum transfer, $W = \sqrt{(m_A + \omega)^2 - \mathbf{q}^2}$ is the invariant mass, Φ and $\Psi^{(-)}$ are the relativistic bound-state and outgoing wave functions.

The single-nucleon neutral current has a $V - A$ structure $J^{(nc)\mu} = J_V^{\mu(nc)} + J_A^{\mu(nc)}$. For a free-nucleon vertex function, $\Gamma^{\mu(nc)} = \Gamma_V^{\mu(nc)} + \Gamma_A^{\mu(nc)}$, we use the vector current vertex function

$$\Gamma_V^{\mu(nc)} = F_V^{(nc)}(Q^2) \gamma^\mu + i \sigma^{\mu\nu} q_\nu F_M^{(nc)}(Q^2) / 2m, \quad (15)$$

and the axial current vertex function

$$\Gamma_A^{\mu(nc)} = F_A^{(nc)}(Q^2) \gamma^\mu \gamma_5 + F_P^{(nc)}(Q^2) q^\mu \gamma_5. \quad (16)$$

The vector form factors $F_i^{(nc)}$ ($i = V, M$) are related to the corresponding electromagnetic ones for protons F_i^p and neutrons F_i^n , plus a possible isoscalar strange-quark contribution F_i^s [2], i.e.

$$F_V^{(nc)} = \tau_3 (0.5 - \sin^2 \theta_W) (F_1^p - F_1^n) - \sin^2 \theta_W (F_1^p + F_1^n) - F_V^s / 2 \quad (17a)$$

$$F_M^{(nc)} = \tau_3 (0.5 - \sin^2 \theta_W) (F_2^p - F_2^n) - \sin^2 \theta_W (F_2^p + F_2^n) - F_M^s / 2, \quad (17b)$$

where $\tau_3 = +(-1)$ for proton (neutron) knockout and θ_W is the Weinberg angle ($\sin^2 \theta_W \approx 0.2313$). The axial $F_A^{(nc)}$ form factor is expressed as

$$\Gamma_A^{\mu(nc)} = (\tau_3 F_A - F_A^s) / 2, \quad (18)$$

where F_A^s describes possible strange-quark contributions. This form factor in the dipole approximation is parametrized as

$$F_A^{(nc)} = \frac{1}{2} \frac{\tau_3 F_A(0) - \Delta s}{(1 + Q^2 / M_A^2)^2}, \quad (19)$$

with $F_A(0) = 1.272$, and Δs describes the possible strange-quark contribution. The contribution of the pseudoscalar form factor $F_p^{(nc)}$, in Eq. (16) is proportional to the mass of the scattered lepton, so vanishes for neutral currents.

Measurements of the strange vector form factors in parity violating electron scattering point to small strangeness of F_i^s form factors [8]. Therefore in this work we neglect the strangeness contributions, i.e., it is supposed that $F_V^s = F_M^s = 0$. For the nucleon form factors $F_i^{p(n)}$ the approximation of Ref. [54] is used. Because the bound nucleons are off-shell we employ the de Forest

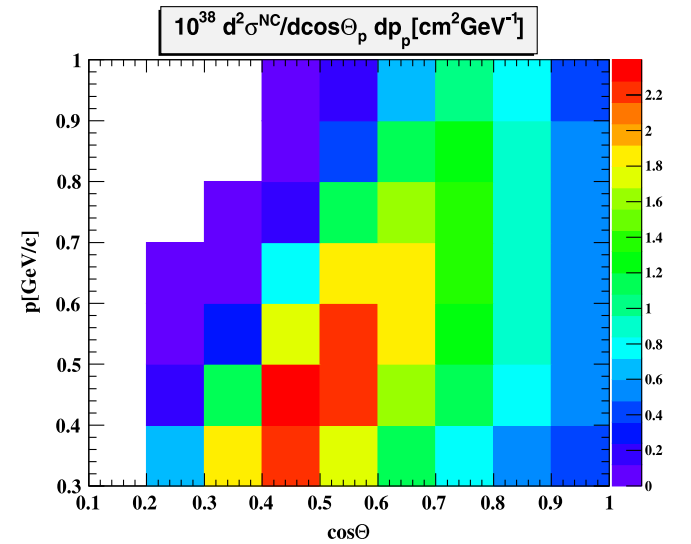


FIG. 1. The flux-integrated double-differential NCE semiexclusive cross section as a function of proton momentum and the cosine of the proton scattering angle.

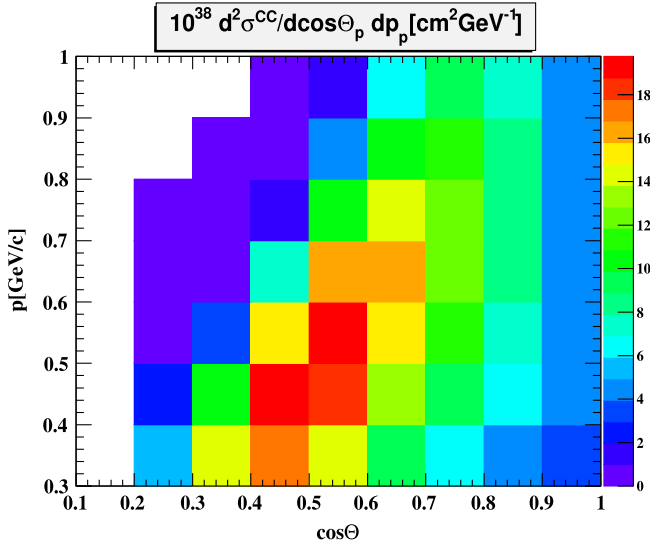


FIG. 2. Same as Fig. 1, but for the CCQE semiexclusive reaction.

prescription [55] and Coulomb gauge for the off-shell vector current vertex Γ_V^n .

In the RDWIA calculations the independent particle shell model (IPSM) is assumed in the calculations of the nuclear

structure. In Eq. (14) the relativistic bound-state wave functions for nucleons Φ are obtained as the self-consistent solutions of relativistic Hartree equations, derived within a relativistic mean-field approach [56,57] with the normalization factors S_α relative to the full occupancy of the IPSM orbital α of ^{40}Ca . For ^{40}Ca and ^{40}Ar an average factor $\langle S \rangle \approx 87\%$. This estimation of depletion of hole states follows from the RDWIA analysis of $^{40}\text{Ca}(e, e'p)$ data [50]. The source of the reduction of the $(e, e'p)$ spectroscopic factors with respect to the mean field values are the short-range and tensor correlations in the ground state, leading to the appearance of the high-momentum and high-energy component in the nucleon distribution in the target. Mean values of proton and neutron binding energies and occupancies of shells are given also in Ref. [50].

In the RDWIA model, final state interaction effects for the outgoing nucleons are taken into account. The system of two coupled first-order Dirac equations is reduced to a single second-order Schrödinger-like equation for the upper component of the Dirac wave function Ψ . This equation contains a phenomenological relativistic optical potential. The optical potential consists of a real part, which describes the rescattering of the ejected nucleon and an imaginary part which accounts for its absorption into

