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Spin effects in quasi-elastic neutrino-nucleus reactions

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Results are presented for the polarization of the ejectile in quasi-elastic neutral-current neutrino (antineutrino) scattering off ^{12}C. A relativistic distorted-wave impulse-approximation model is used for the calculations where the bound state is obtained in the framework of the relativistic mean field theory and the final state interaction is taken into account in the scattering state by means of a relativistic optical potential. The sensitivity to the strange-quark content of the nucleon weak current is discussed.

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I. INTRODUCTION

Polarization phenomena in electron scattering have been the subject of various theoretical and experimental studies. Indeed, only for reactions with polarized particles is it possible to obtain a large number of observables that are sensitive to the small components of the transition amplitude but vanish when sum and/or average over spin states is performed [1]. In the past years, owing to new experimental techniques, a few measurements of polarization observables in electron scattering have been carried out at MIT-Bates [2,3] and JLab [4–6]. Despite the growing interest in neutrino physics, only little attention is generally paid to polarization observables in neutrino-nucleus scattering. The spin dependence of neutral-current (NC) neutrino-induced nucleon knockout was noted in Ref. [7] and systematically investigated in a nonrelativistic plane wave impulse approximation for neutrino energies up to 500 MeV in Ref. [8]. It was found that the ejected nucleon polarization provides a clear way to discriminate between neutrinos and antineutrinos. In nuclear and hadronic physics neutrino-nucleus scattering can give information on the contribution of the sea quarks to the properties of the nucleon. Whereas parity-violating (PV) electron scattering is sensitive to the electric and magnetic strangeness, neutrino-induced reactions are primarily suited to look for the strange contribution to the axial form factor. A first measurement of $\nu(\bar{\nu})$-proton elastic scattering at Brookhaven National Laboratory (BNL) [9] suggested a nonzero value for the strange axial-vector form factor of the nucleon. However, it has been shown in Ref. [10] that the BNL data cannot provide us decisive conclusions about the strange form factors when strange vector form factors are also taken into account. Moreover, as cross section measurements are a very hard experimental task, ratios of cross sections have been usually proposed as alternative ways to search for strangeness. Thus, the FermiLab Intense Neutrino Scattering Scintillator Experiment (FINeSSE) [11,12] aims at performing a detailed investigation of the strangeness contribution to the proton spin via the measurement of the ratio of neutral-to-charged current cross section. When combined with the available PV data, a determination of the strange form factors in the range 0.25 GeV$/c^2 \leqslant Q^2 \leqslant 0.75$ GeV$/c^2$ would have to be possible [13]. Because a large part of the events at FINeSSE will be from ^{12}C, nuclear structure effects must be clearly understood to reach a reliable interpretation of neutrino data.

The sensitivity of the cross sections to the strange-quark contribution was examined in Ref. [14] in a relativistic plane wave impulse approximation (RPWIA). Detailed analyses of nuclear structure effects on the determination of strangeness contribution in NC ν-nucleus scattering were performed in Refs. [15] and [16], where the relativistic Fermi gas (RFG) model as well as a relativistic shell model including final state interactions (FSI) were used. The effects of FSI were also studied in Ref. [17] within the RFG model, in Ref. [18] in the framework of random phase approximation (RPA), and in Ref. [19] in the continuum RPA (CRPA) theory. A CRPA model was developed in Ref. [20], where nucleosynthesis processes were also discussed. The effects of FSI are generally large on the cross section, but they are usually reduced when studying ratios of cross sections [15,21,22]. In Ref. [23] two relativistic models were compared where FSI are treated with an optical potential and with a multiple-scattering Glauber approximation. A different relativistic optical potential model was presented in Ref. [24]. The effects of the strange-quark contribution were recently discussed in Ref. [25]. A first discussion of the sensitivity to the strangeness contribution of the helicity properties of the ejected nucleon was presented in Ref. [26] within the framework of the Glauber approximation.

In this article we present results for polarization observables of the ejectile in quasi-elastic ν- and $\bar{\nu}$-induced nucleon knockout reactions on ^{12}C. Our results are obtained with the relativistic distorted-wave impulse-approximation (RDWIA) model that was already presented in Ref. [27]. The ν-nucleus reaction where one nucleon is emitted is considered semi-exclusive in the hadronic sector and is treated within the same RDWIA approach that was successfully applied in Refs. [28–31] to electromagnetic nucleon knockout reactions.

The formalism is outlined in Sec. II. Results are presented and discussed in Sec. III. Some conclusions are drawn in Sec. IV.

