Iranian Journal of Astronomy and Astrophysics
Vol. 11, No. 1, Winter 2024, 17–30
©Available online at http://ijaa.du.ac.ir
DOI: 10.22128/ijaa.2024.642.1136
Online ISSN: 2383–403X

**Iranian Journal of Astronomy and Astrophysics**

**Research Paper**

# Measurement of Atmospheric Neutrino Cross-Sections on Oxygen, Water and Argon using Nuwro Event Generator

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**Received:** 9 January 2023; **Accepted:** 4 March 2024; **Published:** 3 April 2024

**Abstract**. Neutrinos were produced immediately after Big-bang. These are the most abundant particles after photons. Neutrinos are literally jam packing the Universe and are associated with some of the deepest mysteries of nature. These are excellent carriers of information from the past of Universe through sources like bursting stars and black holes which we do not have a direct access to. Consequently, there has been a surge in the study of neutrinos and their interaction with matter. However, since neutrinos are very weakly interacting particles, these have feeble cross-sections. Nonetheless, cross-section measurement is the basic ingredient for any higher order neutrino studies. Therefore, in this work we report the cross-section measurements of neutrino interactions with three atmospheric gases viz; Oxygen, Water and Argon. This study is done using NuWro event generator. Nuwro is a Polish code developed by some eminent researchers at Wroclaw University of Poland. It is configured using well known physical models of neutrino interaction. The cross-section measurements are taken in an energy interval of hundreds of MeV to a few GeV,which is also best suited to study neutrino oscillations. We also try a novel way to define the scattering potential for neutrino interactions as a function of initial neutrino flux.

*Keywords*: Cross-section, Neutrino-oscillations, Pion production, Neutrino flux

# 1 Introduction

Since neutrinos are very weakly interacting particles, these can be used to probe environments where light or radio waves get diffused due to greater amount and greater density of matter around. As for instance, the photons emitted from the solar core may take 40,000 years to diffuse to the outer layers of the sun [1], but neutrinos generated in stellar fusion can cross this distance practically unimpeded at nearly the speed of light. Similarly, supernovae are known to release approximately 99% of their radiant energy in a short, ten second, burst of neutrinos [2]. Neutrinos can pass through anything and everything. For this ease of transmission through any medium, nothing can beat neutrinos as probes of matter. Neutrinos can also prove extremely useful in communication. For now, electromagnetic waves are the

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best carriers of information. These are easy to transmit and to detect and can carry a bulk of data. However, in certain situations, these may not work well. For example, seawater is opaque to electromagnetic radiation of shorter wavelength which impedes the transmission of information to nuclear submarines. Neutrinos, on the other hand, can easily pass through 1000 light-years of lead, so an ocean would obviously be no problem to them.

Another motivation is to study neutrinos for the sake of neutrinos. These are associated with certain strange phenomena, one such is neutrino oscillation. It is a quantum mechanical phenomenon which arises because the flavour eigen-states of neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ are not identical with their mass eigen-states, due to which there is a flip in their flavour or mass-mixing as these travel large distances [3]. In order to understand neutrino oscillation parameters in a better way, it is needed to build a more complete picture of neutrino interactions. This throws at us a chunk of various theoretical and experimental challenges, since neutrinos are feebly interacting particles. The detection of neutrinos is inferred by the particles they leave behind, in an interaction. As an example, if a muon-neutrino scatters quasi-elastically off a neutron, it produce a charged muon and a proton

$$\nu_\mu + n \longrightarrow \mu^- + p.$$

This suggests that we should design low mass detectors which have extremely fine tracking capability. But due to the extremely small size of neutrino cross-section, there has been a need to build large size and high mass detectors so as to have an enough event rate to perform useful studies. Moreover, the elusive nature of the neutrino and the inherent difficulty in its detection has created many false signals. In this context, neutrino event generators act as an interface between theory and experiment. These play an essential role from conceiving the idea of an experimental design to the final physics results.