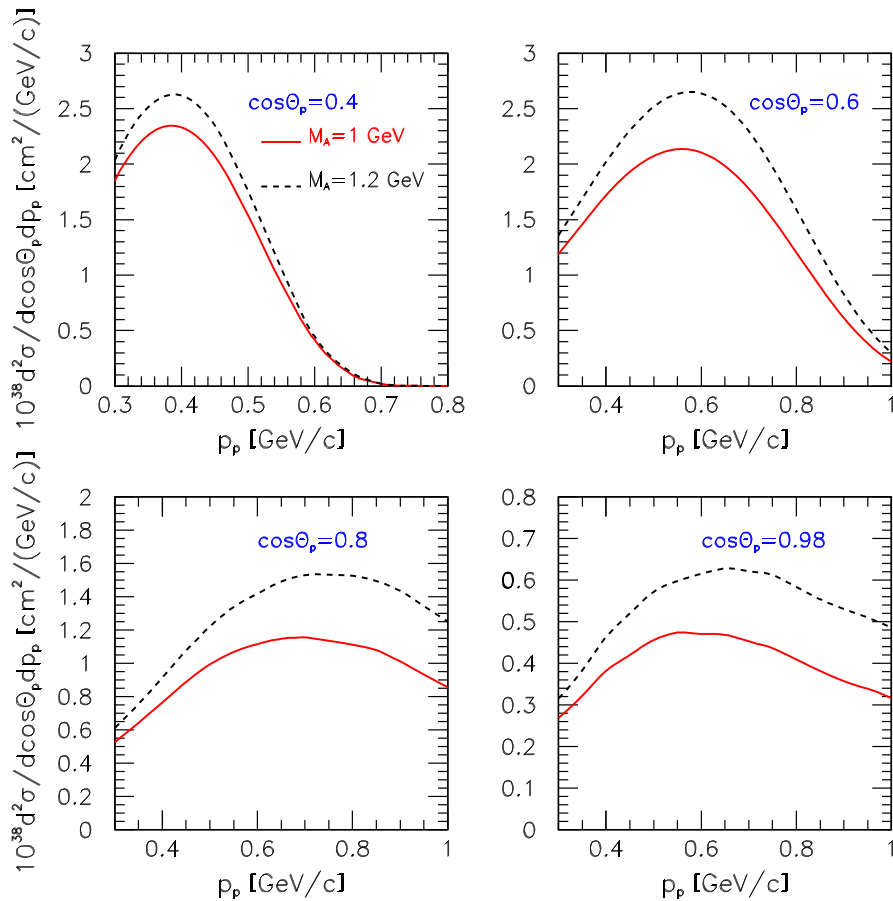


FIG. 3. The flux-integrated semiexclusive NCE $d\sigma^{nc} dp_p$ cross section for $\nu_\mu - ^{40}\text{Ar}$ scattering as a function of p_μ for the four proton scattering angles: $\cos\theta_p = 0.4, 0.6, 0.8,$ and 0.98 . As shown in the key, cross sections were calculated with $M_A = 1$ GeV and 1.2 GeV.

unobserved channels. The LEA program [58] is used for the numerical calculation of the distorted wave functions with the EDAD1 parametrization [59] of the relativistic optical potential for calcium.

The RDWIA model was successfully tested in Ref. [50] against $A(e, e'p)$ data for electron scattering off ^{40}Ca . In Ref. [51] it was shown that this approach describes well the electron scattering data for carbon, calcium, and argon at different kinematics. The calculated and measured inclusive cross sections are in agreement within the experimental uncertainties. The RDWIA calculations are generally expected to be more accurate at higher Q^2 , since QE ($e, e'p$) is expected to be dominated by single-particle interactions in this regime of four-momentum transfer, and two-body currents stemming from meson-exchange currents are not needed to explain the data at this Q^2 [60].

III. RESULTS AND DISCUSSION

A. CCQE and NCE semiexclusive differential cross section

The first measurement of exclusive CCQE-like flux-integrated cross sections was performed using the MicroBooNE LArTPC neutrino detector presented in

Ref. [40]. A specific subset of CCQE-like interactions (CC1p0 π interactions) includes CC $\nu_\mu - ^{40}\text{Ar}$ scattering events with a detected muon and exactly one proton, with momenta greater than 100 and 300 MeV/c, respectively. The data were taken in a phase-space region that corresponds to $0.1 < p_\mu < 1.5$ GeV/c, $0.3 < p_p < 1$ GeV/c, $-0.65 < \cos\theta < 0.95$, and $\cos\theta_p > 0.15$. The MicroBooNE detector is located along the Booster Neutrino Beam at Fermilab. The BNB energy spectrum extends to 2 GeV and peaks around 0.7 GeV [61].

For these CC1p0 π events the flux-integrated $\nu_\mu - ^{40}\text{Ar}$ double differential cross section in muon and proton momenta and angles were measured, as a function of the calorimetric measured neutrino energy and reconstructed momentum transfer. The flux-integrated cross section is defined as

$$\left\langle \frac{d\sigma}{dp d\cos\theta}(p, \cos\theta) \right\rangle = \int W_\nu(\varepsilon_i) \frac{d\sigma}{dp d\cos\theta}(\varepsilon_i, p, \cos\theta) d\varepsilon_i, \quad (20)$$

where W_ν is a unit-normalized neutrino flux

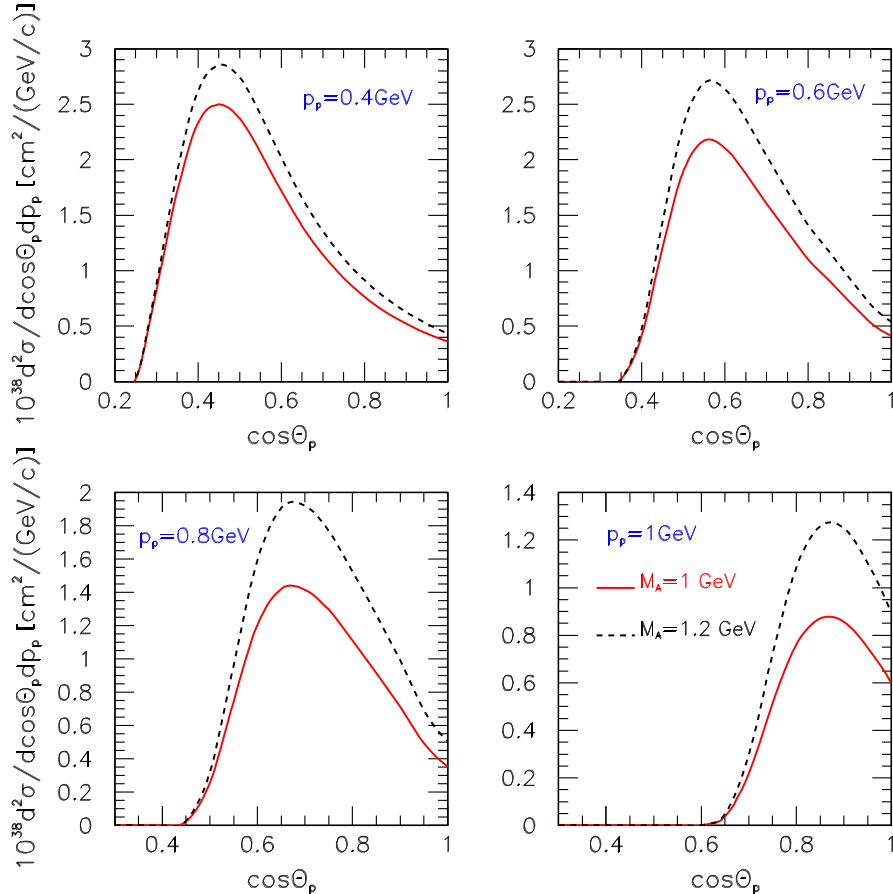


FIG. 4. Same as Fig. 3 but as a function of $\cos\theta_p$ for the four proton momenta: $p_p = 0.4, 0.6, 0.8,$ and 1 GeV/c.

$$W_\nu(\boldsymbol{\varepsilon}_i) = I_\nu(\boldsymbol{\varepsilon}_i)/\Phi_{\text{BNB}} \quad (21)$$

and

$$\Phi_{\text{BNB}} = \int I_\nu(\boldsymbol{\varepsilon}_i) d\boldsymbol{\varepsilon}_i \quad (22)$$

is determined by integration of the neutrino flux over $0 < \boldsymbol{\varepsilon}_i < 3$ GeV. As follows from (20) the differential flux-integrated cross sections depend on the shape of the neutrino spectrum. In Ref. [52] the flux-integrated CCQE semiexclusive cross sections for ν_μ ^{40}Ar scattering were calculated within the RDWIA model and compared with the MicroBooNE data.

In this work we calculate within this approach the semiexclusive neutral-current elastic scattering muon neutrino off argon. A specific subset of this interaction includes signal events with a detected one proton and no other particles (NC1p) in the final state. We do not consider meson-exchange current and nucleon-nucleon pair contributions. The calculations are performed with $M_A = 1$ GeV and 1.2 GeV, taking into account the MicroBooNE momentum threshold for

protons, i.e., $0.3 \leq p_p \leq 1$ GeV/c and $\cos \theta_p > 0.15$. The values $1 \leq M_A \leq 1.2$ GeV are in agreement with the best fit values $M_A = 1.15 \pm 0.03$ GeV and $M_A = 1.2 \pm 0.06$ GeV obtained from the CCQE-like fit of the MiniBooNE and MINERvA data in Refs. [62,63]. For modeling electron and muon neutrinos in Ref. [64] the ‘‘MicroBooNE Tune’’ value of $M_A = 1.1 \pm 0.1$ GeV is used in the GENIE generator, whereas the post-ND280-fit value of $M_A = 1.13 \pm 0.08$ GeV is applied in the NEUT model [65].

