PHYSICAL REVIEW C **87**, 065501 (2013)

Quasielastic and multinucleon excitations in antineutrino-nucleus interactions

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(Received 29 March 2013; published 10 June 2013)

We investigate the MiniBooNE recent data on the antineutrino-nucleus interaction, using the same theoretical description with the same parameters as in our previous work on neutrino interactions. The double differential quasielastic cross section, which is free from the energy reconstruction problem, is well reproduced by our model once the multinucleon excitations are incorporated. A similar agreement is achieved for the Q^2 distribution.

DOI: 10.1103/PhysRevC.87.065501 PACS number(s): 25.30.Pt, 13.15.+g, 24.10.Cn

I. INTRODUCTION

The recent publication [1] by the MiniBooNE group of the antineutrino charged-current (CC) quasielastic cross section on ^{12}C completes the neutrino data [2,3] allowing a full comparison of the theoretical descriptions with the experimental results. In the case of neutrinos a successful description of the quasielastic cross section needs the inclusion of the multinucleon component. Indeed a Cerenkov detector cannot distinguish it from the genuine quasielastic part [4]. When this multinucleon component is introduced, the data are successfully reproduced without any modification of the nuclear axial form factor. The aim of the present work is to test our theoretical description in the different situation provided by the antineutrino interaction. We keep on purpose exactly the same parameters of previous works, [4–6], which successfully reproduce the experimental data. The most significant quantity, as pointed out in Ref. [6], is the double differential cross section which is a function of two measured quantities, the muon energy and the scattering angle; hence it is free from the energy reconstruction problem. This problem has been discussed in Refs. [7–11]. We briefly summarize the essence of our model which is described in detail in Ref. [4] and in Ref. [5] for antineutrinos. Our description treats the genuine quasielastic cross section in the random phase approximation (RPA) scheme. For the multinucleon part, our treatment is based on the work by Alberico *et al.* [12] which aims at the description of the (e,e') transverse response and, in particular, the filling of the dip between the quasielastic and Δ excitations. Alberico *et al.* [12] interpreted this filling as originating from the two-particle–two-hole excitations of the nuclear system by the virtual photon. The part which represents the nonpionic decay of the Δ in the medium is taken in our model from the parametrization of Oset and Salcedo [13]. The work of Alberico *et al.* concerned exclusively the magnetic response, which, by virtue of the couplings, is of isovector nature. For our work on neutrinos, the important observation is that the longitudinal response in (e,e') scattering, i.e., the charge one, does not display an evidence for a cross section excess above the quasielastic peak. This is confirmed by the superscaling analysis [14,15] of electron scattering data. The various components which build the neutrino cross sections are excited by the isovector component of the charge operator, or by the nucleon spin-isospin operators (see Eq. (1) of Ref. [5]). Motivated by these observations, we have introduced the two-particle–two-hole excitations exclusively in the spin-isospin channels, which is a distinct feature of our description. Due to the axial-vector interference term, the spin-isopin contribution is of less importance for antineutrinos. The consequence is that the multinucleon piece should weigh less on the cross section for antineutrinos than for neutrinos. This is not the case in other approaches [16–21]. The model closest in spirit to our treatment is the one of Bodek *et al.* [22] characterized by a modification of the magnetic form factor so as to account for the observed excess in the dip region of the magnetic response. For a comparison between theoretical approaches, see, for example, Ref. [23].

II. ANALYSIS OF THE CROSS SECTIONS

We first recall the expression of the double differential cross section which applies for neutrinos as well as for antineutrinos. For a given "quasielastic" event the muon energy E_μ (or kinetic energy T_μ) and its emission angle θ are measured, while the neutrino energy E_ν is unknown. The expression of the double differential cross section in terms of the measured quantities is

$$\frac{d^2\sigma}{dT_\mu d\cos\theta} = \frac{1}{\int \Phi(E_\nu)dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta}\right]_{\omega=E_\nu-E_\mu} \Phi(E_\nu). \quad (1)$$

In the numerical evaluations we use the antineutrino flux $\Phi(E_\nu)$ from Ref. [1]. As in our work [6], we have applied relativistic corrections to the nuclear responses.