II. FORMALISM FOR THE SEMI-EXCLUSIVE QUASI-ELASTIC SCATTERING

The $\nu(\bar{\nu})$-nucleus cross section for the semi-exclusive process where one nucleon is emitted is given by the contraction between the lepton tensor and the hadron tensor. The lepton tensor is defined in a manner similar to how it is defined in electromagnetic knockout and separates into a symmetrical and an anti-symmetrical component that are written as in Refs. [1,27,32,33]. The hadron tensor is given in its most general form by suitable bilinear products of the transition matrix elements of the nuclear weak-current operator. Assuming that the final states are given by the product of a discrete (or continuum) state of the residual nucleus and a scattering state of the emitted nucleon, in the impulse approximation the transition amplitude reduces to the sum of terms similar to those appearing in the exclusive $(e, e'p)$ knockout reaction [1,28].

The single-particle current operator related to the weak neutral current is

$$j^{\mu} = F_1^V \gamma^{\mu} + i\frac{\kappa}{2M} F_2^V \sigma^{\mu\nu} q_{\nu} - G_A \gamma^{\mu}\gamma^5. \tag{1}$$

The vector form factors F_i^V can be expressed in terms of the corresponding electromagnetic form factors for protons (F_i^p) and neutrons (F_i^n) [34], plus a possible isoscalar strange-quark contribution (F_i^s), i.e.,

$$\begin{aligned} F_i^V &= \tau_3 (0.5 - \sin^2\theta_W)\left\{F_i^p - F_i^n\right\}/2 \\ &\quad - \sin^2\theta_W \left\{F_i^p + F_i^n\right\} - F_i^s/2, \end{aligned} \tag{2}$$

where $\tau_3 = +1(-1)$ for proton (neutron) knockout and θ_W is the Weinberg angle ($\sin^2\theta_W \simeq 0.2313$). The strange vector form factors are taken as [35]

$$\begin{aligned} F_1^s(Q^2) &= \frac{(\rho^s + \mu^s)\tau}{(1+\tau)\left(1 + Q^2/M_V^2\right)^2}, \\ F_2^s(Q^2) &= \frac{(\mu^s - \tau\rho^s)}{(1+\tau)\left(1 + Q^2/M_V^2\right)^2}, \end{aligned} \tag{3}$$

where $Q^2 = |\mathbf{q}|^2 - \omega^2$ is the four-momentum transfer, $\tau = Q^2/(4M_p^2)$, and $M_V = 0.843$ GeV. The quantities μ^s and ρ^s are related to the strange magnetic moment and radius of the nucleus. The axial form factor is expressed as

$$G_A(Q^2) = \tfrac{1}{2}\left(\tau_3 g_A - g_A^s\right) G, \tag{4}$$

where $g_A \simeq 1.26$, g_A^s describes possible strange-quark contributions, and

$$G = \left(1 + Q^2/M_A^2\right)^{-2}. \tag{5}$$

The axial mass has been taken from Ref. [36] as $M_A = (1.026 \pm 0.021)$ GeV.

The differential cross section for the quasi-elastic $\nu(\bar{\nu})$-nucleus scattering is obtained from the contraction between the lepton and hadron tensors, as in Ref. [37]. After performing an integration over the solid angle of the final nucleon, we have

$$\begin{aligned} \frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon \mathrm{d}\Omega \mathrm{d}T_N} &= \frac{G_F^2}{2\pi^2}\varepsilon^2 \\ &\quad \times \cos^2\frac{\vartheta}{2}\left[v_L R_L + v_T R_T + h v_T' R_T'\right]\frac{|\boldsymbol{p}_N| E_N}{(2\pi)^3}, \end{aligned} \tag{6}$$

where $G_F \simeq 1.16639 \times 10^{-11}$ MeV^{-2} is the Fermi constant, ε and ϑ are the energy and the scattering angle of the emitted lepton, E_N and $\boldsymbol{p}_N$ are the relativistic energy and momentum of the outgoing nucleon, and $h = -1(+1)$ corresponds to the incident neutrino (antineutrino) helicity. For charged-current (CC) processes G_F^2 has to be multiplied by $\cos^2\vartheta_C \simeq 0.975$, where ϑ_C is the Cabibbo angle.

