Vol. 37 (2006) ACTA PHYSICA POLONICA B No 8

CHARGED AND NEUTRAL CURRENT NEUTRINO INDUCED NUCLEON EMISSION REACTIONS* **

J. Nieves, M. Valverde

Dept. de Física Atómica, Molecular y Nuclear, Universidad de Granada
18071 Granada, Spain

M.J. Vicente Vacas

Dept. de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC
Institutos de Investigación de Paterna
Aptdo. 22085, 46071 Valencia, Spain

(Received June 19, 2006)

By means of a Monte Carlo cascade method, to account for the rescattering of the outgoing nucleon, we study the charged and neutral current inclusive one nucleon knockout reactions off nuclei induced by neutrinos. The nucleon emission process studied here is a clear signal for neutral-current neutrino driven reactions, and can be used in the analysis of future neutrino experiments.

PACS numbers: 25.30.Pt, 13.15.+g, 24.10.Cn, 21.60.Jz

1. Introduction and theoretical framework

Recently an interest in neutrino scattering off nuclei has raised because of its implications in the experiments on neutrino oscillations based on large Cerenkov detectors. The presence of neutrinos, being charge-less particles, can only be inferred by detecting the secondary particles they create when colliding and interacting with matter. Nuclei are often used as neutrino detectors, thus a trustable interpretation of neutrino oscillation data heavily relies on detailed and quantitative knowledge of the features of the neutrino-nucleus interaction [1]. For instance, in the case of neutrino processes driven by the electroweak Neutral Current (NC), the energy spectrum and angular distribution of the ejected nucleons are the unique observables. Besides, the study of these distributions might also help to improve on our knowledge of

* Presented by J. Nieves at the XX Max Born Symposium "Nuclear Effects in Neutrino Interactions", Wrocław, Poland, December 7–10, 2005.

** This work was supported by DGI and FEDER funds, contracts BFM2005-00810 and BFM2003-00856, by the EU Integrated Infrastructure Initiative Hadron Physics Project contract RII3-CT-2004-506078 and by the Junta de Andalucía (FQM-225).

the quark and gluon substructure of the nucleon, and in particular on the amount of nucleon spin carried by strange quarks [2].

At intermediate energies, above the nuclear giant resonance and below the $\Delta(1232)$ regions, neutrino–nucleus interactions have been studied within several approaches. Several different Fermi gas, Random Phase Approximation (RPA) and shell model based calculations have been developed during the last 15 years [3, 14] to compute neutrino or antineutrino induced single-nucleon emission cross sections. Most of the calculations use the plane wave and distorted wave impulse approximations (PWIA and DWIA, respectively), including or not relativistic effects. The PWIA constitutes a poor approximation, since it neglects all types of interactions between the ejected nucleon and the residual nuclear system. The DWIA describes the ejected nucleon as a solution of the Dirac or Schrödinger equation with an optical potential obtained by fitting elastic proton–nucleus scattering data. The imaginary part accounts for the absorption into unobserved channels. This scheme is incorrect to study nucleon emission processes where the state of the final nucleus is totally unobserved, and thus all final nuclear configurations, either in the discrete or on the continuum, contribute. The distortion of the nucleon wave function by a complex optical potential removes all events where the nucleons collide with other nucleons. Thus, in DWIA calculations, the nucleons that interact are lost when in the physical process they simply come off the nucleus with a different energy, angle, and maybe charge, and they should definitely be taken into account. A clear example which illustrates the deficiencies of the DWIA models is the neutron emission process: $(\nu_l, l^- n)$. Within the impulse approximation neutrinos only interact via Charged Current (CC) interactions with neutrons and would emit protons, and therefore, the DWIA will predict zero cross sections for CC one neutron knock-out reactions. However, the primary protons interact strongly with the medium and collide with other nucleons which are also ejected. As a consequence there is a reduction of the flux of high energy protons but a large number of secondary nucleons, many of them neutrons, of lower energies appear.