The results for the double differential cross section are displayed in Fig. 1, with and without the inclusion of the multinucleon (np-nh) component, and compared to the MiniBooNE experimental data [1]. A similar comparison has been recently reported in Ref. [19]. Our evaluation, as all those of this article, is done with the free value of the axial mass. The agreement between our predictions and the data is

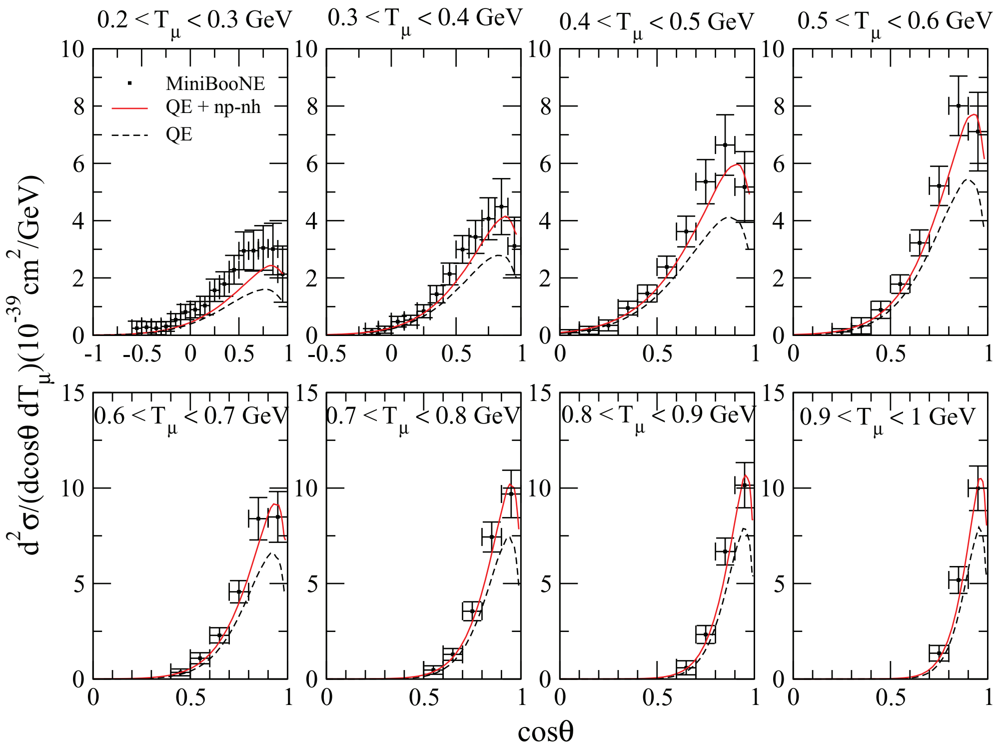

FIG. 1. (Color online) MiniBooNE flux-averaged CC “quasielastic” $\bar{\nu}_\mu$-^{12}C double differential cross section per proton for several values of muon kinetic energy as a function of the scattering angle. Dashed curve: pure quasielastic (1p-1h) cross section calculated in the RPA; solid curve: with the inclusion of the multinucleon (np-nh) component. The experimental MiniBooNE points with the shape uncertainty are taken from Ref. [1]. For the data there is an additional normalization uncertainty of 17.2% not shown here.