For NC reactions the coefficients v are given by

$$\begin{aligned} v_L &= 1, \\ v_T &= \tan^2\frac{\vartheta}{2} + \frac{Q^2}{2|\boldsymbol{q}|^2}, \\ v_T' &= \tan\frac{\vartheta}{2}\left[\tan^2\frac{\vartheta}{2} + \frac{Q^2}{|\boldsymbol{q}|^2}\right]^{\frac{1}{2}}, \end{aligned} \tag{7}$$

where the neutrino mass has been neglected. The corresponding response functions are expressed as suitable bilinear combinations of the hadron tensor components, i.e.,

$$\begin{aligned} R_L &= \int \mathrm{d}\Omega_N \left[W^{00} + \frac{\omega^2}{|\boldsymbol{q}|^2} W^{zz} - 2\frac{\omega}{|\boldsymbol{q}|}\mathrm{Re}(W^{0z})\right], \\ R_T &= \int \mathrm{d}\Omega_N [W^{xx} + W^{yy}], \\ R_T' &= \int \mathrm{d}\Omega_N 2\,\mathrm{Im}(W^{xy}). \end{aligned} \tag{8}$$

The single differential cross section with respect to the outgoing nucleon kinetic energy T_N is obtained after performing an integration over the energy and the angle of the final lepton.

Because in NC reactions the momentum transfer cannot be reconstructed, the only direction that can be defined is that of the outgoing nucleon. Hence, polarization studies have to focus on the longitudinal component, i.e., the component of the spin of the nucleon along its momentum. The different yields for the two possible longitudinal polarization states of the outgoing nucleon can be expressed as the polarization asymmetry, i.e.,

$$\mathcal{A} = \frac{\left[(\mathrm{d}\sigma/\mathrm{d}T_N)_{\uparrow} - (\mathrm{d}\sigma/\mathrm{d}T_N)_{\downarrow}\right]}{\left[(\mathrm{d}\sigma/\mathrm{d}T_N)_{\uparrow} + (\mathrm{d}\sigma/\mathrm{d}T_N)_{\downarrow}\right]}, \tag{9}$$

where the subscript ↑ (↓) stands for the spin component of the ejectile parallel (antiparallel) to its momentum.

III. RESULTS AND DISCUSSION

Results are presented for polarization observables of the ejectile in neutrino and antineutrino scattering from ^{12}C in a beam energy range up to 2000 MeV. The main aim of our investigation is to study the effects of FSI and of a nonzero contribution of the strangeness to the form factors.

In the calculations a pure shell model (SM) description is assumed for nuclear structure. Therefore, the residual nucleus is assumed to be a one-hole state in the SM, the initial bound state is a single-particle SM state with a unitary spectral strength, and the transition amplitude includes a sum over all the occupied states in the SM. In this way we include the contributions of all the nucleons in the nucleus but disregard effects of correlations. These effects, however, are expected to be small on the semi-exclusive cross section and, moreover, should not affect the role of FSI and of the strange-quark content of the form factors, which are the aims of the present investigation.

FSI are described by means of a relativistic complex optical potential where the imaginary part gives an absorption of flux that is correct for an exclusive reaction, but is conceptually wrong for an inclusive reaction where all the channels contribute and the total flux must be conserved. Here we consider semi-inclusive situations where an emitted nucleon is detected and treat the quasi-elastic neutrino scattering as a process where the cross section is obtained from the sum of all the integrated exclusive one-nucleon knockout channels. Some of the reaction channels that are responsible for the imaginary part of the optical potential, like multistep processes, fragmentation of the nucleus, absorption, etc., are not included in the experimental cross section because an emitted proton is always detected. However, the outgoing proton can be reemitted after rescattering in the detected channel, thus simulating the kinematics of a quasi-elastic reaction. We note that the same uncertainties are also present in other semi-inclusive experiments, like, for instance, in the analysis of the $(e, e'p)$ reaction at the quasi-elastic peak, when the emission from deep states is considered. A discussion of these effects was presented in a nonrelativistic framework for $(e, e'p)$ in Ref. [38]. Their relevance depends on kinematics, but a sizable contribution is obtained only at high excitation energies and missing momenta. An alternative treatment of FSI in neutrino reactions can be found in Ref. [39].

In the calculations we used the same relativistic bound state wave functions and optical potentials as in Refs. [28,29,40,41], where our RDWIA model was able to reproduce $(e, e'p)$, (γ, p), and (e, e') data. The bound states were obtained from Ref. [42], where relativistic Hartree-Bogoliubov equations are solved in the context of a relativistic mean field theory and reproduce single-particle properties of several spherical and deformed nuclei. The scattering states were computed by means of the energy-dependent and A-dependent EDAD1 complex phenomenological optical potential of Ref. [43], which is fitted to proton elastic scattering data on several nuclei in an energy range up to 1040 MeV. The neutron scattering states were computed with the same optical potential but neglecting the Coulomb interaction.