The purpose of event generators is to evaluate the feasibility of a proposed experiment by way of optimizing the design of the detector, analyse the collected data samples and evaluate systematic errors and therefore assess its physics reach. In order for the simulation to be accepted in the scientific community, these have to mimic the experimental results. If the two data sets are comparable, then these have some credibility.

In the neutrino experiments, event generators are used to provide information about the signal and the background events in the detectors. Though one may desire to simulate all the possible neutrino interactions and cover entire kinematical region using appropriate models, but it is not possible to perfectly do so and thus, there are always simplifications and assumptions in the actual implementation of the simulation programs. Different experiments have developed their own event generators some of which are NEUT [4], GENIE [5] and NUANCE [6].

The event generator used for the present study is Nuwro [7]. It is developed by researchers at Wroclaw university Poland. Nuwro is written in C++. It's input file is a plane text file and its output file is a root file. In order to build this code we need to install root software [8] on our computer system configured with pythia6 library [9]. Root software takes care of detector geometry and pythia6 contains the information about physical models used. Nuwro is enabled for five different dynamics viz; quasi-elastic (QE), resonance excited scattering (RES), deep inelastic scattering (DIS), coherent pion production (COH) and meson exchange (MEC) processes. Each process can further be analysed through two channels of interaction viz; charged current (CC) and neutral current (NC). The weak interactions are mediated by charged $W^\pm$ and neutral $Z^0$ bosons. The feature of weak interactions is interesting because it implies that neutrinos can probe such environments in which the electromagnetic waves or radio waves diffuse and cannot penetrate much. Nuwro is a generator of interactions only and is very well suited for cross-section measurements of neutrino interactions with matter. Impulse approximation is the basic assumption according to which nucleus is a

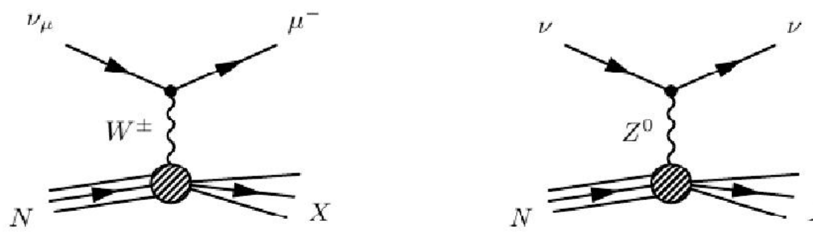


Figure 1: Charged-Current (CC) neutrino interactions; Neutral-Current (NC) neutrino interactions.

set of quasi free nucleons and a primary interaction occurs on one of them. Neutrinos are selected according to information about the beam such as its energy and flavor (whether single or mixed). Then a target is selected and a dynamics is chosen.

As far as the physical models are concerned, Nuwro uses Llewellyn-Smith model [10] for charged-current Quasi-elastic Scattering. Most generators like NEUT and GENIE use Rein-Sehgal model [11] but in Nuwro, Adler-Rarita-Schwinger formalism [12] is used to calculate $\Delta$ resonance explicitly. Similarly, Quark-Parton Model [13] is used for deep inelastic scattering. All these models are extensively tested using electron-nucleus scattering data and have been published.

The three key processes of neutrino interaction can be summarised in the following table. In a few GeV energy range, quasi-elastic processes constitute a large fraction of the signal

| **Charged-Current $W^\pm$ Exchange** | **Neutral-Current $Z^0$ Exchange** |
|---|---|
| -Quasi-elastic Scattering<br>(Target changes but no break-up)<br>$\nu_\mu + n \to \mu^- + p$ | -Elastic Scattering<br>(Target doesn't break-up or change)<br>$\nu_\mu + N \to \nu_\mu + N$ |
| -Nuclear Resonance Production<br>(Target goes to excited state)<br>$\nu_\mu + n + \pi^0(N^* or \Delta) \to \mu^- + p$ | -Nuclear Resonance Production<br>(Target goes to excited state)<br>$\nu_\mu + N \to \nu_\mu + N(N^* or \Delta)$ |
| -Deep In-elastic Scattering<br>(Target broken-up)<br>$\nu_\mu + quark \to \mu^- + quark'$ | -Deep In-elastic Scattering<br>(Target broken-up)<br>$\nu_\mu + quark \to \nu_\mu + quark$ |