quite good in all the measured ranges once the multinucleon component is incorporated. This is remarkable in view of the fact that no parameter has been changed with respect to our calculations in the neutrino mode. The only panel presenting some disagreement, of which we do not know the origin, corresponds to the lowest T_μ values, 0.2 MeV $< T_\mu < 0.3$ MeV, where the theoretical prediction is below the experimental data. Notice that this underestimate at low T_μ has little influence on the once integrated quantity, $d\sigma/d\cos\theta$, shown in Fig. 2, while Fig. 3 displays the quantity $d\sigma/dT_\mu$. In both cases our results are fully compatible with the experimental ones. Nevertheless a small, but systematic, underestimation shows up with respect to data, at least using the present normalization. We recall that there is an additional normalization uncertainty of 17.2% in the data [1]. Within this error margin the agreement can be considered as excellent. We observe in Fig. 2 that the antineutrino cross section falls more rapidly with angle than the neutrino one (compare with Fig. 9 of Ref. [6]). This also shows up in the Q^2 distribution which peaks at smaller Q^2 values than the neutrino one. The double differential cross section as a function of T_μ, for the interval $0.8 < \cos\theta < 0.9$, is displayed in Fig. 4. It shows the same trend of systematic underestimation. We have chosen this angle band to be able to compare it with the similar curve for neutrinos (Fig. 6 of Ref. [6]). It happens that for this band the theoretical underevaluation is the most pronounced (see the corresponding point in Fig. 2). As this trend is nevertheless present we may investigate its origin. On purely theoretical grounds, we describe the genuine quasielastic cross section in the RPA approach where the repulsive particle-hole interaction produces a quenching effect [24]. In Fig. 4 this RPA quenching explicitly appears when the cross sections with and without the RPA are compared. We recall that for neutrinos the RPA effect is needed in order to reproduce the double differential cross sections as well as the Q^2 distribution as was shown in Ref. [6]. The only freedom that we have for antineutrinos is then the RPA effect for the isovector response. It does not affect the neutrino cross sections in view of the small weight of this response. We have further investigated the influence of this RPA suppression in the isovector response. It has no effect for neutrinos and even for antineutrinos since it is too small to produce a significant increase of the cross section. It offers no solution for the slight, but systematic, theoretical underevaluation trend. It seems that this must be found instead in the uncertainty of the data, which is 17.2%. An overall reduction of the data by this amount is sufficient to make the theory-experiment agreement excellent, as good as the one for neutrinos.

The Q^2 distribution is shown in Fig. 5 with and without the multinucleon component. The bare genuine quasielastic result is also shown. As for neutrinos the RPA effects disappear beyond $Q^2 \gtrsim 0.3$ GeV^2, for which the presence of the multinucleon component is required. The agreement between theory and experiment is quite good. The experimental points are given in terms of the reconstructed value of Q^2 while in our theory it is the real value. The influence of this difference

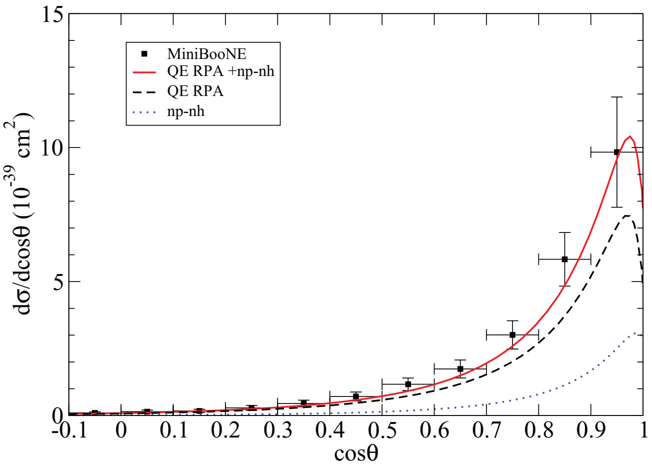

FIG. 2. (Color online) MiniBooNE flux-averaged CC "quasielastic" $\bar{\nu}_\mu$-^{12}C differential cross section per proton as a function of the muon scattering angle. Note that in order to compare with the data the integration is performed over the muon kinetic energies 0.2 GeV $< T_\mu <$ 2.0 GeV. Dashed curve: pure quasielastic (1p-1h) cross section; solid curve: with the inclusion of the np-nh component; dotted line: np-nh contribution. The experimental MiniBooNE points with the shape uncertainty are taken from Ref. [1]. There is an additional normalization uncertainty of 17.2% not shown here.