In Fig. 1 the differences between $\nu(\bar{\nu})$-induced contributions to the differential cross section for spin parallel $(\sigma\uparrow)$ or antiparallel $(\sigma\downarrow)$ proton knockout from ^{12}C are displayed as a function of the ejected proton kinetic energy at $E_\nu = 500$ and 1000 MeV. The unpolarized cross section is given by the sum of the two cross sections. In Fig. 2 the same contributions are displayed for the case of polarized neutron knockout. The transverse responses R_T and R'_T are the leading terms for the total cross section whereas the longitudinal contribution R_L is usually small. The only difference between neutrino and antineutrino nucleon knockout is given by the sign of the helicity h in front of the R'_T response in Eq. (6). This originates different and large interference effects between the transverse responses R_T and R'_T that make the antineutrino cross sections smaller than the neutrino ones. This difference increases with the incident energy. In the case of neutrino scattering the $\sigma\downarrow$ contribution largely dominates over the $\sigma\uparrow$ one. For an incident antineutrino the two contributions are somewhat energy dependent, with the spin-up nucleon knockout more significant at small energies, whereas the spin-down contribution becomes more important as the antineutrino energy increases [8].

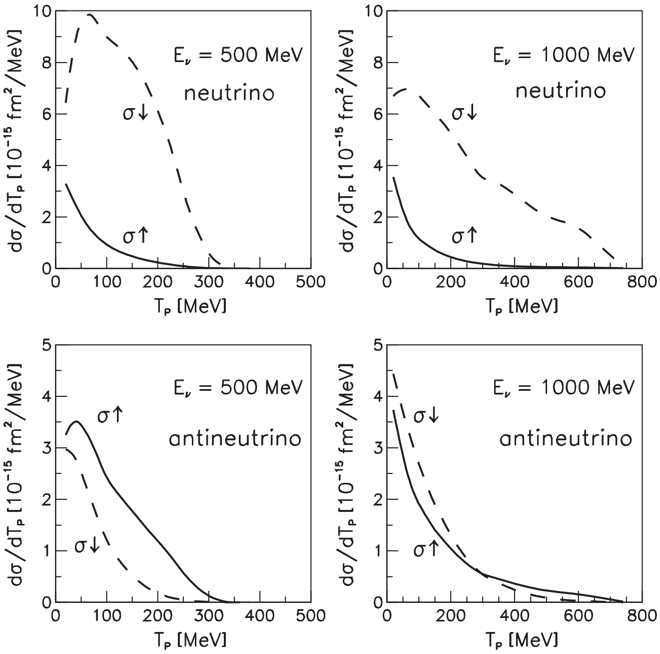

FIG. 1. Different contributions of the polarization of the emitted proton to the differential cross sections of the $\nu(\bar{\nu})$ quasi-elastic scattering on ^{12}C as a function of the outgoing proton kinetic energy T_p. Solid and dashed lines are the results for spin-up $(\sigma\uparrow)$ and spin-down $(\sigma\downarrow)$ proton knockout, respectively.

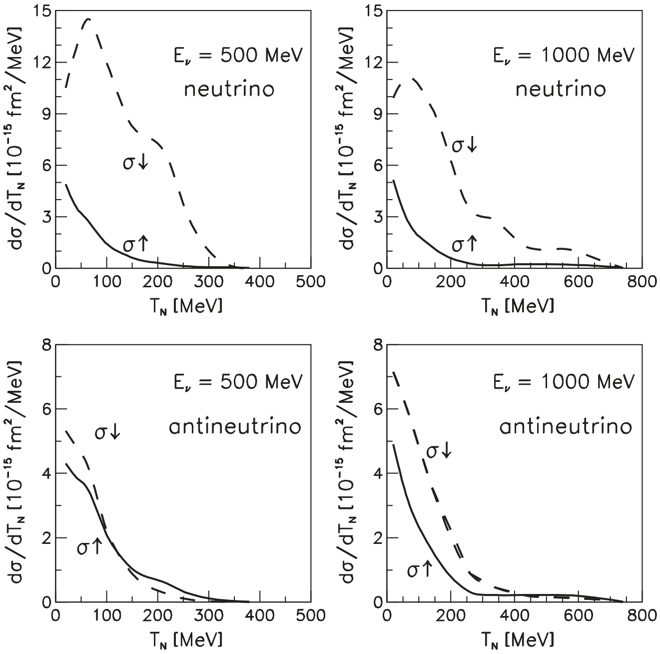

FIG. 2. The same as in Fig. 1, but for neutron knockout.