population. In these processes, the nucleus is typically described in terms of individual quasi-free nucleons (baryons). These baryons undergo a change in electric charge to accommodate the exchange of the charged $W^\pm$ boson. If, instead of simply altering the charge of the target baryon, the $W^\pm$ boson transfers enough momentum to promote the target into a low-mass resonance state, then the decay of the resonance typically produces a nucleon and a pion mainly through the resonant mechanisms. These are called resonance excited scattering processes. The deep inelastic scattering processes, on the other hand, become significant towards higher energies. Adequate theoretical descriptions of quasi-elastic, resonance mediated, and deep inelastic scattering have been formulated earlier [14]. However, there is still a need of uniform description which can globally describe the transition between these processes. Moreover, the full extent to which nuclear effects can impact this region is a topic that has only recently been appreciated [15].

## 2 Atmospheric neutrino production

Atmospheric neutrinos are produced as the decay products of the cosmic ray interactions in the atmosphere. The cosmic showers mostly consist of protons, 5% He nuclei and smaller traces of some heavier nuclei typically producing pions and less abundantly kaons. Though the Kaon production cross-section is not known accurately [16], the pions are known to further decay to neutrinos by the following scheme of reactions.

$$\begin{aligned}
&\pi^+ \longrightarrow \mu^+ + \nu_\mu, \\
&\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu_\mu}, \\
&\pi^- \longrightarrow \mu^- + \bar{\nu_\mu}, \\
&\mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu_e}.
\end{aligned}$$

The uncertainties in the calculation of atmospheric neutrino fluxes depend on their energies. For neutrinos with energies around 1 GeV, the primary fluxes of cosmic ray components are relatively well known. On the other hand, the cosmic ray fluxes of energies around 10 GeV are modulated by solar activity and are also affected by the geomagnetic field [16].

In this work we find the atmospheric neutrino cross-sections for their interaction with oxygen, Argon and water which are found in moderate to greater abundance in the atmosphere . We are performing our measurements in the lower energy regime from hundreds of MeV to a few GeV. The results can be discussed under the following two headings.

### 2.1 Saturating Cross-sections

In general, the cross-section gives a probability that a specific process or interaction may take place when some kind of radiant excitation or particle beam intersects a target. From the knowledge of scattering theory of waves and particles [17], the flux $\Phi$ of the incident beam for a target of thickness $dz$, changes as follows

$$\frac{d\Phi}{dz} = -n\sigma\Phi. \tag{1}$$

Solving this equation gives the exponential attenuation of the beam intensity as follows

$$\Phi = \Phi_o e^{-n\sigma z}, \tag{2}$$

where $\Phi_o$ is the initial flux, $z$ is the total thickness of the material and $\sigma$ is the total cross-section of all processes including scattering, absorption, or transformation to another species. In case of neutrinos, transformation would mean oscillating to other flavours. Moreover, neutrinos traverse materials of any thickness practically unimpeded, so $z$ will remain a constant or an insignificant parameter. Taking the initial flux $\phi_0$ as constant, the neutrino cross-section would essentially depend on change in flux and on $n$, the volumetric number density of scattering centres. This can be written as

$$\sigma = \frac{-1}{nz} \ln \frac{\Delta\phi}{\phi_0}. \tag{3}$$

Neutrinos don't get absorbed, these just pass through and diffuse. Therefore one can attempt to describe neutrino interactions in terms of Fick's law of diffusion [18] which is written as

$$q = -D\frac{\Delta\phi}{\Delta Z}, \tag{4}$$

where $q$ represents the flow of particles per unit area per second, $D$ is the diffusion coefficient (or diffusivity) and $\Delta\phi$ is the change in flux across the material of thickness $\Delta Z$.