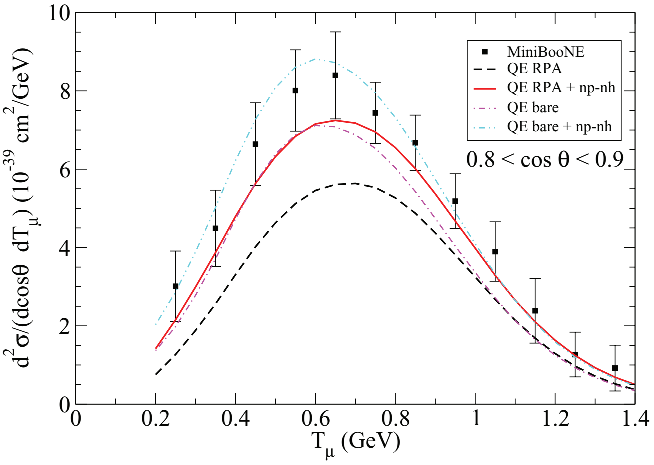

FIG. 4. (Color online) MiniBooNE flux-averaged CC "quasielastic" $\bar{\nu}_\mu$-^{12}C double differential cross section per proton for $0.8 < \cos\theta < 0.9$ as a function of the muon kinetic energy. Dashed curve: pure quasielastic calculated in the RPA; solid curve: RPA quasielastic with the inclusion of the np-nh component; dot-dot-dashed: bare quasielastic with the inclusion of the np-nh component; dot-dashed curve: bare quasielastic. The experimental MiniBooNE points with the shape uncertainty are taken from Ref. [1]. There is an additional normalization uncertainty of 17.2% not shown here.

has been shown to be small by Lalakulich *et al.* [10]. For information we show in the right panel of Fig. 5 the effect on this distribution of a systematic reduction of the data by 17%. In this case the agreement becomes excellent, as the one that we have found previously for neutrinos.

Finally we discuss the case of the total cross section as a function of the antineutrino energy, shown in Fig. 6 together with experimental data. We recall that this experimental quantity is not model independent, contrary to the double differential cross section. These experimental data are plotted as a function of the reconstructed antineutrino energy and not of the genuine one. Hence one deals with an effective cross section which depends on the shape of the antineutrino energy distribution. We have discussed in detail the problem of the energy reconstruction in two recent works [7,8]. Figure 6 shows the influence of the energy reconstruction by comparing the effective cross section with the theoretical one, which is

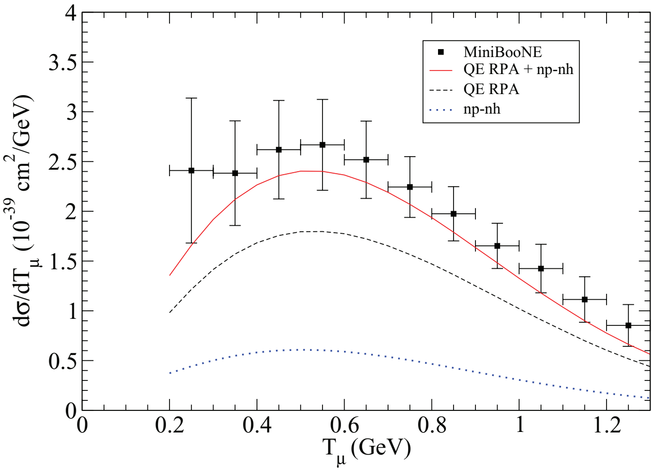

FIG. 3. (Color online) MiniBooNE flux-averaged CC "quasielastic" $\bar{\nu}_\mu$-^{12}C differential cross section per proton as a function of the muon kinetic energy. Dashed curve: pure quasielastic (1p-1h) cross section; solid curve: with the inclusion of np-nh component; dotted line: np-nh contribution. The experimental MiniBooNE points with the shape uncertainty are taken from Ref. [1]. There is an additional normalization uncertainty of 17.2% not shown here.

