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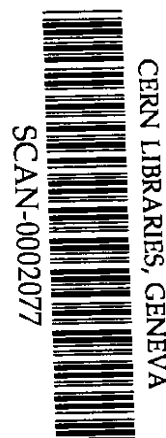
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**Nuclear effects in neutrino-nucleus interactions**

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# Nuclear effects in neutrino-nucleus interactions

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## Abstract

The apparent anomaly in the ratio of muon to electron atmospheric neutrinos has been confirmed by several collaborations using different detection techniques. Together with the asymmetry in the zenithal distributions of the  $\nu_\mu$  events in Super-Kamiokande, it gives a strong support to the neutrino oscillation hypothesis and to the existence of a non vanishing mass for the neutrinos. In this work we are interested by the role of nuclear physics in the neutrino-oxygen reactions, which are relevant for the Čerenkov detectors. We point out that multi-nucleon excitations of  $np$ - $n\bar{h}$  type and nuclear correlations could modify an experimental analysis *à la* Super-Kamiokande because they lead to a substantial enhancement of the number of 1 Čerenkov ring retained events.

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## 1 INTRODUCTION

The apparent anomaly in the numbers of  $\nu_\mu$  and  $\nu_e$  produced by interactions of cosmic rays in the atmosphere has been confirmed by several experiments (1; 2; 3; 4). While the expected ratio of  $\nu_\mu$  to  $\nu_e$  should be of the order of two in favor of the muonic neutrinos, if you follow simple arguments on the hadronic cascades leading to the production of atmospheric neutrinos which have "typical" energies around 1 GeV, the measured ratio is significantly lower. Indeed the double ratio  $r = (R_{\mu/e})_{exp}/(R_{\mu/e})_{MC}$  between the experimental and the simulated flavor ratios ( $R_{\mu/e}$ ) is found to be of the order of  $\sim 0.6$ . The Monte-Carlo simulations use different theoretical inputs for the atmospheric neutrinos fluxes (5; 6). Although the uncertainties on these fluxes are rather high (it is currently assumed that the fluxes are not known with an accuracy better than 20 %), it has been shown that they cancel partially when one considers the

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double ratio  $r$  (the uncertainties due to the fluxes are estimated to be around 5%). Furthermore a comparative study has allowed the identification of the main discrepancies between the two major models used in the analysis, and has shown that the double ratio does not depend much on them (7).

It is also argued that the uncertainties on the neutrino-nucleus cross-sections (around 20 %) cancel in the double ratio where the overall uncertainty due to the nuclear effects is taken around 5%. This result has been confirmed by theoretical studies (8; 9). In ref. (8) in particular, the authors have examined several phenomena in the low energy region of the nuclear excitation spectrum. They studied the effects of the Coulomb interactions of outgoing nucleons and leptons, and the effects of the nuclear short range correlations. They also compared infinite nuclear matter calculations with realistic finite-volume mean field models. Their conclusion was that these usually neglected effects could not account for the atmospheric neutrino anomaly. Here we will extend their work to the high energy part of the nuclear excitation spectrum and examine the effects of nuclear correlations up to the Delta resonance region within a realistic finite-size model.

This work is absolutely necessary in the analysis which are based on the *absolute* events yields and not only on the double ratio. Indeed the most striking indication in favor of neutrino oscillations is the observation by Super-Kamiokande of an asymmetry in the zenithal distributions of the  $\nu_\mu$  events (both sub- and multi-GeV) (2). It appears that the number of upward-going  $\nu_\mu$  (*i.e.* coming from the antipodes) is smaller than expected while the number of downward-going  $\nu_\mu$  corresponds to the expectations. Together with the symmetric behaviour of the zenithal distributions of the  $\nu_e$  events and the results of the Chooz experiment (10) which excludes the possible  $\nu_\mu \rightarrow \nu_e$  solution to the Super-Kamiokande results, this favours a solution of the atmospheric neutrino problem in the  $\nu_\mu \rightarrow \nu_X$  oscillations channels, with  $\nu_X = \nu_\tau$  or  $\nu_X = \nu_{sterile}$ . However before drawing these conclusions it is important to quantify in particular the nuclear effects, which play a significant role in the analysis.

## 2 ROLE OF NUCLEAR PHYSICS

In this work we are interested in the experiments using large underground water Čerenkov detectors: Kamiokande and Super-Kamiokande, IMB. These experiments retain events where only one Čerenkov ring (Č.R.) is detected. These events are usually assumed to be produced by quasi-elastic charged current interactions in which a charged lepton is emitted above Čerenkov threshold and leads to the detected ring. The nucleon which is ejected from the nucleus is in general below threshold (a very good approximation in water) and therefore does not produce another ring. However we know that the

complex nuclear dynamics implies the existence of others sources of "1 Č.R." events, which have been identified and studied in a previous work (11).