However, the most general way of writing Fick's law would be

$$J = -D\Delta\Phi, \tag{5}$$

where $J$ is the current (coming and going of particles) across a given thickness of matter. It gives the diffusion flux or the rate of mass transport along $z$ direction. In general, the driving force for particle flux is a potential gradient. Therefore, finding potential would be akin to finding $\phi$ and consequently, a changing flux will be indicative of a changing potential. Here, we can make a bold assumption that $\phi = aV$ which gives

$$\Delta\phi = a\Delta V, \tag{6}$$

where $a$ is a constant to be determined experimentally. Since cross-section has a dependence on change in flux $\Delta\phi$, the trend exhibited by flux with respect to change in energy would reflect the trend of cross-section changes. As Nuwro is enabled to determine neutrino flux, we draw a plot to show the change in flux with respect to neutrino energy by simply plugging the output of NuWro for two processes (QE and RES) taken together. This theoretical plot is shown in Figure 2 below.

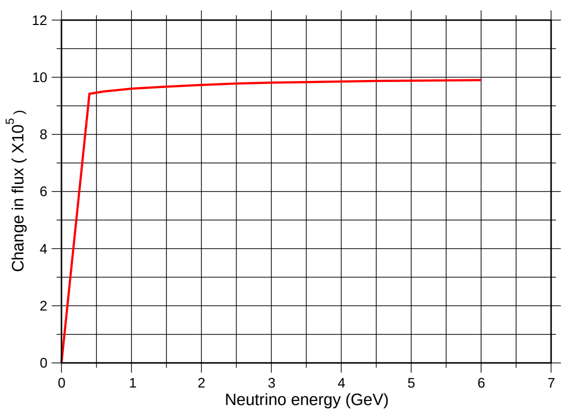


Figure 2: Theoretical change in neutrino flux with neutrino energy during scattering processes (using NuWro)

The result shows that the change in flux is steep in the beginning and decreases or saturates towards higher neutrino energy. This is much similar to the trend exhibited by neutrino interaction cross-section as shown in Figures 3–8 using Nuwro event generator. These results have been carried out by targeting neutrinos on three abundant atmospheric gases like oxygen, water and argon.

It is pertinent to mention that the results obtained using Nuwro are much in conformity with the existing experimental measurements of cross-sections as a function of neutrino energy from both historical and recent measurements [19]. The studies carried out in [19] are one of the most comprehensive. However, the measurements of direct neutrino scattering at high energies are unavailable. Therefore, predictions rely heavily on the existing knowledge of event generators until a well-formulated model of the relevant quark structure functions is brought up through proper experimentation and computation for higher energy regime.

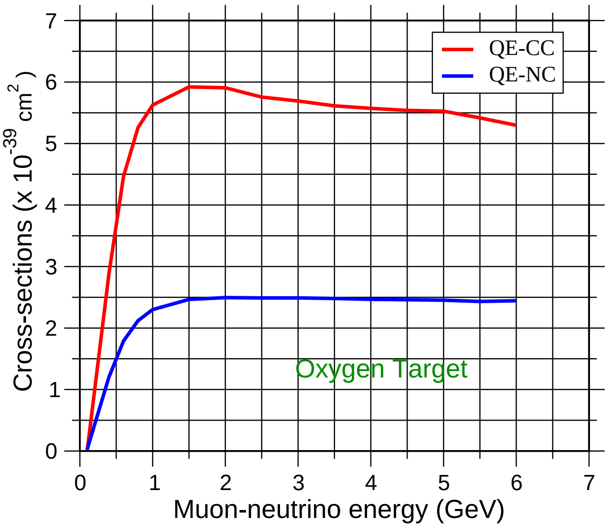


Figure 3: cross-section of QE neutrino-oxygen scattering (using NuWro)