In this talk, we present results for the QE $(\nu_l, \nu_l N)$, $(\nu_l, l^- N)$, $(\bar\nu_l, \bar\nu_l N)$ and $(\bar\nu_l, l^+ N)$ reactions in nuclei. We use a Monte Carlo (MC) simulation method to account for the rescattering of the outgoing nucleon. The first step is the gauge boson ($W^\pm$ and Z^0) absorption in the nucleus, we take this reaction probability[1] from the microscopical many body framework devel-

[1] It is given by the inclusive QE cross sections $d^2\sigma/d\Omega' dE'$ (Ω', E' are the solid angle and energy of the outgoing lepton), for a fixed incoming neutrino or antineutrino laboratory (LAB) energy. We also compute differential cross sections with respect to d^3r. Thus, we also know the point of the nucleus where the gauge boson was absorbed, and we can start from there our MC propagation of the ejected nucleon.

oped in Refs. [15,16] for CC and NC induced reactions. Starting from a Local Fermi Gas (LFG) picture of the nucleus, which automatically accounts for Pauli blocking, several nuclear effects are taken into account in that scheme: *(i)* a correct energy balance, using the experimental Q-values, is enforced, *(ii)* Coulomb distortion of the charged leptons is implemented by using the so called "modified effective momentum approximation", *(iii)* medium polarization (RPA), including Δ-hole degrees of freedom and explicit pion and rho exchanges in the vector–isovector channel of the effective nucleon–nucleon force, and Short Range Correlation (SRC) effects are computed, and finally *(iv)* the nucleon propagators are dressed in the nuclear medium, which amounts to work with a LFG of interacting nucleons and it also accounts for reaction mechanisms where the gauge boson, $W^{\pm}$ or Z^0, is absorbed by two nucleons. This model is a natural extension of previous studies on electron [17], photon [18] and pion [19, 20] dynamics in nuclei and predicts QE neutrino–nucleus (differential and integrated) cross sections with an accuracy of about 10–15%, at intermediate energies [21, 22].

After the absorption of the gauge boson, we follow the path of the ejected nucleon through its way out of the nucleus using a MC simulation method to account for the secondary collisions. Details on the MC simulation can be found in [16]. This MC method was designed for single and multiple nucleon and pion emission reactions induced by pions [23, 24] and has been successfully employed to describe inclusive (γ,π), (γ,N), $(\gamma,NN),\ldots,$ $(\gamma,N\pi),\ldots$ [25,26], $(e,e'\pi)$, $(e,e'N)$, $(e,e'NN),\ldots,$ $(e,e'N\pi),\ldots$ [27] reactions in nuclei or the neutron and proton spectra from the decay of Λ hypernuclei [28]. Thus, we are using a quite robust and well tested MC simulator.

2. Results and concluding remarks

The nucleon spectra produced by CC processes induced by muon neutrinos and antineutrinos of 500 MeV are shown in Fig. 1 for argon. Of course, neutrinos only interact via CC with neutrons and would emit protons, but these primary protons interact strongly with the medium and collide with other nucleons which are also ejected. As a consequence there is a reduction of the flux of high energy protons but a large number of secondary nucleons, many of them neutrons, of lower energies appear. Our cascade model does not include the collisions of nucleons with kinetic energies below 30 MeV. Thus, the results at those low energies are not meaningful and are shown for illustrative purposes only in Fig. 1.

The flux reduction due to the quasielastic NN interaction can be easily accommodated in optical potential calculations. However, in those calculations the nucleons that interact are lost when in the physical process they simply come off the nucleus with a different energy and angle, and may be charge, and they must be taken into account.