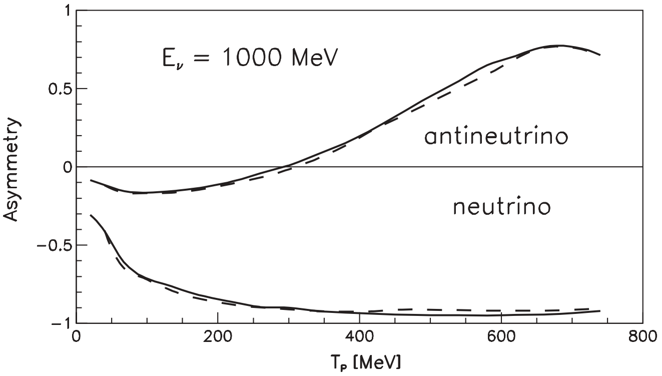

FIG. 3. The polarization asymmetry for the $\nu(\bar{\nu})$ quasi-elastic scattering on ^{12}C as a function of T_p at $E_\nu = 1000$ MeV. Solid lines are the RDWIA results; dashed lines are the RPWIA results.

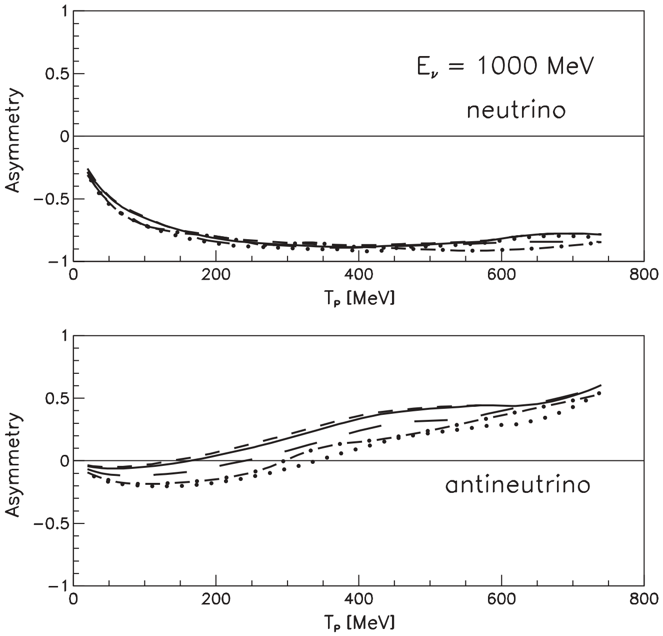

FIG. 5. The polarization asymmetry for the $\nu(\bar{\nu})$ quasi-elastic scattering on ^{12}C as a function of T_p at $E_{\nu(\bar{\nu})} = 1000$ MeV. Long dashed lines are the results with $g_A^s = -0.10$; solid lines the results with $g_A^s = -0.10$, $\rho^s = -1$, and $\mu^s = +0.30$; dashed lines the results with $g_A^s = -0.10$, $\rho^s = +1$, and $\mu^s = +0.30$; dot-dashed lines the results with $g_A^s = -0.10$, $\rho^s = +1$, and $\mu^s = -0.30$; and dotted lines the results with $g_A^s = -0.10$, $\rho^s = -1$, and $\mu^s = -0.30$.

To investigate possible effects of strange-quark contributions, ratios of cross sections have been widely discussed. The effects of FSI are largely suppressed in the ratios, thus facilitating the extraction of more exotic effects. Moreover, a ratio is less sensitive to uncertainties in the determination of the incident neutrino flux. In Fig. 3 our results for the longitudinal asymmetry defined in Eq. (9) for $\nu(\bar{\nu})$-scattering on ^{12}C are displayed at $E_\nu = 1000$ MeV in RPWIA and RDWIA. FSI effects are strongly suppressed in the asymmetry and the RDWIA and RPWIA results are almost coincident (up to a few percent). The longitudinal asymmetry was introduced in Ref. [8] as a way to distinguish between neutrinos and antineutrinos. However, as already noted in Ref. [26], this is correct up to incident energies of $\simeq$1000 MeV. In Fig. 4 our RDWIA results for the longitudinal asymmetry, both for an incident neutrino and antineutrino, are shown for impinging energies up to 2000 MeV. Results for neutrino scattering are negative and largely independent of the incident energy. In contrast, for antineutrino scattering the polarization asymmetry changes from positive to negative values as the incident energy increases. Hence, the discriminative power of the longitudinal asymmetry tends to be suppressed when higher beam energies are considered, even if the difference between ν and $\bar{\nu}$ cross sections is increasing.