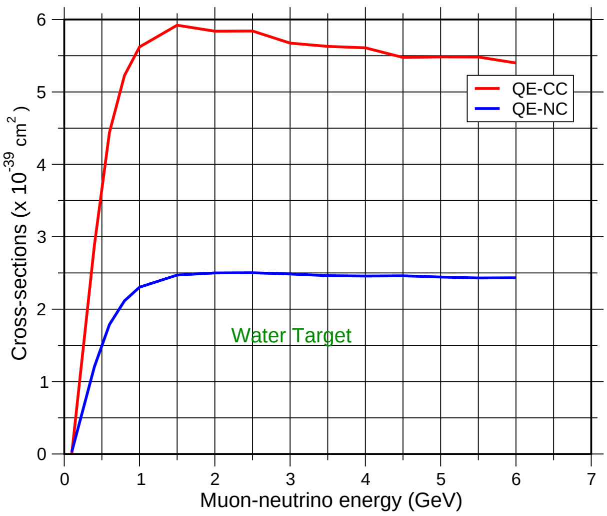


Figure 4: cross-section of QE neutrino-water scattering (using NuWro)

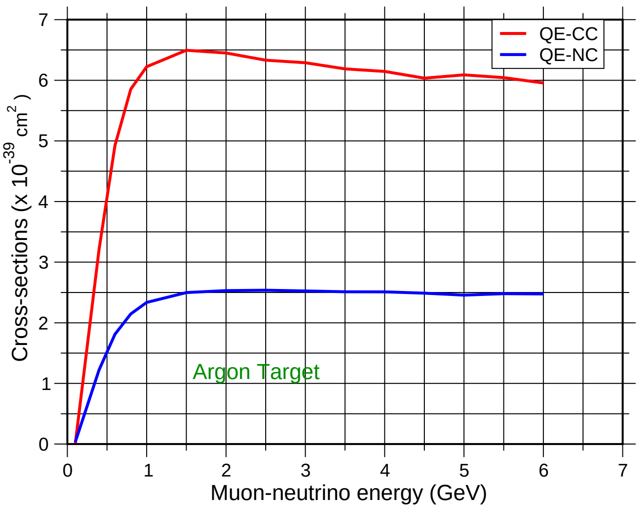


Figure 5: cross-section of QE neutrino-argon scattering (using NuWro)

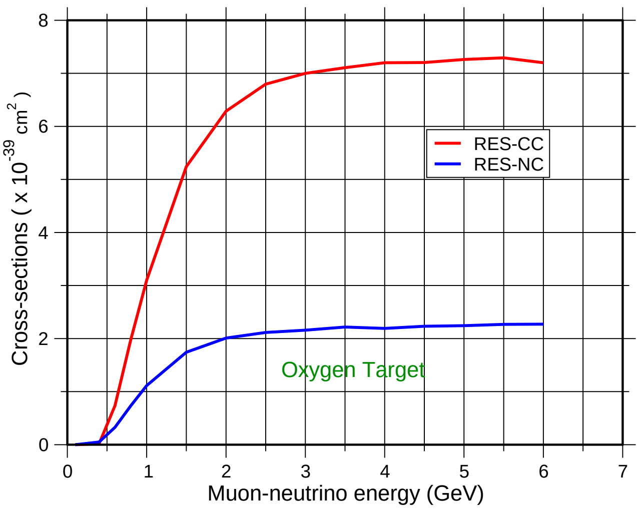


Figure 6: cross-section of RES neutrino-oxygen scattering(using NuWro)

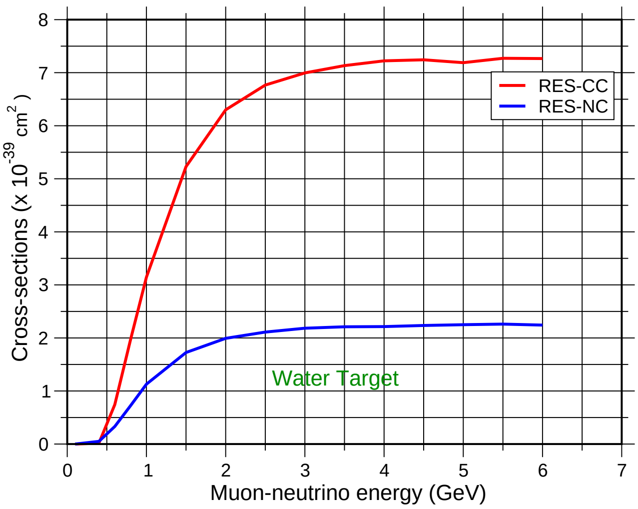


Figure 7: cross-section of RES neutrino-water scattering (using NuWro)