The flux-integrated double-differential cross sections $d^2\sigma/dp_p d\cos\theta_p$ of the semiexclusive NCE and CCQE $\nu_\mu - ^{40}\text{Ar}$ scattering are presented in Figs. 1 and 2, respectively as functions of proton momentum and scattering angle. Here, the results were obtained with the value of $M_A = 1$ GeV and $\Delta s = 0$. The maximum of the calculated cross sections is in the region $0.3 \leq p_p \leq 0.6$ GeV/c and $0.4 \leq \cos\theta_p \leq 0.6$. Moreover, the shapes of the $d^2\sigma^{nc}/dp_p d\cos\theta_p$ and $d^2\sigma^{cc}/dp_p d\cos\theta_p$ distributions are very similar.

Figure 3 shows the flux-integrated NCE $d\sigma^{nc}/dp_p$ cross sections calculated with $\Delta s = 0$ as a function of p_p for several values of the proton scattering angle and Fig. 4

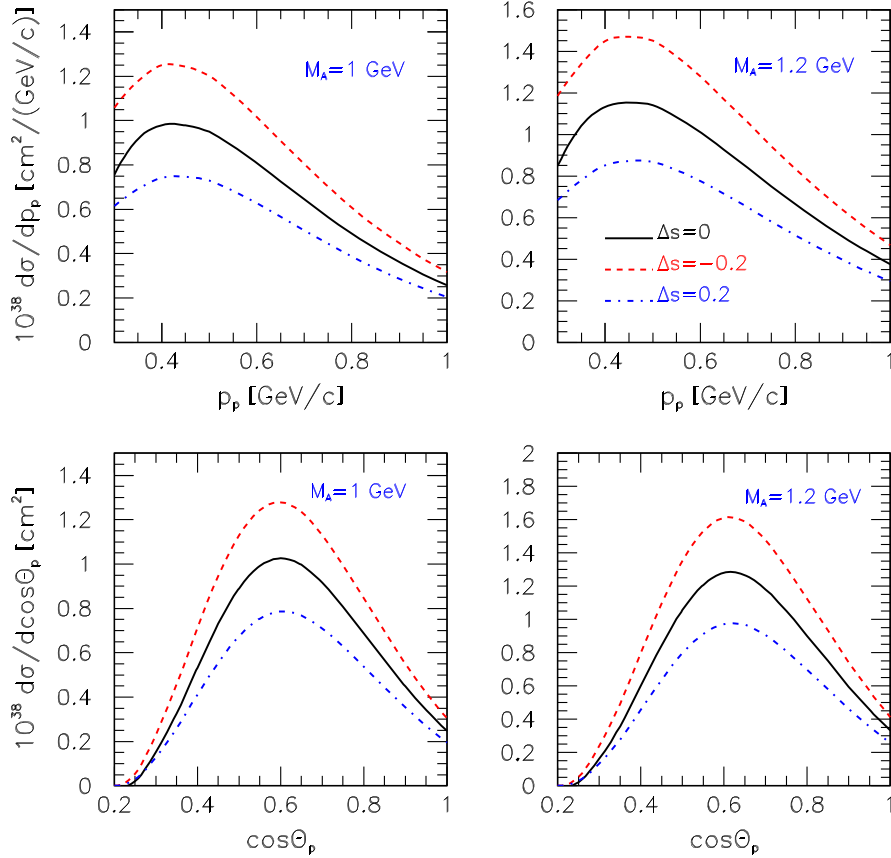


FIG. 5. The flux-integrated differential $d\sigma^{nc}/dp_p$ cross section (upper panel) as a function of proton momentum and $d\sigma^{nc}/d\cos\theta_p$ cross section (lower panel) as a function of $\cos\theta_p$. As shown in the key the semiexclusive cross sections were calculated with $M_A = 1$ GeV and 1.2 GeV. Also shown is the strange quark effect on the NCE cross section with a value $\Delta s = -0.2$ (dashed line), $\Delta s = 0$ (solid line), and $\Delta s = 0.2$ (dashed-dotted line).

shows the $d\sigma^{nc}/d\cos\theta_p$ cross section as a function of $\cos\theta_p$ for several values of the proton momentum. One can observe from Fig. 3 that in the region of the NCE peak the cross sections calculated with $M_A = 1.2$ GeV at $\cos\theta_p = 0.4(0.98)$ are larger than ones calculated with $M_A = 1$ GeV by about 15%(45%).

The flux-integrated differential cross sections $d\sigma^{nc}/dp_p$ as a function of proton momentum and $d\sigma^{nc}/d\cos\theta_p$ as a function of the cosine of the proton scattering angle, calculated with $M_A = 1$ GeV and 1.2 GeV are shown in Fig. 5. The effect of a nonzero strange quark contribution to the nucleon NC axial form factor also shown by comparing the results obtained with $\Delta s = 0$, $\Delta s = -0.2$, and $\Delta s = 0.2$. These values span the almost whole range of the values of Δs , extracted from experimental data. Note that the cross sections decrease when increasing Δs . For example, at the NCE peak the cross sections are reduced by about 65% when Δs running from $\Delta s = -0.2$ to $\Delta s = 0.2$.

Figure 6 shows the flux-integrated differential cross section $d\sigma^{nc}/dQ^2$ and a $R = \text{NCE}/\text{CCQE} = \langle\sigma^{nc}/dQ^2\rangle/\langle\sigma^{cc}/dQ^2\rangle$ cross section ratio as a function of Q^2 ,

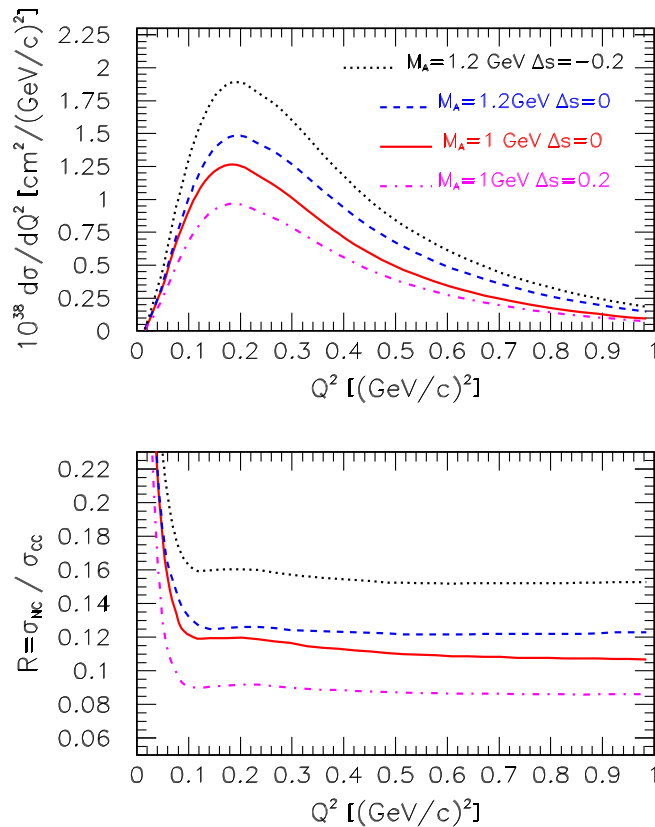


FIG. 6. The flux-averaged $d\sigma^{nc}/dQ^2$ cross section (upper panel) for neutrino scattering on ^{40}Ar and NCE/CCQE cross section ratio (lower panel) as a function of Q^2 . The cross section and ratio are calculated with values of $M_A = 1.2$ GeV and $\Delta s = -0.2$ (dotted line); $M_A = 1.2$ GeV and $\Delta s = 0$ (dashed line); $M_A = 1$ GeV and $\Delta s = 0$ (solid line); $M_A = 1$ GeV and $\Delta s = 0.2$ (dashed-dotted line).

calculated with $M_A = 1(1.2)$ GeV and $\Delta s = -0.2, 0$, and 0.2 . The semiexclusive $\langle d\sigma^{cc}/dQ^2 \rangle$ cross section was calculated in Ref. [52]. One can observe that the ratio decreases slowly as Q^2 increases, and in the range of the NCE peak the $d\sigma^{nc}/dQ^2$ cross section, calculated with $M_A = 1.2$ GeV and $\Delta s = -0.2$ is about two times larger than one obtained with $M_A = 1$ GeV and $\Delta s = 0.2$. The NCE/CCQE ratio is used to search for strangeness effects because the uncertainties of the absolute neutrino flux as well as the sensitivity to the value of M_A and nuclear effects are reduced in this ratio. For example, in the range of the maximum the ratio calculated with $M_A = 1.2$ GeV and $\Delta s = -0.2$ is about 1.7 times larger than the ratio calculated with $M_A = 1$ GeV and $\Delta s = 0.2$. So, the theoretical uncertainties on the $d\sigma^{nc}/dQ^2$ cross section and NCE/CCQE ratio due to uncertainties of the values of M_A and Δs can reach 75–100%. A LArTPC detector's ability to detect low-energy protons translates into ability to measure F_A^s at low four-momentum transfer where $F_A^s \sim \Delta s$. Neutrino-argon scattering experiments are a suitable tool for extracting information about the contribution of strange quark to the neutral current axial current.