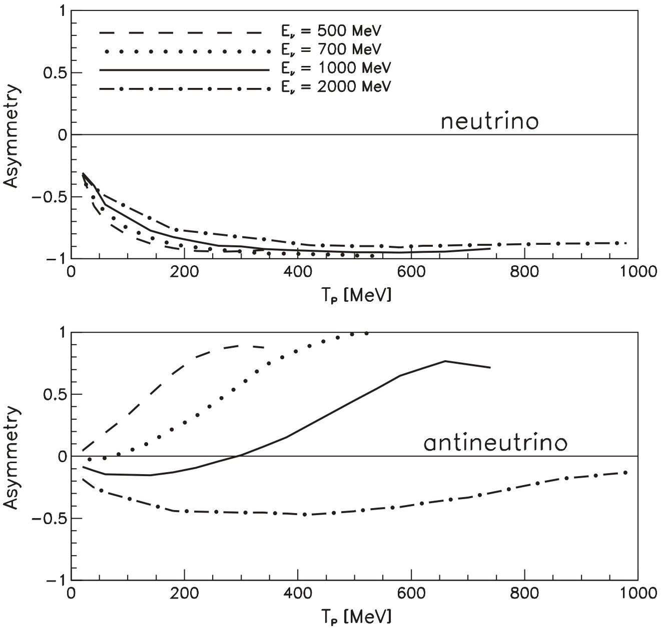

FIG. 4. The polarization asymmetry for the $\nu(\bar{\nu})$ quasi-elastic scattering on ^{12}C as a function of T_p for four different beam energies.

The effects of a nonzero strange-quark contribution to the form factors on the longitudinal asymmetry are displayed in Figs. 5 and 6 for proton emission and in Fig. 7 for neutron emission for an incident ν and $\bar{\nu}$ energy of 1000 MeV, where quasi-elastic one-nucleon knockout is expected to give the most important contribution to the cross section.

The SAMPLE Collaboration [44] at the MIT-Bates Laboratory has reported [45,46] a determination of the strange-quark contribution to the proton magnetic form factor through a measurement of the PV helicity asymmetry at $Q^2 = 0.1$ (GeV/c)^2 and backward direction. A revised analysis of data in combination with the axial form factor of the proton [47] seems to indicate a relatively small strangeness contribution to the proton magnetic moment [48]. The HAPPEX Collaboration [49,50] at Jefferson Laboratory (JLab) investigated such an asymmetry at $Q^2 = 0.1$ and 0.5 (GeV/c)^2 and forward direction for electron-proton scattering and at $Q^2 = 0.1$ (GeV/c)^2 for scattering on ^{4}He, respectively. The G0 experiment [51] at JLab has measured the scattering of electrons by protons at forward angles over the range $0.1 \leqslant Q^2 \leqslant 1$ (GeV/c)^2 to investigate the energy dependence of the strangeness contribution. Another measurement of

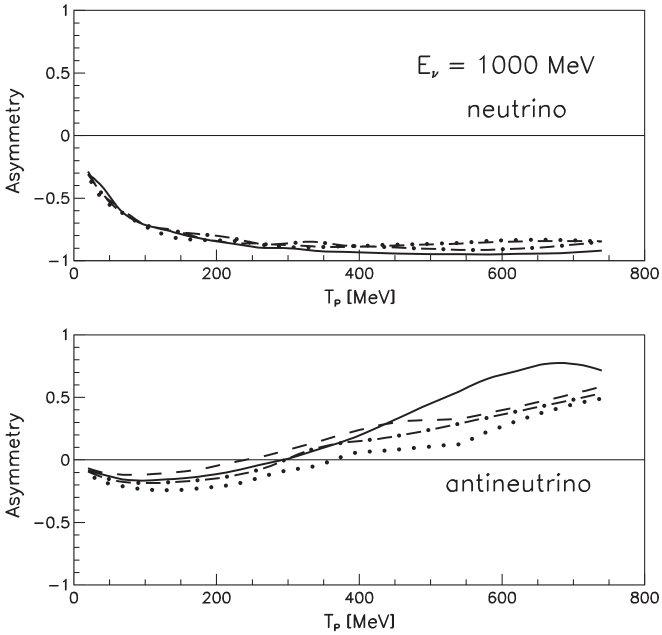

FIG. 6. The polarization asymmetry for the $\nu(\bar{\nu})$ quasi-elastic scattering on ^{12}C as a function of T_p at $E_{\nu(\bar{\nu})} = 1000$ MeV. Solid lines are the results with no strangeness contribution; dashed lines the results with $g_A^s = -0.10$; dotted lines the results with $g_A^s = 0$, $\rho^s = +1$, and $\mu^s = -0.30$; and dot-dashed lines the results with $g_A^s = -0.10$, $\rho^s = +1$, and $\mu^s = -0.30$.

parity violating asymmetry has been performed at the Mainz Microtron [52]. The available PV data at $Q^2 = 0.1$ (GeV/c)^2 suggests opposite signs for the electric (G_E^s) and magnetic (G_M^s) strange form factors, with hints for a positive value of μ^s; however, they are still compatible with 0 at 95% confidence level. A negative value for g_A^s was extracted from deep inelastic double-polarized scattering [53] and is in agreement with results of combined analyses of PV and neutrino scattering data [13].