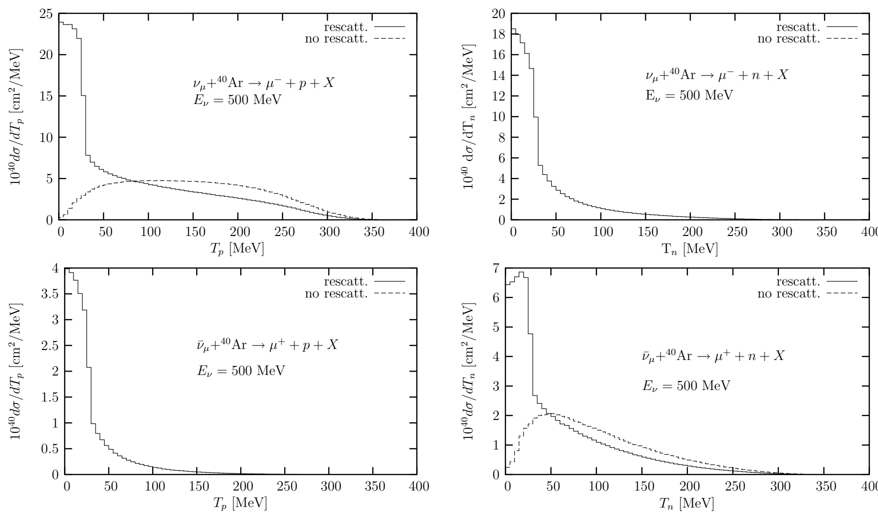

Fig. 1. Charged current ${}^{40}\mathrm{Ar}(\nu_\mu, \mu^- + N)$ (upper panels) and ${}^{40}\mathrm{Ar}(\bar{\nu}_\mu, \mu^+ + N)$ (lower panels) cross sections as a function of the kinetic energy of the final nucleon for an incoming neutrino or antineutrino energy of 500 MeV. Left and right panels correspond to the emission of protons and neutrons, respectively. The dashed histogram shows results without nucleon rescattering; the solid one the full model.

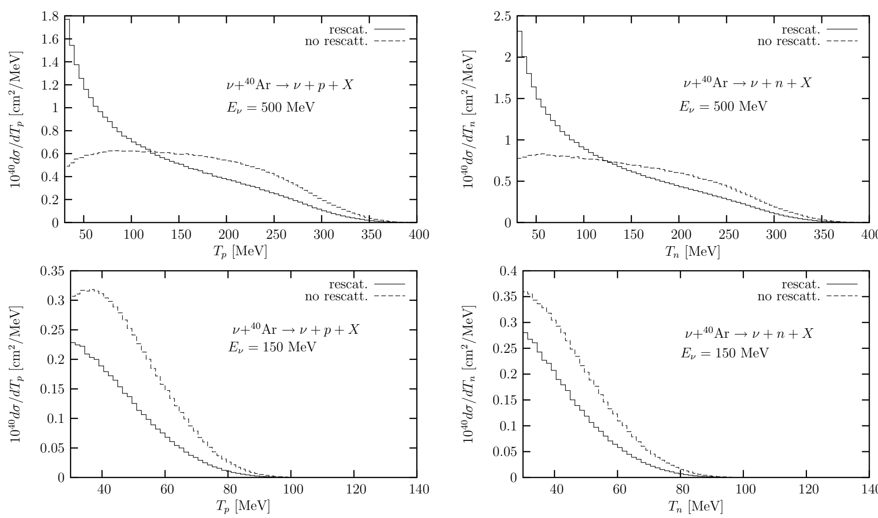

Fig. 2. Neutral current ${}^{40}\mathrm{Ar}(\nu, \nu + N)$ at 500 MeV (upper panels) and 150 MeV (lower panels) cross sections as a function of the kinetic energy of the final nucleon. Left and right panels correspond to the emission of protons and neutrons, respectively. The dashed histogram shows results without rescattering; the solid one the full model.

The energy distributions of nucleons emitted after a NC interaction are shown in Figs. 2 and 3. In Fig. 2, we show the results for ^{40}Ar at two different energies. In both cases we find the large effect of the rescattering of the nucleons. For 500 MeV neutrinos the rescattering of the outgoing nucleon produces a depletion of the higher energies side of the spectrum, but the scattered nucleons clearly enhance the low energies region. For lower neutrino energies, most of the nucleons coming from nucleon nucleon collisions would show up at energies below the 30 MeV cut.