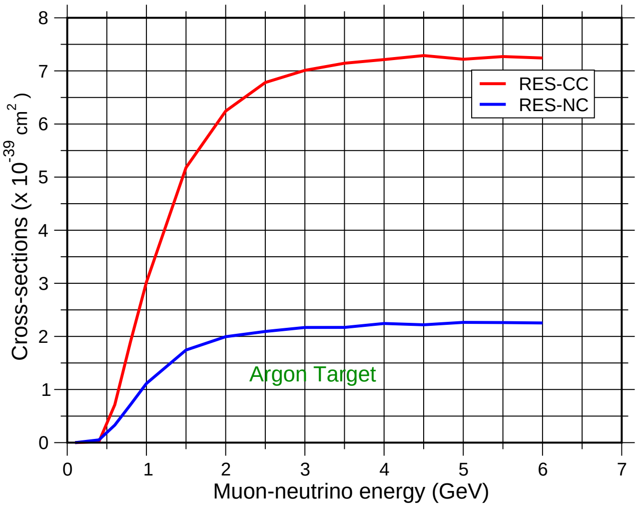


Figure 8: cross-section of RES neutrino-argon scattering (using NuWro)

One would also be interested in defining the nature of scattering potential determining the neutrino interactions. For this, one can begin with the idea of the nuclear potential by adding a nucleon to another nucleon or nucleus. In general, a point at a distance $r$ from a point nuclear charge $Q$ will experience an attractive nuclear potential of the form

$$V = kQ/r^x. \tag{7}$$

This is similar to the electrostatic and gravitational potentials, whose known expressions take the above form by putting $x = 1$. Now, in order to find an expression for the nuclear potential felt by a point $B$ exterior to an extensive nuclear charge $Q_A$, we consider the spherical symmetry so as to integrate the interactions of the point $B$ with every differential volume element constituting the sphere $A$. This is a well known approach [20]. In this way, the resultant potential $V$ felt by the point $B$ is expressed as

$$V = \frac{3kQ_A\left\{(r-R_A)^{3-x}[r-(x-3)R_A]-(r-R_A)^x(r+R_A)^3[r+(x-3)R_A]\right\}}{2(x-4)(x-3)(x-2)R_A^3 r}, \tag{8}$$

where $r$ is the distance of $B$ from the sphere centre $A$. Since the nuclear interaction is short-range, it is strongly dependent on $r$. However, a satisfactory value for $x$ is not well known. We propose $x = 6$ which is supported by experimental data [21,22]. In this way, the above equation reduces to

$$V = -kQ_A/(r^2 - R_A^2)^3. \tag{9}$$

Thus, for a nucleus with a given ($Q_A$ and $R_A$), the potential at a point is dependent on $r$ only. Using equation (9) in equation (6) we get

$$\Delta\phi = \frac{6akQ_A r}{(r^2 - R_A^2)^4}, \tag{10}$$

hence, from equation (3) we get

$$\sigma = \frac{-1}{nz} \ln \frac{6akQ_A r}{\phi_0 (r^2 - R_A^2)^4}. \tag{11}$$

This theoretical result proposes a novel way to describe the scattering potential in neutrino-nucleus interactions and the dependence of cross-section thereof. Keeping other parameters constant, we find that cross-section will rise as the initial flux $\phi_0$ gradually diminishes.

## 2.2 Rising Cross-sections

QE and RES processes dominate at lower energies and their interaction cross-section saturates towards rising energies. This saturation marks the boundary of QE and RES processes after which the nuclear form factors begin to play the role. Form factors [23] are intimately related to the internal nuclear structure and are measured by elastically scattering electrons or muons on nucleons.