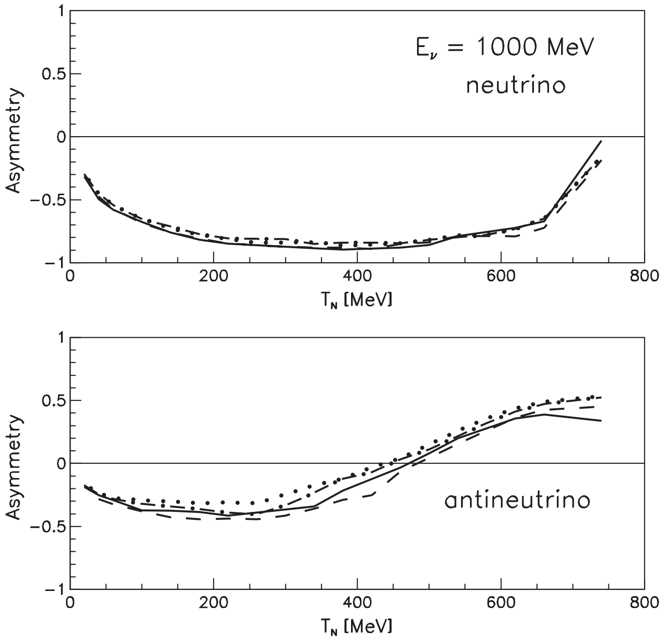

FIG. 7. The polarization asymmetry for the $\nu(\bar{\nu})$ quasi-elastic scattering on ^{12}C as a function of T_n at $E_{\nu(\bar{\nu})} = 1000$ MeV. Solid lines are the results with no strangeness contribution; dashed lines the results with $g_A^s = -0.10$, dotted lines the results with $g_A^s = 0$, $\rho^s = +1$, and $\mu^s = -0.30$; and dot-dashed lines the results with $g_A^s = -0.10$, $\rho^s = +1$, and $\mu^s = -0.30$.

A precise determination of the values of g_A^s, μ^s, and ρ^s is beyond the scope of this article. In our calculations we have used $g_A^s = -0.10$, $\mu^s = +0.30(-0.30)$, and $\rho^s = -1(+1)$. The opposite signs but small absolute values for μ^s and ρ^s agree with the PV data. We believe that these values are significantly representative to show up the effects of a strangeness contribution on the results. We are aware that the value of g_A^s is correlated to the value of the axial mass M_A and that the values of μ^s and ρ^s are also highly correlated [22].

The effects of the inclusion of the strangeness parameters are small when neutrino scattering is considered. This is related to the fact that neutrinos highly favor $\sigma\downarrow$ scattering with respect to the $\sigma\uparrow$ one. Hence, any strangeness contribution almost disappears in the ratio of Eq. (9). When an incident antineutrino is considered, the $\sigma\uparrow$ and $\sigma\downarrow$ cross sections have similar strengths and, therefore, antineutrinos are better probes to look for possible strange-quark effects. The sensitivity to the inclusion of a strange contribution in the form factor is generally mild and more significant in the case of proton knockout. In Fig. 5 the sensitivity to the vector strangeness parameters is shown, taking as baseline the results with $g_A^s = -0.10$. The results with $\mu^s = +0.30(-0.30)$ are greater (smaller) than the results with also the axial strangeness. The effects of ρ^s are almost negligible. In Figs. 6 and 7 it can be seen that the results with a nonzero strange-quark contribution in g_A^s, μ^s, and ρ^s are reduced with respect to the nonstrange results and the difference increases with the energy of the outgoing proton. The results with only the strange component of the axial form factor and those with the simultaneous inclusion of the strange magnetic moment and radius are similar to the results where all the three strange form factors are included.

In recent years the ratio of the neutral-to-charged (NC/CC) cross sections has been considered as the most attractive quantity to extract experimental information about the strange-quark contribution. In fact, although sensitive to strangeness only in the numerator, the NC/CC ratio is simply related to the number of events with an outgoing proton and a missing mass with respect to the events with an outgoing proton in coincidence with a muon, thus avoiding the explicit measurement of the cross section. With $g_A^s = -0.10$ an enhancement of the NC/CC ratio of $\simeq$15% relative to the case of no strangeness is obtained. The inclusion of μ^s and ρ^s produces a further increase of the ratio [27].