Indeed the region of energy transfer relevant for atmospheric neutrinos reactions extends from the quasi-elastic peak to the Delta resonance region.

The quasi-elastic interactions have been extensively studied (8). The intermediate region (the so-called "dip" region) is known to be populated by higher order excitations of  $n$  particles -  $n$  holes type (with  $n = 2,3 \dots$ ). The role of these excitations has been pointed out for instance in the  $(e, e')$  scattering (12) where they add a substantial amount of strength in the dip region. They lead to the emission of  $n$  nucleons in the final state and the event will therefore have the same signature than a quasi-elastic one if the nucleons and the residual nucleus are under threshold.

At still higher energy (energy transfer  $\geq 300$  MeV), the interaction may result in the excitation of a Delta resonance. If the Delta decays into a pion and a nucleon and if the pion escapes from the nuclear medium above threshold ( $\sim 70$  MeV in water for a pion), then one gets two Č.R.'s (one for the charged lepton and one for the pion). Such events are rejected by the experimental cuts. However the pion in the nucleus is a quasi-particle with a broad width and can decay for instance into a  $p$ - $h$  excitation. Such an event, where at least two nucleons and no pion are ejected from the nucleus, belongs to the "1 Č.R." class.

The previous arguments lead to the conclusion that a full calculation of the neutrino-oxygen cross sections beyond the quasi-elastic assumption is necessary. Indeed the total number of "1 Č.R." events gets contributions from the quasi-elastic interactions but also from others nuclear channels which are not separated by the Čerenkov detectors (absence of identification of the hadronic cascades).

### 3 CROSS SECTIONS AND EVENTS RATES

The starting point is the charged-current  $\nu - {}^{16}\text{O}$  cross section, which we can write in the compact form (11):

$$\frac{\partial^3 \sigma}{\partial^2 \Omega \partial k'} \propto f(R_\tau^{NN}, R_{\sigma\tau(L)}^{PP'}, R_{\sigma\tau(T)}^{PP'}), \quad (1)$$

where  $k'$  is the final lepton momentum,  $\Omega$  the scattering solid angle and  $f$  a linear function. We have introduced the *isospin* ( $R_\tau^{NN}$ ), *spin-isospin longitudinal* ( $R_{\sigma\tau(L)}^{PP'}$ ) and *spin-isospin transverse* ( $R_{\sigma\tau(T)}^{PP'}$ ) nuclear responses functions corresponding to the isospin operator ( $\tau_\alpha$ ) and to the different projections of the spin-isospin operators ( $\sigma \tau_\alpha$ ) on the direction of the momentum transfer ( $\mathbf{q}$ ). The upper indices denote which kind of  $P$ - $h$  state ( $P=N,\Delta$ ) are excited

at the initial and final vertices. The challenging task is the evaluation of the various nuclear responses for the quasi-elastic, the resonant and the  $np-nh$  channels. For this we use the model developed by Delorme and Guichon (13) which is based on a semi-classical approximation. The responses are proportional to the imaginary part of the polarization propagator  $\Pi$  which reduces to the well known Lindhard function (14) for a quasi-elastic *nucleon-hole* excitation in a Fermi gas. The semi-classical approximation allows to compute the polarization propagators of the  $p-h$  excitations in a finite size system by the use of experimental nuclear densities depending on the distance.

In this model the correlations between  $p-h$  states are properly taken into account by the exact resolution of the RPA equations in the *ring*-approximation:  $\Pi = \Pi_0 + \Pi_0 V \Pi$  where  $\Pi$  and  $\Pi_0$  represent the polarization propagators with and without short range correlations respectively. The interaction potential  $V$  is parameterized by a pure contact force (with a parameter of Landau-Migdal  $f' = 0.6$ ) in the isospin channel and by a  $(\pi + \rho)$ -exchange plus a contact force (Landau-Migdal parameter  $g' \in [0.5, 0.7]$ ) in the spin-isospin channel.

The modified Delta width in the nuclear medium is split into the contributions of different decay channels (15): the "quasi-elastic" channel ( $\Delta \rightarrow \pi N$ ), modified by the Pauli blocking of the nucleon and the distortion of the pion, the two-body ( $2p-2h$ ) and three-body ( $3p-3h$ ) absorption channels. These parameterizations lead to a good description of the pion-nucleus reactions. There are others ( $2p-2h$ ) excitations which are not reducible to a modified Delta width and evaluated by extrapolating the calculations of two-body pion absorption at threshold (16). This procedure is however more approximate.