B. The flux-integrated cross sections and short baseline neutrino oscillations

The CCQE and NCE signals are a two-body interaction with fully constrained kinematics if the incoming and outgoing 4-vectors are known. In the LArTPC detector the neutrino CCQE interaction products (one lepton and one proton) can be accurately reconstructed. For these events, energy-momentum conservation constraints allow the neutrino energy to be determined from the final-state lepton energy and angle, the final-state proton energy and scattering angle, or a combination of the final-state lepton and proton measurements. In practice, the reconstructed kinematics of the CCQE and NCE events may suffer substantial from smearing in the initial nucleon momentum, which is unknown, and from final state interactions as the proton exits the nucleus.

We assume that the neutrino scatters off a single nucleon at rest and ignores nuclear effects, including nucleon-nucleon correlations and nuclear recoil in the quasielastic and elastic interactions. Then, the incoming neutrino energy can be determined in the following ways:

$$\epsilon_{\text{rec}}^l = \frac{\epsilon_f(m - \epsilon_b) - (\epsilon_b^2 + m_l^2 - 2m\epsilon_b)/2}{(m - \epsilon_b) - \epsilon_f + k_f \cos\theta} \quad (23a)$$

$$\epsilon_{\text{rec}}^p = \frac{T_p(m - \epsilon_b) - (m_l^2 - \epsilon_b^2)/2}{p_x \cos\theta_p - (T_p + \epsilon_b)} \quad (23b)$$

$$\epsilon_{\text{rec}}^{lp} = \epsilon_f + T_p + \epsilon_b, \quad (23c)$$

where T_p is proton kinetic energy determined from the track length and ϵ_b is the nucleon binding energy. For the

NCE scattering, where the outgoing neutrino is unmeasured, to reconstruct the incoming neutrino energy we use the kinematics of the outgoing proton, i.e., Eq. (23b) with $m_l = 0$. In the case of well-reconstructed CCQE events $\mathbf{e}_{\text{rec}}^l$ and $\mathbf{e}_{\text{rec}}^p$ will be in good agreement with $\mathbf{e}_{\text{rec}}^{lp}$.

We write the double differential cross section for the CCQE and NCE scattering in terms of the final state proton momentum p_p and reconstructed neutrino energy $\mathbf{e}_{\text{rec}}^p$, using Eqs. (13) and (23b)

$$\frac{d^2\sigma}{dp_x d\mathbf{e}_{\text{rec}}^p} = R_{e_p} \frac{d^2\sigma}{dp_x d \cos\theta_p}, \quad (24)$$

where

$$R_{e_p} = \frac{p_x^2 + m_l^2 - (T_x + \epsilon_b)^2}{2p_x (\mathbf{e}_{\text{rec}}^p)^2}. \quad (25)$$

Note that in Eq. (25) $m_l = 0$ for the case of NCE scattering. The differential cross section as a function of $\mathbf{e}_{\text{rec}}^p$ is given by

$$\frac{d\sigma}{d\mathbf{e}_{\text{rec}}^p} = \int_{p_{\text{min}}}^{p_{\text{max}}} \frac{d^2\sigma}{d\mathbf{e}_{\text{rec}}^p dp_x} dp_x, \quad (26)$$

where $p_{\text{min}} = 0.3$ GeV/c and $p_{\text{max}} = 1$ GeV/c correspond a phase-space region where the data were taken in the MicroBooNE experiment.

In the SBN program three detectors are used to measure the same neutrino beam at different distances from the source. SBND, a 112 ton LArTPC is the near detector will be located 110 m downstream from the BND target and 60 m from the downstream face of the decay region to measure the unoscillated neutrino flux. The far detector is the 476 ton active mass ICARUS-T600 detector sited 600 m from the target. The locations of the near and far detectors are optimized for maximal sensitivity in search for ~ 1 eV sterile neutrino [22]. In a sterile neutrino search based on NCE interactions, the signal is the disappearance of any active neutrinos. The NC disappearance provides the only means of directly constraining on the admixture of mass state ν_4 in the sterile flavor state ν_s .

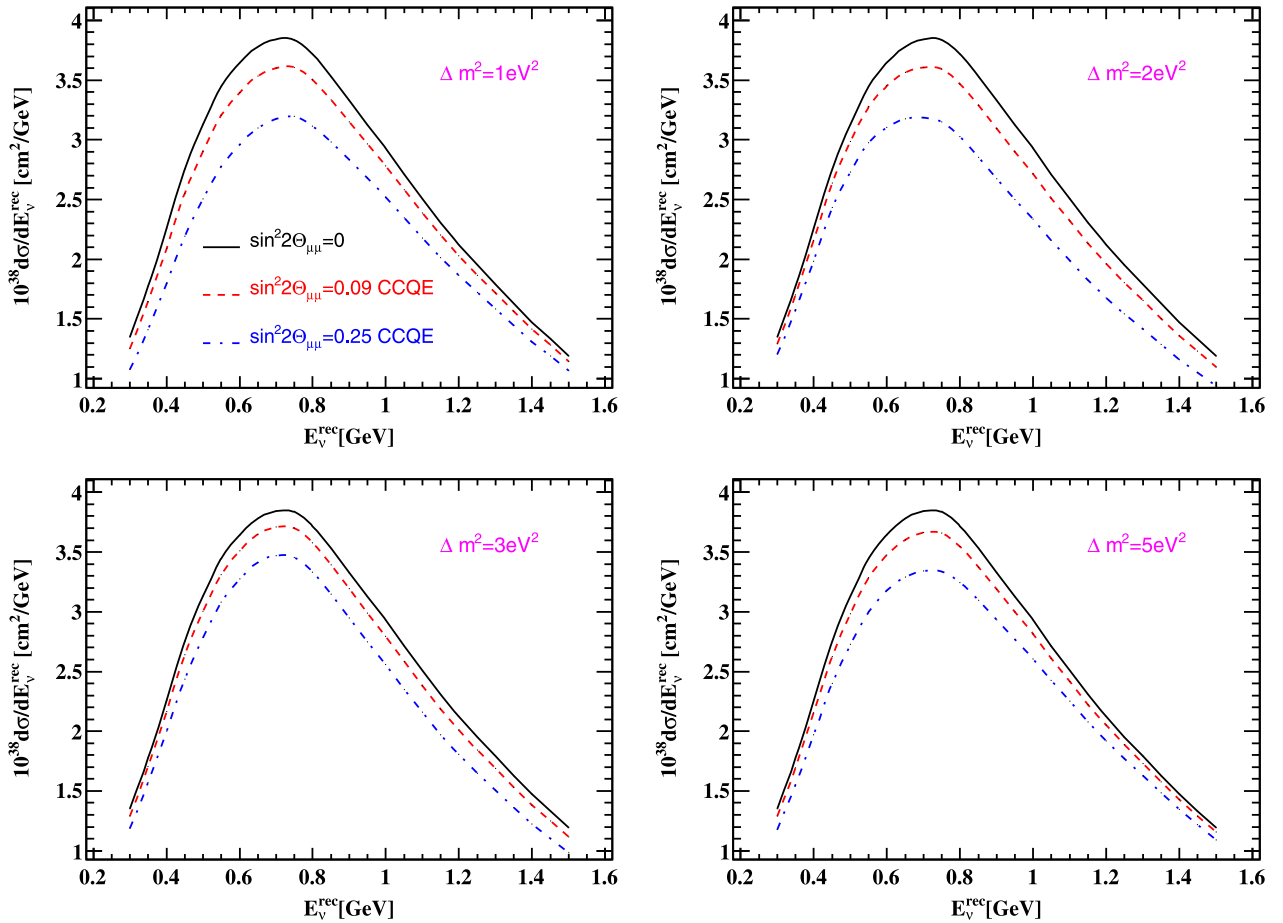


FIG. 7. The flux-integrated semiexclusive CCQE cross section as a function of E_{ν}^{rec} for the four values of $\Delta m_{41}^2 = 1, 2, 3,$ and 5 eV 2 . The solid line is result obtained with $\sin^2 2\theta_{\mu\mu} = 0$, whereas the dashed and dash-dotted lines are results for $\sin^2 2\theta_{\mu\mu} = 0.05$ and 0.25 , respectively.