In Fig. 8 our RDWIA results for the NC/CC ratio are presented as a function of the outgoing proton kinetic energy for polarized proton emission. The RPWIA results are almost coincident and are not shown in the figure. The inclusion of a nonzero strangeness content largely enhances the results corresponding to the spin-up proton emission which present a maximum at $T_P \simeq 0.6\ E_\nu$. The dominant effect on the ratio is due to the inclusion of g_A^s, whereas the inclusion

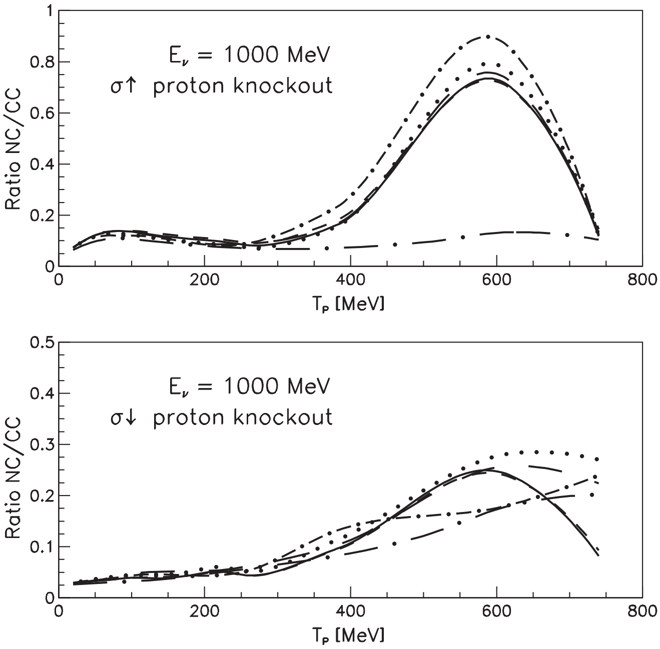

FIG. 8. Ratio of neutral-to-charged current polarized cross sections of the quasi-elastic ν scattering on ^{12}C as a function of T_p. Long dot-dashed lines are the results with no strangeness contribution; long dashed lines the results with $g_A^s = -0.10$; solid lines the results with $g_A^s = -0.10$, $\rho^s = -1$, and $\mu^s = +0.30$; dashed lines the results with $g_A^s = -0.10$, $\rho^s = +1$, and $\mu^s = +0.30$; dotted lines the results with $g_A^s = -0.10$, $\rho^s = -1$, and $\mu^s = -0.30$; and dot-dashed lines the results with $g_A^s = -0.10$, $\rho^s = +1$, and $\mu^s = -0.30$.

of μ^s and ρ^s produces a minor effect. The results with all the three strangeness contributions included are similar to those where only g_A^s is considered. The results for spin-down proton emission are different. The ratio is enhanced when g_A^s is included. Moreover, at higher values of T_P there are visible effects also from the vector strangeness.

Even if it is intriguing to look for strangeness effects, we are aware that a measurement of the NC/CC ratio of polarized cross sections is extremely challenging with the presently available neutrino facilities. Moreover, the fact that the most sizable strangeness effects correspond to an energy regime where the cross sections become very small requires a very precise measurement to obtain a clear result. Here we can only note that in the region where the effect of strangeness is dominant the cross section becomes a factor five lower than its maximum while strangeness could give an enhancement of a factor six on the NC/CC ratio of polarized cross sections.

IV. SUMMARY AND CONCLUSIONS

We have presented relativistic DWIA calculations for the polarization properties of the ejectile in neutral-current $\nu(\bar{\nu})$-nucleus quasi-elastic scattering. The reaction mechanism is assumed to be a direct one; i.e., the incident neutrino (antineutrino) interacts with only one nucleon in the nucleus and the other nucleons behave as spectators. A sum over all single-particle occupied states is performed, using an independent particle model to describe the structure of the nucleus. The scattering state is an optical-model wave function. Results for the ^{12}C target nucleus have been presented at neutrino (antineutrino) energies up to 2000 MeV. The nucleon polarization asymmetry is almost independent of FSI. The results for neutrino scattering are negative and independent of the incident energy. The antineutrino proton asymmetry changes from positive to negative values as $E_{\bar{\nu}} \geqslant 1000$ MeV. The sensitivity to the strange-quark content of the form factor has been investigated. The polarization asymmetry for neutrino scattering is almost unaffected by the strangeness contribution whereas more visible effects are obtained in the case of antineutrino scattering. The ratio of neutral-to-charged current cross sections is very sensitive to the strangeness contribution.

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