Note that the polarization propagator without correlation is built as a sum of partial contributions: quasi-elastic,  $np-nh$  (with  $p = N, \Delta$ ) and  $\Delta \rightarrow \pi N$ . Therefore it is easy to compute the nuclear responses of these partial reaction channels and to classify them with respect to the particles present in the final state. This procedure allows us, within the few rough assumptions described previously (emitted pions and nucleons respectively above and under Čerenkov threshold), to separate our events into "1 Č.R." or "2 Č.R." events. The calculations are more complicated in the RPA case because the partial channels are coupled. Using the ring-RPA equations it is however possible to split the total ("inclusive") responses into their partial contributions ( $R = \sum R_{\text{partial}}$ ) and to apply the previous principles of events classification.

The results for the cross sections computed with the RPA nuclear responses are shown on fig. (1) in the case of incident  $\nu_\mu$  (the conclusions drawn for  $\nu_e$  are essentially the same). The left figure displays the differential cross section  $\partial\sigma/\partial k'$  at a fixed neutrino energy  $E_\nu = 1$  GeV versus the energy transfer while the right figure displays the total cross section  $\sigma$  as a function of neutrino energy. In both cases the "inclusive" cross sections (thick curves) get their main contribution from the quasi-elastic channel (thin full curve) which peaks at low energy transfer (see left figure). For a sake of comparison we have

shown the contribution of the quasi-elastic channel without RPA (thin long dashed line). We observe that the differential cross section is slightly reduced and hardened in the RPA case. This is due to the fact that the spin-isospin transverse response is dominant in the neutrino-nucleus reactions (indeed it has been shown that the longitudinal spin-isospin response is suppressed at the leading order (11)) and that the RPA-interaction is repulsive in that channel. The RPA correlations are less important in the others partial channels. A very interesting feature is the importance of the  $(np-nh)$  channels (dotted curve) which give a large contribution to the inclusive cross sections. The differential cross section shows an extended spectrum from the quasi-elastic to the Delta peaks. We recover here the results relative to the presence of strength in the "dip" region.

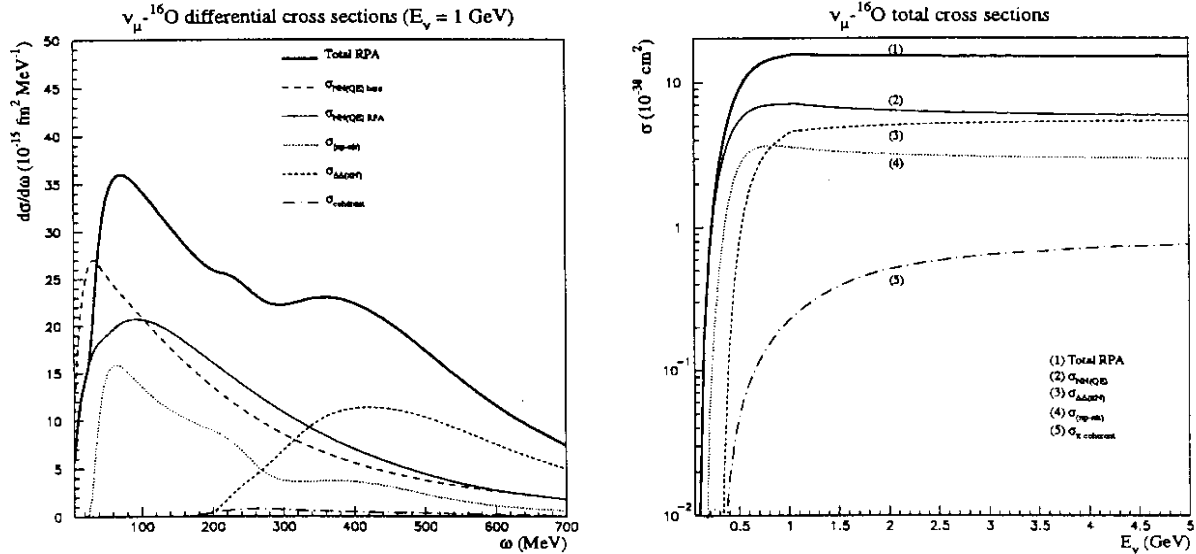


Fig. 1.  $\nu_\mu -^{16}\text{O}$  charged-current reactions: differential cross-section vs energy transfer (left figure) and total cross-section vs neutrino energy (right).