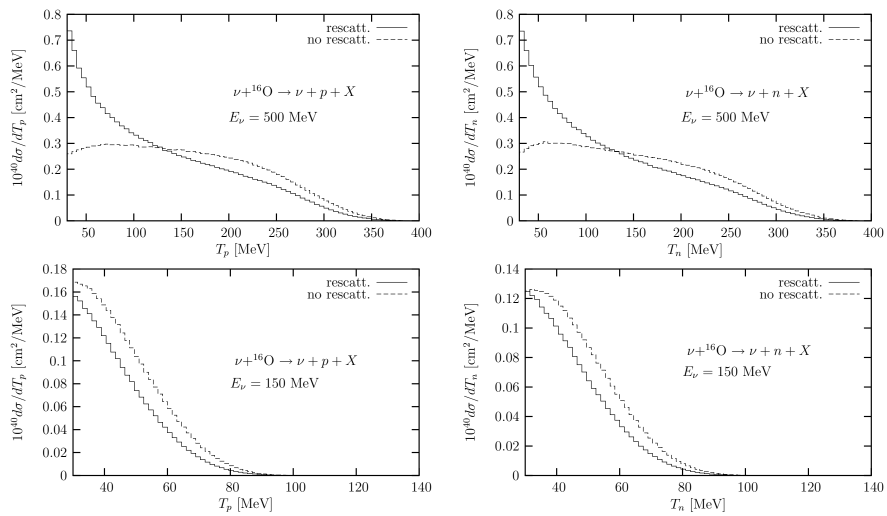

Fig. 3. Same as Fig. 2 for oxygen.

As expected, the rescattering effect is smaller in lighter nuclei as can be seen in Fig. 3 for oxygen. In all cases the final spectra of protons and neutrons are very similar.

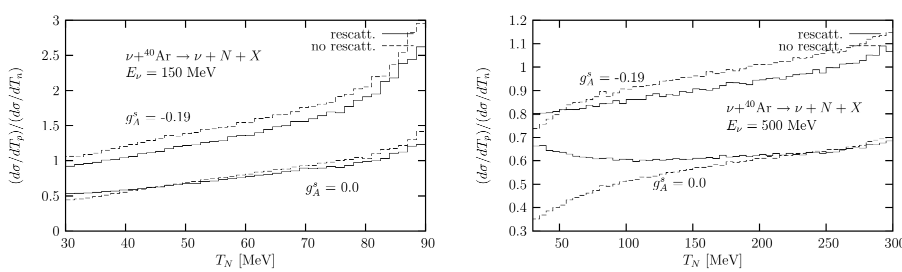

Fig. 4. Ratio of $d\sigma/dE$ for protons over that for neutrons for $E_\nu = 150$ MeV and $E_\nu = 500$ MeV in the reaction $\nu+^{40}\mathrm{Ar} \to \nu' + N + X$ as a function of the nucleon kinetic energy. Dashed histogram: without nucleon rescattering. Solid histogram: full model.

The ratio of proton to neutron QE cross section could be very sensitive to the strange quark axial form factor of the nucleon, and thus to the $g_{\rm A}^s$ parameter [3, 4, 6, 11]. The sensitivity to the collisions of the final nucleons is larger for both heavier nuclei and for larger energies of the neutrinos. In Fig. 4, one can clearly appreciate the importance of the secondary nucleons at the low energies side of the spectrum.

REFERENCES

[1] Proceedings of the RCCN International Workshop On Sub-dominant Oscillation Effects in Atmospheric Neutrino Experiments Kashiwa, 2004, Eds. T. Kajita and K. Okumura, Universal Academy Press, Inc. Tokyo, Japan.

[2] FINeSSe Collaboration, L. Bugel *et al.*, `hep-ex/0402007`; S.F. Pate, *Eur. Phys. J.* **A24S2**, 67 (2005).

[3] G.T. Garvey, S. Krewald, E. Kolbe, K. Langanke, *Phys. Lett.* **B289**, 249 (1992); G. Garvey, E. Kolbe, K. Langanke, S. Krewald, *Phys. Rev.* **C48**, 1919 (1993).

[4] C.J. Horowitz, H.C. Kim, D.P. Murdock, S. Pollock, *Phys. Rev.* **C48**, 3078 (1993).

[5] S.L. Mintz, M. Pourkaviani, *Nucl. Phys.* **A594**, 346 (1995).

[6] W.M. Alberico, M.B. Barbaro, S.M. Bilenky, J.A. Caballero, C. Giunti, C. Maieron, E. Moya de Guerra, J.M. Udías, *Nucl. Phys.* **A623**, 471 (1997); *Phys. Lett.* **B438**, 9 (1998); *Nucl. Phys.* **A651**, 277 (1999).