The SBN physics program also includes the study of neutrino-argon cross sections. The multi-detector configuration allows simultaneous observation of neutrino interaction at difference distances and independently measure at the near and far detectors the flux-integrated CCQE and NCE cross sections as functions of the reconstructed neutrino energy. Taking into account sterile neutrino oscillation the flux-integrated cross section measured at the far detector can be written as

$$\left(\frac{d\sigma^{(cc)(nc)}}{d\mathbf{e}_{\text{rec}}^p}\right)_{\text{far}} = \int W_\nu(\mathbf{e}_i) P_{(\nu_\mu\nu_\mu)(\nu_s)}^{(cc)(nc)}(\mathbf{e}_i) \frac{d\sigma^{(cc)(nc)}}{d\mathbf{e}_{\text{rec}}^p}(\mathbf{e}_i, \mathbf{e}_{\text{rec}}^p) d\mathbf{e}_i, \quad (27)$$

where $P_{\nu_\mu\nu_\mu}^{(cc)}$ and $P_{\nu_s}^{(nc)}$ are probabilities of survival of muon and active neutrino, respectively. If the unit-normalized neutrino flux at the near detector W_ν^{ND} is the same as at the far detector W_ν^{FD} , the oscillation signal can be identified by observing any variation in the ratio of the cross sections measured at the far and near detectors, i.e.,

$$R = (d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{far}} / (d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{near}}, \quad (28)$$

where

$$\left(\frac{d\sigma^{(cc)(nc)}}{d\mathbf{e}_{\text{rec}}^p}\right)_{\text{near}} = \int W_\nu(\mathbf{e}_i) \frac{d\sigma^{(cc)(nc)}}{d\mathbf{e}_{\text{rec}}^p}(\mathbf{e}_i, \mathbf{e}_{\text{rec}}^p) d\mathbf{e}_i \quad (29)$$

is the cross section measured at the near detector.

In the SBN experiment W_ν^{ND} at the near SBND is not exactly the same as W_ν^{FD} at the ICARUS detector due to neutrino flux divergence [22]. To search for the oscillation effects we need use the ratio of the measured and predicted cross section at the far detector

$$R_\sigma^{\text{exp}} = (d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{FD}}^{\text{data}} / (d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{FD}}^{\text{pred}}. \quad (30)$$

The predicted cross section can be expressed as

$$(d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{FD}}^{\text{pred}} = F(\mathbf{e}_{\text{rec}}^p) (d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{FD}}^{\text{cal}}, \quad (31)$$

where $(d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{FD}}^{\text{cal}}$ is the flux-integrated cross section at the far detector calculated with no-oscillation and $W_\nu = W_\nu^{\text{FD}}$. Discrepancy between measured and calculated with $W_\nu = W_\nu^{\text{ND}}$ cross sections at the near detector (29)

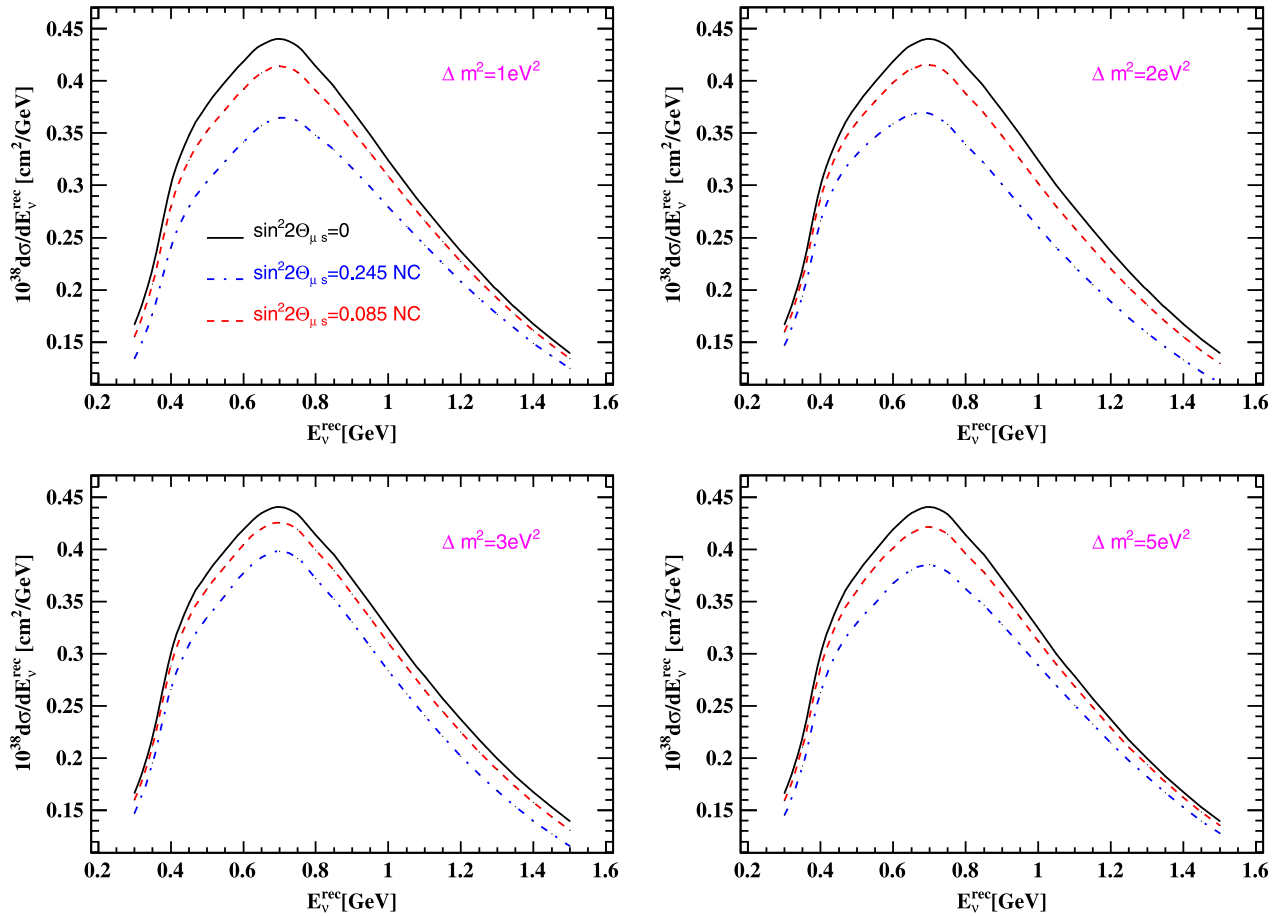


FIG. 8. Same as Fig. 7, but for NCE cross section and $\sin^2 2\theta_{\mu s} = 0, 0.085, \text{ and } 0.245$.

$$F(\mathbf{e}_{\text{rec}}^p) = (d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{ND}}^{\text{data}} / (d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{ND}}^{\text{cal}} \quad (32)$$

is extrapolated to produce the predicted cross section at the far detector for the some oscillation hypothesis

$$(d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{osc}}^{\text{pred}} = F(\mathbf{e}_{\text{rec}}^p)(d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{osc}}^{\text{cal}}, \quad (33)$$

where $(d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{osc}}^{\text{cal}}$ is given by Eq. (27) with $W_\nu = W_\nu^{\text{FD}}$. Then the ratio

$$R_\sigma = (d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{osc}}^{\text{cal}} / (d\sigma^{(cc)(nc)}/d\mathbf{e}_{\text{rec}}^p)_{\text{FD}}^{\text{cal}} \quad (34)$$

can be used to determine significance of the muon and active neutrino disappearance observed at the far detector, but it not suitable for the determination of the oscillation parameters, since this ratio is not a function of the true neutrino energy.