In general, any atom or nucleus is described by a many-body wave-function. The charge density $\rho(x, y, z)$ for an atom or nucleus is associated with an effective potential that is arrived at by averaging over the motion of the constituent particles and the form factor $f(Q)$ is Fourier transform of the same. Form factors give information about charge distributions of nuclei by a Fourier transform of a spatial density distribution of the scattering object from real space to momentum space also known as reciprocal space [24].

Therefore, in QE and RES processes, we can conclude that a linearly rising cross-section is damped by the form factors as the energy increases. From here, DIS processes start getting dominant. In our observations using Nuwro, the DIS processes start appearing on the scene at and around 0.8 GeV.

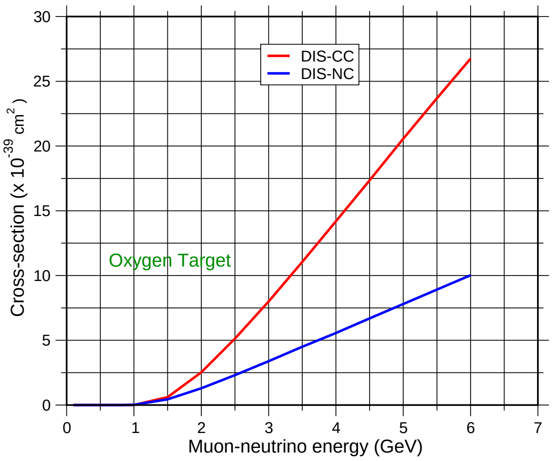


Figure 9: cross-section of DIS neutrino-oxygen scattering (using NuWro)

However, as already stated that transition between these processes is still not clear and is an open question to be addressed. Moreover, as the neutrinos get well inside the nucleus, the factor $(r^2 - R_A^2)^4$ reduces to a constant since $r$ becomes negligible in comparison to $R_A$. At these higher energies, neutrinos further begin to probe the nucleons at quark degrees of freedom and the cross-section rises linearly.

There is a point like scattering or one to one interaction, between neutrinos and the quarks which leads to a linear dependence of neutrino cross-sections. The Nuwro results for DIS processes are shown in Figures 9–11 using the same targets as earlier viz; oxygen, argon and water.

To further ascertain the linear behaviour, we have drawn another theoretical plot by using NuWro output as shown in Figure 12 for change in neutrino flux with respect to neutrino energy for DIS processes. This is logically consistent since a sharp fall in the neutrino flux can be associated to a sharp rise in the neutrino interaction cross-section. This is also in agreement with the predictions of equations (10) and (11). This linearity, however, breaks down at lower energies by the sensing of nuclear effects by projectile [25].

The results obtained in this work are in agreement with another comprehensive studies on the subject of neutrino-nucleus interaction cross-sections published by the authors [26,27] for a broader range of neutrino energies. Here, our discussion is limited to a few GeV range of neutrino energy since this range is important for the study of neutrino oscillations [3].

## 3 Conclusion and discussion

In this study, we have found that neutrino cross-sections are merely a reflection of changing flux which in turn is dependent on nuclear potentials encountered by them. We have

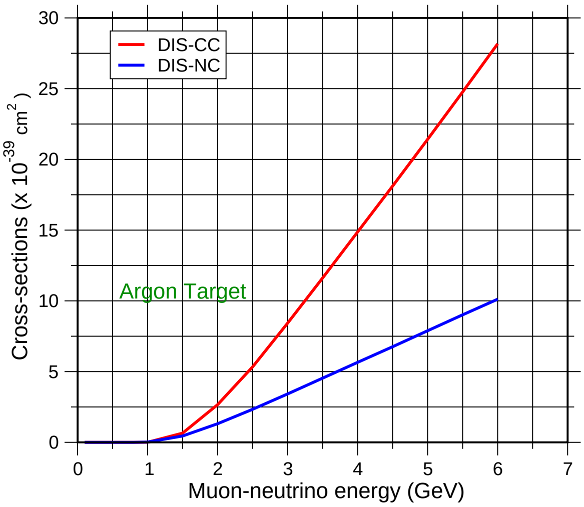


Figure 10: cross-section of DIS neutrino-argon scattering (using NuWro)