[7] C. Volpe, N. Auerbach, G. Colo, T. Suzuki, N. Van Giai, *Phys. Rev.* **C62**, 015501 (2000).

[8] C. Bleve, G. Co', I. De Mitri, P. Bernardini, G. Mancarella, D. Martello, A. Surdo, *Astropart. Phys.* **16**, 145 (2001).

[9] C. Maieron, M.C. Martinez, J.A. Caballero, J.M. Udias, *Phys. Rev.* **C68**, 048501 (2003).

[10] A. Meucci, C. Giusti, F.D. Pacati, *Nucl. Phys.* **A739**, 277 (2004); A. Meucci, C. Giusti, F.D. Pacati, *Nucl. Phys.* **A744**, 307 (2004).

[11] B.I.S. van der Ventel, J. Piekarewicz, *Phys. Rev.* **C69**, 035501 (2004).

[12] N. Jachowicz, K. Vantournhout, J. Ryckebusch, K. Heyde, *Phys. Rev. Lett.* **93**, 082501 (2004).

[13] M.C. Martinez, P. Lava, N. Jachowicz, J. Ryckebusch, K. Vantournhout, J.M. Udias, *Phys. Rev.* **C73**, 024607 (2006).

[14] K.M. Graczyk, J.T. Sobczyk, *Eur. Phys. J.* **C31**, 177 (2003); C. Juszczak, J.A. Nowak, J.T. Sobczyk, *Eur. Phys. J.* **C39**, 195 (2005).

[15] J. Nieves, J.E. Amaro, M. Valverde, *Phys. Rev.* **C70**, 055503 (2004); Erratum *Phys. Rev.* **C72**, 019902 (2005).

[16] J. Nieves, M. Valverde, M.J. Vicente Vacas, *Phys. Rev.* **C73**, 025504 (2006).

[17] A. Gil, J. Nieves, E. Oset, *Nucl. Phys.* **A627**, 543 (1997).

[18] R.C. Carrasco, E. Oset, *Nucl. Phys.* **A536**, 445 (1992).

[19] E. Oset, H. Toki, W. Weise, *Phys. Rep.* **83**, 281 (1982).

[20] J. Nieves, E. Oset, C. García-Recio, *Nucl. Phys.* **A554**, 509 (1993); *Nucl. Phys.* **A554**, 554 (1993); J. Nieves, E. Oset, *Phys. Rev.* **C47**, 1478 (1993); E. Oset, P. Fernández de Córdoba, J. Nieves, A. Ramos, L.L. Salcedo, *Prog. Theor. Phys. Suppl.* **117**, 461 (1994); C. Albertus, J.E. Amaro, J. Nieves, *Phys. Rev. Lett.* **89**, 032501 (2002); *Phys. Rev.* **C67**, 034604 (2003).

[21] M. Valverde, J.E. Amaro, J. Nieves, `hep-ph/0604042`.

[22] J.E. Amaro, A.M. Lallena, J. Nieves, *Nucl. Phys.* **A623**, 529 (1997); J.E. Amaro, C. Maieron, J. Nieves, M. Valverde, *Eur. Phys. J.* **A24**, 343 (2005).

[23] L.L. Salcedo, E. Oset, M.J. Vicente Vacas, C. García Recio, *Nucl. Phys.* **A484**, 557 (1988).

[24] M.J. Vicente Vacas, E. Oset, *Nucl. Phys.* **A568**, 855 (1994).

[25] R.C. Carrasco, E. Oset, L.L. Salcedo, *Nucl. Phys.* **A541**, 585 (1992).

[26] R.C. Carrasco, M.J. Vicente Vacas, E. Oset, *Nucl. Phys.* **A570**, 701 (1994).

[27] A. Gil, J. Nieves, E. Oset, *Nucl. Phys.* **A627**, 599 (1997).

[28] A. Ramos, M.J. Vicente Vacas, E. Oset, *Phys. Rev.* **C55**, 735 (1997), Erratum **C66**, 039903 (2002).