C. Oscillation model

We use the 3 + 1 neutrino framework with an extended 4×4 unitary Pontekorvo-Maki-Nakagava-Sakata (PMNS)

matrix $[U_{ai}]$. The flavor ν_α and mass ν_i states are now connected by PMNS matrix $\nu_\alpha = \sum U_{ai}\nu_i$. Assuming the fourth neutrino mass eigenstates is much heavier than the others ($m_4 \gg m_3, m_2, m_1$) the short-baseline survival probability for muon neutrino takes the form

$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \Delta_{41} \quad (35)$$

and for active neutrinos

$$P_{\nu_s} = 1 - \sin^2 2\theta_{\mu s} \sin^2 \Delta_{41}, \quad (36)$$

where $\Delta_{41} = \Delta m_{41}^2 L/4E = 1.267(\Delta m_{41}^2/\text{eV}^2)(\text{GeV}/E) \times (L/\text{km})$ and $\theta_{\alpha\beta}$ is defined as the effective mixing angle. These angles are expressed in terms of the matrix elements as

$$\sin^2 2\theta_{\mu\mu} = 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \quad (37a)$$

$$\sin^2 2\theta_{\mu s} = 4|U_{\mu 4}|^2|U_{s4}|^2. \quad (37b)$$

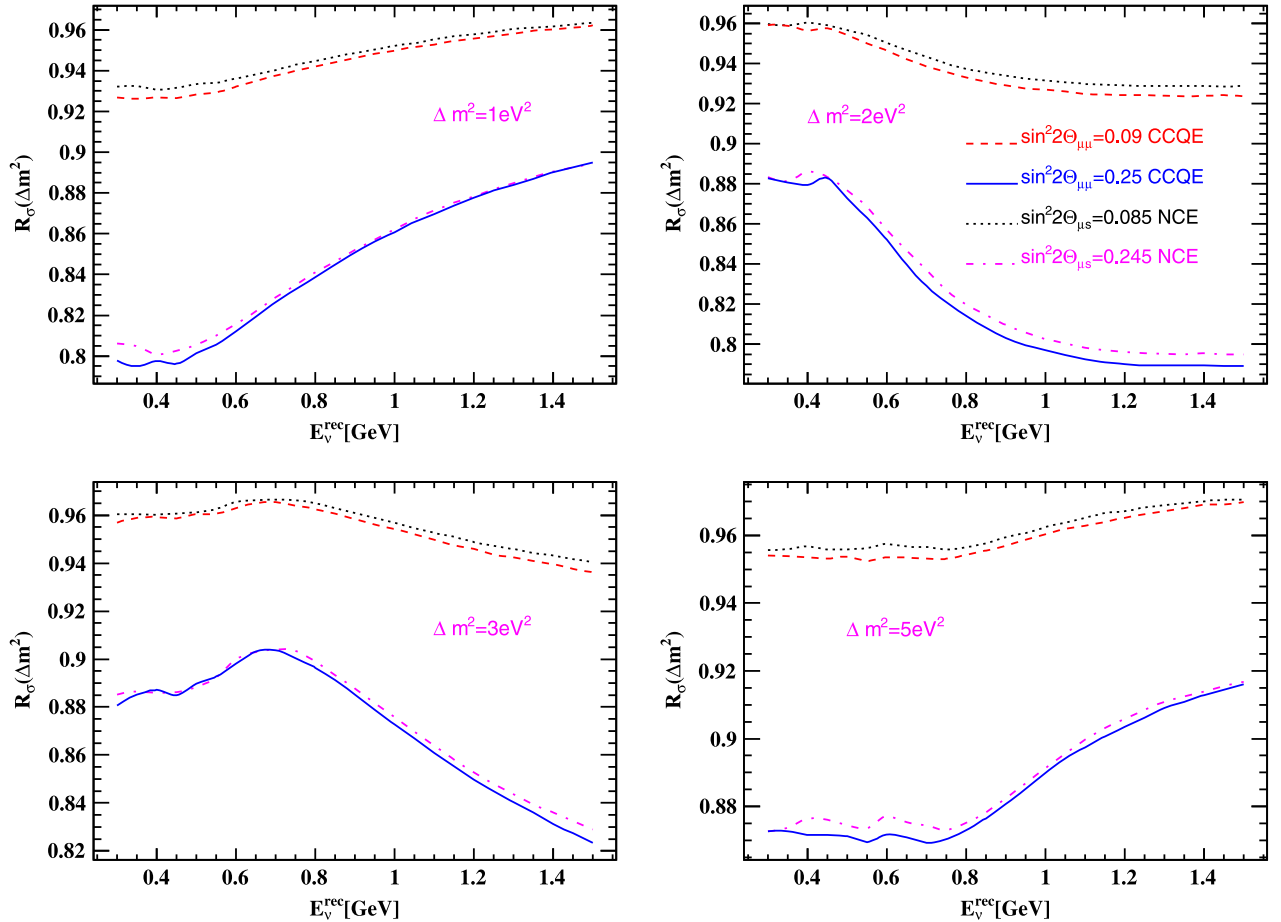


FIG. 9. The ratio R_σ of the flux-integrated semiexclusive CCQE and NCE cross sections as a function of E_ν^{rec} . The cross sections at the far detector are calculated for the four values of $\Delta m_{41}^2 = 1, 2, 3,$ and 5 eV^2 . The solid and dashed lines are results obtained for CCQE interactions with $\sin^2 2\theta_{\mu\mu} = 0.09$ and 0.25 , respectively. The dotted and dash-dotted lines are results obtained for NCE interactions with $\sin^2 2\theta_{\mu s} = 0.085$ and 0.245 , respectively.

The effective mixing angle $\sin^2 2\theta_{\mu s}$ can be related to other mixing angles by imposing unitarity on the 4×4 PMNS matrix

$$\sum_{i=e,\mu,\tau,s} |U_{i4}|^2 = 1. \quad (38)$$

This equation relates the effective angles

$$\sin^2 2\theta_{\mu s} = \sin^2 2\theta_{\mu\mu} - \sin^2 2\theta_{\mu e} - \sin^2 2\theta_{\mu\tau} \quad (39)$$

and provides a constraint $\sin^2 2\theta_{\mu\mu} \geq \sin^2 2\theta_{\mu s}$. To study sensitivities of the flux-integrated differential CCQE and NCE cross sections to neutrino oscillations we use the allowed values of $(\Delta m_{41}^2, \sin^2 2\theta_{\mu\mu})$ found in the MicroBooNE experiment [66], i.e., $1 \leq \Delta m_{41}^2 \leq 5 \text{ eV}^2$ and $0.09 \leq \sin^2 2\theta_{\mu\mu} \leq 0.25$. In this experiment the $3 + 1$ model was tested with data using CCQE $1\mu 1p$ events and muon neutrino disappearance was not observed. On the other hand, to our knowledge, a global analysis of sterile neutrino induced NC disappearance does not exist. Therefore, we estimated the range of the allowed values of $\sin^2 2\theta_{\mu s}$ as

$0.085 \leq \sin^2 2\theta_{\mu s} \leq 0.245$, using Eq. (39) and assuming that $\sin^2 2\theta_{\mu\tau} + \sin^2 2\theta_{\mu e} < 0.05$ [67].

D. Sensitivity of the flux-averaged $d\sigma/d\epsilon_{\text{rec}}^p$ cross sections to the short baseline neutrino oscillations

The flux-integrated semiexclusive differential CCQE and NCE cross sections of $\nu_{\mu}^{40}\text{Ar}$ scattering are presented in Figs. 7 and 8, respectively. The figures show $d\sigma/dE_{\nu}^{\text{rec}}$ cross sections as functions of reconstructed neutrino energy $E_{\nu}^{\text{rec}} = \epsilon_{\text{rec}}^p$ (23c), calculated with $M_A = 1 \text{ GeV}$ and $\Delta s = 0$. Here, the results obtained for the near detector with null oscillation effects (i.e., with $\sin^2 2\theta_{\mu\mu} = \sin^2 2\theta_{\mu s} = 0$) are presented by the solid lines. Also shown in these figures are the cross sections, calculated for the far detector at the distance $L = 600 \text{ m}$, with the oscillation parameters $\Delta m_{41}^2 = 1, 2, 3, \text{ and } 5 \text{ eV}^2$, $\sin^2 2\theta_{\mu\mu} = 0.09, 0.25$, $\sin^2 2\theta_{\mu s} = 0.085, 0.245$. Note that the maximum of the cross sections occurs at the same energy $\epsilon_i \simeq 0.7 \text{ GeV}$ as in BNB. To show the effect of muon and active neutrino disappearance we present in Fig. 9 the ratios R_{σ} of the cross sections (39), as a function of E_{ν}^{rec} . This figure demonstrates