Having computed the cross section we are in position to evaluate the neutrino-oxygen events yields at fixed charged lepton momentum  $Y(k') = \int dE_\nu \Phi_\nu \partial\sigma/\partial k'$  where  $\Phi_\nu$  the incoming neutrinos flux taken from ref. (5) and to compare the "1  $\check{C}$ .R." events yields to the quasi-elastic ones. The results are shown in fig. 2 which displays the "1  $\check{C}$ .R." events yields, the full curves corresponding to the total yields (quasi-elastic+ $np-nh$ ) and the dashed curves to the sole quasi-elastic. We give the results of the calculations without (thin curves) and with (thick curves) RPA. First we observe that the RPA tends to reduce the events yields. Indeed it shifts the cross section towards high energies which are disfavored by the neutrino flux. As expected, the  $(np-nh)$  excitations on the contrary increase the absolute events yields. *At the maximum value of the yields, the enhancement of the total yield with respect to the "bare" quasi-*

elastic one is around 20 %. We can conclude that the neglected reactions of the atmospheric neutrinos on pairs of correlated particles in an oxygen nucleus, which lead to "1 Č.R." events, are a possible explanation for the underestimation of the experimental  $\nu_e + \bar{\nu}_e$  data by the Monte-Carlo simulations in Super-Kamiokande <sup>2</sup>. This could affect the experimental analysis in terms of neutrino oscillations parameters which include the distributions of the *absolute events rates*. The importance of this effect could be checked by including (if possible) the neglected nuclear correlations in the cross-sections used in the Monte-Carlo simulations. The main difficulty of this procedure is the possible double-counting with absorption effects for example which are partially accounted for both in the simulations and in the present calculations (17). Nevertheless it seems absolutely necessary to reconsider the possible impact of the nuclear effects on the analysis of the Čerenkov experiments.

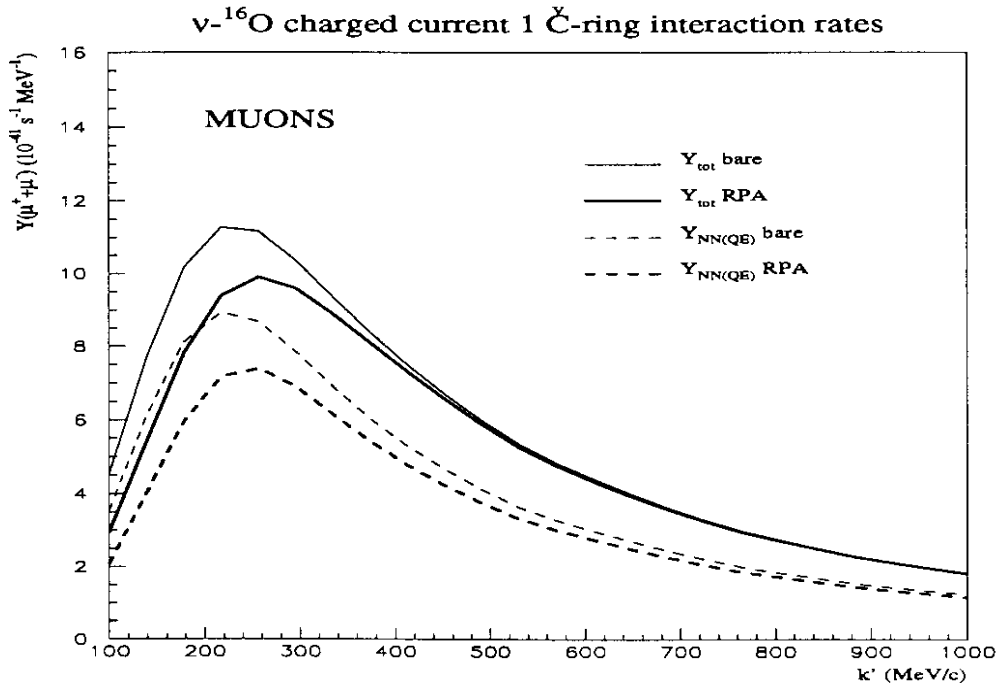


Fig. 2.  $\nu_\mu$  -<sup>16</sup>O "1 Čerenkov-ring" events yields vs muon momentum.

#### 4 CONCLUSION

In this work we studied the role of nuclear physics in the neutrino-oxygen reactions, relevant for the atmospheric neutrinos Čerenkov detectors. Within

<sup>2</sup> We thank Pr. Y. Declais who caught our attention on this point.



a few assumptions we perform a classification of the events rates with respect to the number of "Čerenkov rings" produced in the various nuclear processes considered. We conclude that the effect of the RPA correlations on the quasi-elastic channel, which gives the largest contribution to the "1 Čerenkov ring" class of events retained in Super-Kamiokande, is rather weak. However others sources of "1 Čerenkov ring" events, such as  $(np-nh)$  excitations, could enhance the total events rates by a factor as large as 20 %. The effect in the analysis of the low energy events should be rather large and has to be investigated further.

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