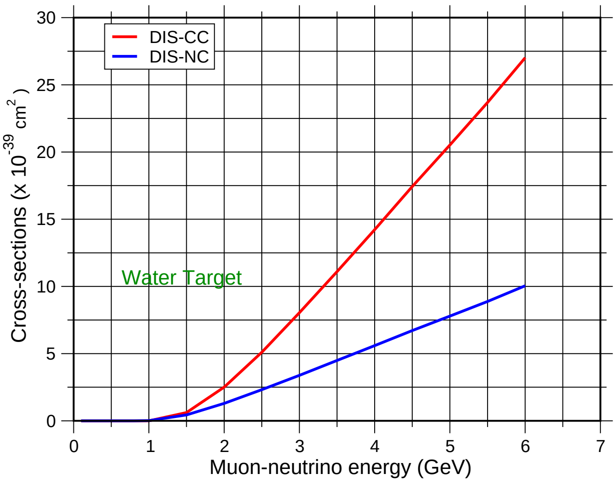


Figure 11: cross-section of DIS neutrino-water scattering (using NuWro)

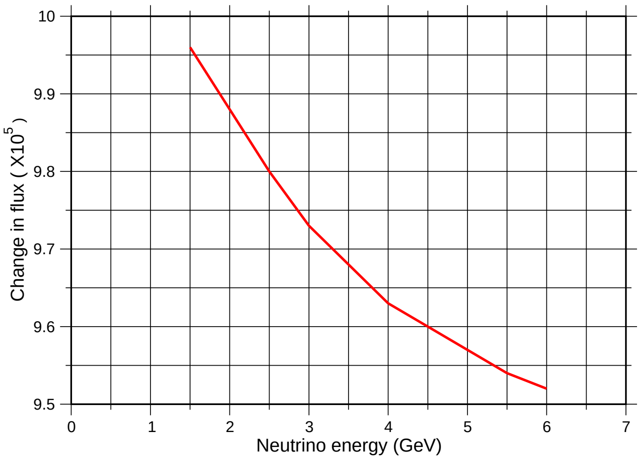


Figure 12: change in neutrino flux at higher neutrino energy interactions (using NuWro)

attempted a novel way to define the scattering potential for various neutrino interaction processes and the trend exhibited by cross-sections thereof. The results in Figures 2–12 have been obtained using Nuwro event generator which are in line with the experimental observations and also with the theoretical results attempted in this study. We have mainly investigated three types of dynamics viz; quasi-elastic (QE) scattering, resonance excited scattering (RES) and deep inelastic scattering (DIS) processes of neutrino interaction. These processes are analysed each through two channels namely, charged-current (CC) interaction and neutral-current (NC) interaction. Nuwro is enabled for more processes of neutrino interactions and a range of targets and energy regimes. However, in the present study we are focussing only on atmospheric neutrinos and their interactions with matter. Though the results do not improve upon precision, these can serve as a useful cross-check in an area where limited experimental data is available.

Neutrinos are known to interact through weak interactions and to some extent through gravity on account of having a feeble mass. However, one cannot stop there only, and there is a possibility that neutrinos might be interacting through other forces and potentials which we are yet to explore. If changing neutrino flavour throws a hint at their mass, changing flux should be indicative of an associated potential. We have attempted to define that potential in a novel way, to the best of our understanding. However, it is only a beginning and yet inconclusive.


## Acknowledgment

We are thankful to Dr. Jan Sobczyk of Wroclaw University Poland, for his guidance as and when needed.


## Authors' Contributions

All authors have the same contribution.

## Data Availability

No data available.

## Conflicts of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

## Ethical Considerations

The authors have diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

## Funding

The work is supported and funded by Department of Science, Technology and Innovation Council (JKST&IC), government of J&K, INDIA.

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