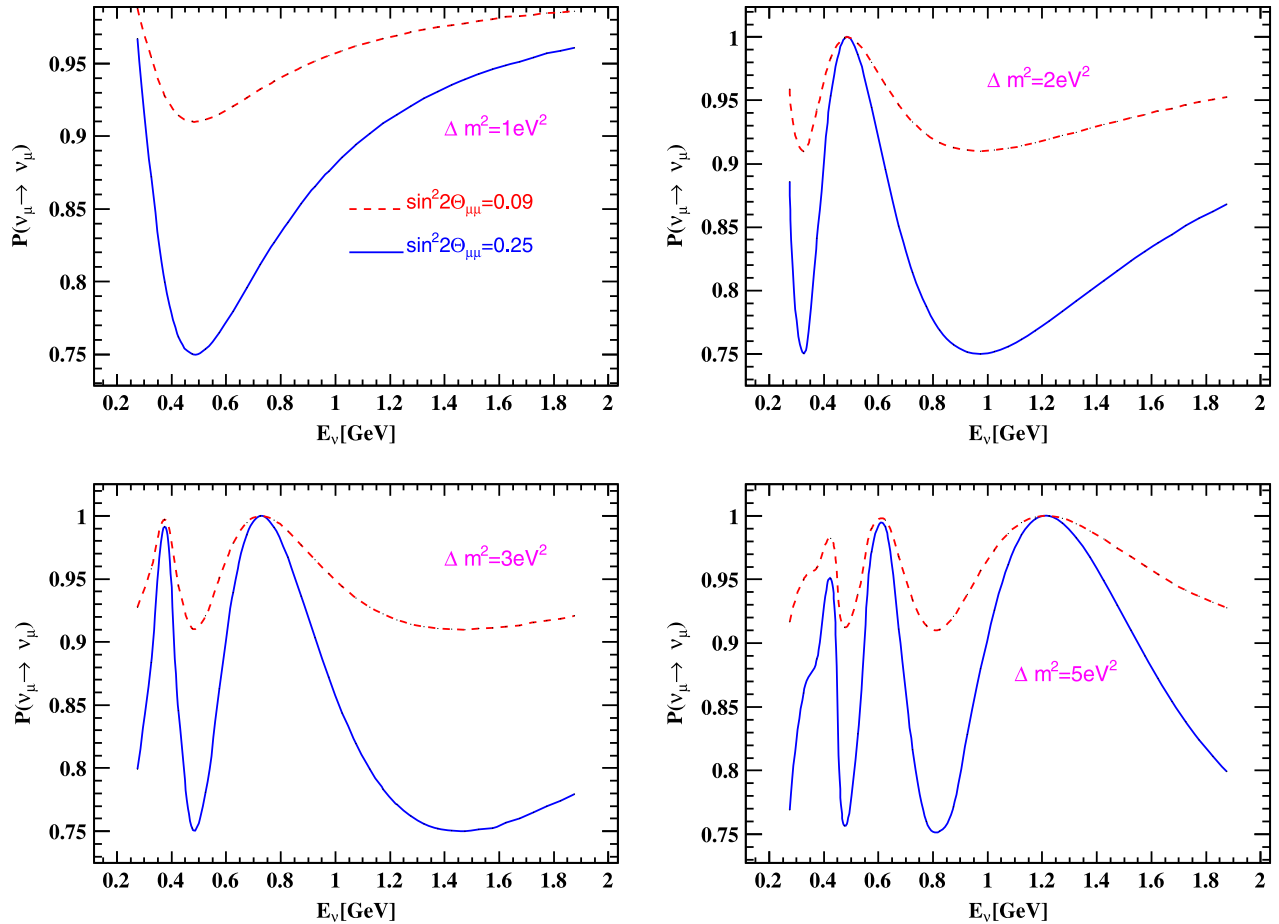


FIG. 10. Survival probability for muon neutrino as a function of neutrino energy, calculated at $L = 600 \text{ m}$ for the values of $\Delta m_{41}^2 = 1, 2, 3, \text{ and } 5 \text{ eV}^2$. The solid and dashed lines are results obtained with $\sin^2 2\theta_{\mu\mu} = 0.25$ and 0.09 , respectively.

that the form of the $R_\sigma(E_\nu^{\text{rec}})$ dependence is sensitive to the value of Δm_{41}^2 . In Fig. 10 the survival probability for muon neutrino $P_{\nu_\mu\nu_\mu}$ at the distance $L = 600$ m, calculated for the same values of Δm_{41}^2 and $\sin^2 2\theta_{\mu\mu}$ is shown as a function of neutrino energy ϵ_i , for comparison. One can observe from these figures that the position of the minimum $\epsilon_{\min}^{\text{rec}}$ and maximum $\epsilon_{\max}^{\text{rec}}$ in the $R_\sigma(E_\nu^{\text{rec}})$ distribution depends on the value of Δm_{41}^2 and correlates strongly with the values of the energy, that correspond to the first minimum $E_{\min} = 2.57\Delta m_{41}^2 L/\pi$ and maximum $E_{\max} = E_{\min}/2$ in the $P_{\nu_\mu\nu_\mu}$. For example, $\epsilon_{\min}^{\text{rec}}(E_{\min}) \approx 0.45(0.48)$ GeV at $\Delta m_{41}^2 = 1$ eV²; $\epsilon_{\min}^{\text{rec}}(E_{\min}) \approx 1.25(1.0)$ GeV, $\epsilon_{\max}^{\text{rec}}(E_{\max}) \approx 0.45(0.48)$ GeV at $\Delta m_{41}^2 = 2$ eV²; $\epsilon_{\min}^{\text{rec}}(E_{\min}) \approx 1.5(1.44)$ GeV, $\epsilon_{\max}^{\text{rec}}(E_{\max}) \approx 0.75(0.75)$ GeV at $\Delta m_{41}^2 = 3$ eV². In the region of $\epsilon_{\min}^{\text{rec}}$ the effect of neutrino oscillation is predicted to be $0.8 \leq R_\sigma \leq 0.96$.

Statistics of the CCQE and NCE-like candidate events collected at these detectors will allow the determination of R_σ ratios with high precision. Therefore they can be used to search for the short baseline oscillations for ~ 1 eV sterile neutrino, since with $\Delta m_{41}^2 > 2$ eV² it is necessary to take into account the effects of oscillations at the near detector.

IV. CONCLUSIONS

In this article we study semiexclusive CCQE and NCE neutrino scattering on argon in the framework of the RDWIA approach. We calculate the flux-integrated differential cross sections with $M_A = 1$ GeV and 1.2 GeV. The elastic scattering cross sections are also evaluated with different strange quark contributions to the NC axial form factor. It is shown that the maxima of the $d^2\sigma^{cc}/dp_p d\cos\theta_p$ and $d^2\sigma^{nc}/dp_p d\cos\theta_p$ are in the

region $0.3 \leq p_p \leq 0.6$ GeV/c and $0.4 \leq \cos\theta_p \leq 0.6$. Moreover, the shapes of these distributions are very similar. We calculate the flux-integrated NCE $d\sigma^{nc}/dp_p$, $d\sigma^{nc}/d\cos\theta_p$, and $d\sigma^{nc}/dQ^2$ cross sections, as well as the NCE/CCQE ratio with $\Delta s = -0.2, 0, 0.2$. Theoretical uncertainties in these cross sections and ratio due to uncertainties in the NC axial form factor (in M_A and Δs) can reach 75-100%.

The flux-integrated semiexclusive differential CCQE and NCE cross sections as functions of the reconstructed neutrino energy are calculated for the far detector of the SBN experiment with no-oscillation and taking into account the short baseline sterile neutrino oscillation effects leading to the disappearance of ν_μ and ν_{active} . We use the $3 + 1$ framework with the values of oscillation parameters $1 \leq \Delta m_{41}^2 \leq 5$ eV² and $0.09(0.085) \leq \sin^2 2\theta_{\mu\mu(\mu s)} \leq 0.25(0.245)$. To show the oscillation effects we have also calculated the R_σ ratio of the cross sections at the far detector. We found that the positions of minimum and maximum of the R_σ ratio depend on the value of Δm_{41}^2 and correlate with the positions of the first minimum and maximum in the survival probability for muon and active neutrino at the far detector.

Therefore, the ratio of the measured and predicted cross sections at the far detector of the SBN experiment can be used in a sterile-based oscillation study.

ACKNOWLEDGMENTS

The author greatly acknowledges A. Habig for fruitful discussions and a critical reading of the manuscript. I would like to thank A. Olshevskiy, V. Naumov, O. Samoylov, N. Anfimov, I. Kokorin, and L. Kolupaeva for their constructive comments and suggestions.