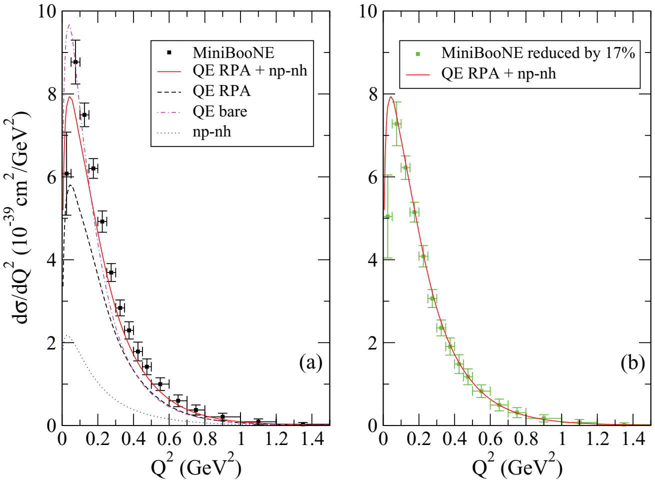

FIG. 5. (Color online) (a) MiniBooNE flux-averaged $\bar{\nu}_\mu$ CC Q^2 distribution per proton. Dashed curve: pure quasielastic (1p-1h); solid curve: with the inclusion of the np-nh component; dotted line: np-nh component; dot-dashed line: bare distribution. The experimental MiniBooNE points with the shape uncertainty are taken from Ref [1]. For the data there is an additional normalization uncertainty of 17.2%. (b) A reduction of 17% of the MiniBooNE data is performed.

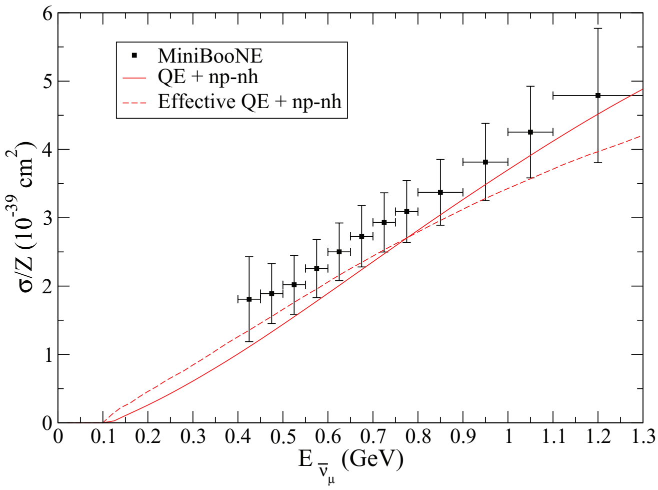

FIG. 6. (Color online) Theoretical (solid line) and effective (dashed line) $\bar{\nu}_\mu$-^{12}C cross section per proton including the multinucleon component. The experimental MiniBooNE result with the total error taken from Ref. [1] is also shown.

a function of the true antineutrino energy. The experimental data are also displayed. As in Ref. [8], the reconstruction produces some increase at low energy and lowers the cross section at large ones. Notice that this difference depends on the shape of the flux. Contrary to previous cases, the error bar on the experimental points in the present case includes the renormalization uncertainty. Our theoretical curve is within the error band, although on the low side, as expected from the trend of the various differential cross sections.

III. CONCLUSION

In this work we have investigated in detail the antineutrino-^{12}C cross sections in connection with MiniBooNE data. Our theoretical approach is, in all aspects, identical to the one used in our previous works on neutrinos. The most significant quantity is the double differential cross section which does not involve any reconstruction of the antineutrino energy. For this quantity the agreement of our RPA approach with data is good, once the np-nh component is included. We have also examined the Q^2 distribution which establishes the necessity of the multinucleon contribution, independently of the RPA quenching. It confirms our first suggestion that there is no need for a change in the axial mass once the multinucleon processes are taken into consideration. In spite of the identity of the inputs, which are the nuclear response functions, the various responses have a different weight in the respective cross sections for neutrinos and antineutrinos. This generates an asymmetry of the nuclear effects for neutrinos and antineutrinos. This is discussed in detail in Ref. [5]. We suggested there that the antineutrino cross section would offer a crucial test of our nuclear model. The conclusion of the present investigation is that, after its success in the neutrino case, our model stands quite well the test of the comparison with the recent antineutrino data which are well reproduced by our theoretical description. With a 17% reduction of the data, as is compatible with the stated normalization uncertainty, an even better agreement is reached, of the same quality as for neutrinos. The asymmetry between neutrinos and antineutrinos interactions is important for the investigation of CP violation effects. We have shown that nuclear effects generate an additional asymmetry. It has been the object of the present work to test successfully our understanding of this asymmetry.

ACKNOWLEDGMENTS

We thank Joe Grange for useful discussions. This work was partially supported by the Communauté Française de Belgique (Actions de Recherche Concertées).

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