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- [1] G. T. Garvey, W. C. Louis, and D. H. White, *Phys. Rev. C* **48**, 761 (1993).
 - [2] W. M. Alberico, S. M. Bilenyk, and C. Maieron, *Phys. Rep.* **358**, 227 (2002).
 - [3] K. A. Aniol *et al.* (HAPPEX Collaboration), *Phys. Rev. Lett.* **82**, 1096 (1999); *Eur. Phys. J. A* **31**, 597 (1999).
 - [4] D. T. Spayde, T. Averett, D. Barkhuff, D. H. Beck, E. J. Beise, C. Benson *et al.*, *Phys. Rev. Lett.* **84**, 1106 (2000); *Phys. Lett. B* **583**, 79 (2004).
 - [5] F. E. Maas, P. Achenbach, K. Aulenbacher, S. Baunack, L. Capozza, J. Diefenbach *et al.*, *Phys. Rev. Lett.* **93**, 022002 (2004).
 - [6] F. E. Maas, K. Aulenbacher, S. Baunack, L. Capozza, J. Diefenbach, B. Glaser *et al.*, *Phys. Rev. Lett.* **94**, 152001 (2005).
 - [7] D. S. Armstrong *et al.* (G0 Collaboration), *Phys. Rev. Lett.* **95**, 092001 (2005).
 - [8] J. Liu, R. D. McKeown, and M. J. Ramsey-Musolf, *Phys. Rev. C* **76**, 025202 (2007).
 - [9] R. Gonzalez-Jimenez, J. A. Caballero, and T. W. Donnelly, *Phys. Rep.* **524**, 1 (2013).
 - [10] L. A. Ahrens, S. H. Aronson, P. L. Connolly, B. G. Gibbard, M. J. Murtagh, S. J. Murtagh *et al.*, *Phys. Rev. D* **35**, 785 (1987).
 - [11] S. Brice *et al.* (FINeSSE Collaboration), [arXiv:hep-ex/0402007](https://arxiv.org/abs/hep-ex/0402007).
 - [12] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), *Phys. Rev. D* **82**, 092005 (2010).
 - [13] C. Athanassopoulos, L. B. Auerbach, R. L. Burman, I. Cohen, D. O. Caldwell, B. D. Dieterle *et al.* (LSND Collaboration), *Phys. Rev. Lett.* **77**, 3082 (1996).

- [14] A. A. Aguilar-Arevalo, B. C. Brown, L. Bugel, G Cheng, J. M. Conrad, R. L. Cooper *et al.* (MiniBooNE Collaboration), *Phys. Rev. Lett.* **121**, 221801 (2018).
- [15] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier, and A. Letourneau, *Phys. Rev. D* **83**, 073006 (2011).
- [16] W. Hampel *et al.* (GALLEX Collaboration), *Phys. Lett. B* **420**, 114 (1998).
- [17] V. V. Barinov, B. T. Cleveland, S. N. Danshin, H. Ejiri, S. R. Elliott, D. Frekers *et al.* (BEST Collaboration), *Phys. Rev. Lett.* **128**, 232501 (2022).
- [18] P. Adamson *et al.* (MINOS+ Collaboration), *Phys. Rev. Lett.* **122**, 091803 (2019).
- [19] M. G. Aartsen *et al.* (IceCube Collaboration), *Phys. Rev. D* **102**, 052009 (2020).
- [20] M. A. Acero *et al.* (NOVA Collaboration), *Phys. Rev. Lett.* **127**, 201801 (2021).
- [21] Q. R. Ahmad *et al.* (SNO Collaboration), *Phys. Rev. Lett.* **89**, 011301 (2002).
- [22] M. Antonello *et al.* (MicroBooNE, LAr1-ND, and ICARUS-WA104 Collaborations), [arXiv:1503.01520](https://arxiv.org/abs/1503.01520).
- [23] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. Lett.* **128**, 241801 (2022).
- [24] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. D* **105**, 112003 (2022).
- [25] W. M. Alberico, M. B. Barbado, S. M. Bilenky, J. A. Caballero, C. Giunti, C. Maieron, E. Moya de Guerra, and J. M. Udias, *Nucl. Phys.* **A623**, 471 (1997).
- [26] M. B. Barbaro, A. De Pace, T. W. Donnelly, A. Molinari, and M. J. Musolf, *Phys. Rev. C* **54**, 1954 (1996).
- [27] M. C. Martinez, P. Lava, N. Jachowicz, J. Ryckebusch, K. Vantournhout, and J. M. Udias, *Phys. Rev. C* **73**, 024607 (2006).
- [28] J. Nieves, M. Valverde, and M. J. Vicente Vacas, *Phys. Rev. C* **73**, 025504 (2006).
- [29] T. Leitner, L. Alvarez-Ruso, and U. Mosel, *Phys. Rev. C* **74**, 065502 (2006).
- [30] A. V. Butkevich and D. Perevalov, *Phys. Rev. C* **84**, 015501 (2011).
- [31] R. Gonzalez-Jimenez, J. A. Caballero, A. Meucci, C. Giusti, M. B. Barbaro, M. V. Ivanov, and J. M. Udias, *Phys. Rev. C* **88**, 025502 (2013).
- [32] A. Meucci and C. Giusti, *Phys. Rev. D* **89**, 057302 (2014).
- [33] R. Gonzalez-Jimenez, M. V. Ivanov, M. B. Barbaro, J. A. Caballero, and J. M. Udias, *Phys. Lett. B* **718**, 1471 (2013).
- [34] N. Rocco, C. Barbieri, O. Benhar, A. De Pace, and A. Lovato, *Phys. Rev. C* **99**, 025502 (2019).
- [35] C. Giusti and M. I. Ivanov, *J. Phys. G* **47**, 024001 (2020).
- [36] R. Acciarri *et al.* (DUNE Collaboration), Report No. FER-MILAB-DESIGN-2016-03.
- [37] L. Gu *et al.* (Jefferson Lab Hall A Collaboration), *Phys. Rev. C* **103**, 034604 (2021).
- [38] L. Jiang *et al.* (Jefferson Lab Hall A Collaboration), *Phys. Rev. D* **105**, 112002 (2022).
- [39] L. Jiang *et al.* (Jefferson Lab Hall A Collaboration), *Phys. Rev. D* **107**, 012005 (2023).
- [40] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. Lett.* **125**, 201803 (2020).
- [41] L. Ren (MicroBooNE Collaboration), *Proc. Sci. NuFact2021* (2022) 205.
- [42] A. Picklesimer, J. W. Van Orden, and S. J. Wallace, *Phys. Rev. C* **32**, 1312 (1985).
- [43] A. Picklesimer and J. W. Van Orden, *Phys. Rev. C* **35**, 266 (1987).
- [44] J. J. Kelly, *Adv. Nucl. Phys.* **23**, 75 (1996).
- [45] J. J. Kelly, *Phys. Rev. C* **59**, 3256 (1999).
- [46] J. M. Udias, J. A. Caballero, E. Moya de Guerra, Javier R. Vignote, and A. Escuderos, *Phys. Rev. C* **64**, 024614 (2001).
- [47] A. Meucci, C. Giusti, and F. D. Pacati, *Nucl. Phys.* **A739**, 277 (2004).
- [48] A. V. Butkevich and S. A. Kulagin, *Phys. Rev. C* **76**, 045502 (2007).
- [49] A. V. Butkevich, *Phys. Rev. C* **82**, 055501 (2010).
- [50] A. V. Butkevich, *Phys. Rev. C* **85**, 065501 (2012).
- [51] A. V. Butkevich and S. V. Luchuk, *Phys. Rev. C* **102**, 024602 (2020).
- [52] A. V. Butkevich, *Phys. Rev. C* **105**, 025501 (2022).
- [53] S. A. Kulagin and R. Petti, *Nucl. Phys.* **A765**, 126 (2006).
- [54] P. Mergell, U.-G. Meissner, and D. Drechsel, *Nucl. Phys.* **A596**, 367 (1996).
- [55] T. de Forest, *Nucl. Phys.* **A392**, 232 (1983).
- [56] C. J. Horowitz and Brian D. Serot, *Nucl. Phys.* **A368**, 503 (1981).
- [57] C. J. Horowitz, D. P. Murdock, and Brian D. Serot, in *Computational Nuclear Physics I: Nuclear Structure* edited by K. Langanke, J. A. Maruhn, and Steven E. Koonin (Springer-Verlag, Berlin, 1991), p. 129.
- [58] J. J. Kelly, <http://www.physics.umd.edu/enp/jjkelly/LEA>.
- [59] E. D. Cooper, S. Hama, B. C. Clark, and R. L. Mercer, *Phys. Rev. C* **47**, 297 (1993).
- [60] K. G. Fissum *et al.*, *Phys. Rev. C* **70**, 034606 (2004).
- [61] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), *Phys. Rev. D* **79**, 072002 (2009).
- [62] C. Wilkinson *et al.*, *Phys. Rev. D* **93**, 072010 (2016).
- [63] A. V. Butkevich and S. V. Luchuk, *Phys. Rev. D* **99**, 093001 (2019).
- [64] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. D* **105**, 072001 (2022).
- [65] K. Abe *et al.* (T2K Collaboration), *Phys. Rev. D* **103**, 112008 (2021).
- [66] MicroBooNE Collaboration, MicroBooNE Public Note (2022), p. 1106.
- [67] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. Lett.* **130**, 011801 (2023).