# Neut

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## Contents

- Brief History ~ Requirements
- Neutrino interactions above ~100MeV
- Procedure of the neutrino event generation
- Used models for each neutrino interaction mode
- Nuclear effects (Final state interactions of hadrons)
- Remaining issues

Minimal SU(5) GUT predicts nucleon decay.

Major decay mode of proton is  $p \rightarrow e^+ + \pi^0$ 

- Ring imaging water Cherenkov detector has high efficiency in reconstructing electrons and low momentum  $\pi^0$ s.
- Possible to build massive detector to search for the nucleon decay predicted by the theory.

But  $\pi^0$  may interact in nucleus if the proton in Oxygen decays.



Study of interaction of  $\pi$  in Oxygen is important for the analysis.

Need simulation program to determine the event selection criteria and to estimate the detection efficiency.

Ring imaging water Cherenkov detectors

Japan 1983 : Kamiokande ( 3,000 ton, ~ 1,000 20inch PMTs ) 1996 : Super-Kamiokande ( 50,000 ton, ~12,000 20inch PMTs )

\*) Also in US, IMB experiment started in 1982.

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(7,000 ton tank, ~ 2,000 5(8)inch PMTs)
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Detect relativistic particles

running through the detector medium ( water )

using the Cherenkov light.

- Number of the Cherenkov rings
  - = Observed number of particles
- Energy (momentum) is reconstructed using the total charge of the ring.
- Direction is reconstructed using the image of the ring.
- Particle type is identified using the shape of the ring.
  - Electron / gamma
  - Muon etc.

- : Diffused
- : Sharp

Neut was initially developed for the Kamiokande experiment.

The major background in searching for the nucleon decay is caused by the atmospheric neutrinos.

One of the neutrino interaction in a few GeV region Single pion production

 $\overline{\nu_{e}} + p \rightarrow e^{+} + n + \pi^{0}$  $\nu_{e} + n \rightarrow e^{-} + p + \pi^{0} \quad \text{etc.}.$ 



Basically, the electron (positron) and  $\pi^0$ from primary neutrino interaction have different energy/momentum from nucleon decay products.

But re-scattering of  $\pi$  in Oxygen changes its charge or momentum.

Need precise simulation program to estimate the background.

- Primary neutrino interaction with water
  - ( = neutrino interaction with Oxygen or proton )
- $\pi$  re-scattering in Oxygen

Indication of neutrino oscillation

from the observation of solar and atmospheric neutrino

Super-Kamiokande

Massive (50kt) Water Cherenkov detector

~30 times larger statistics High precision observation.

1998 Evidence of neutrino oscillation

 Accelerator based neutrino experiment K2K ~ SciBooNE

Beam experiment ~ High statistics @ near detectors.

Several types of the detectors with various target material Water Chrenkov detector Water target tracking detector Scintillator detector Iron target muon range detector

Need much more precise neutrino interaction simulation program. New experimental data and models make various improvements possible.



## 2. Neutrino interactions

Charged current quasi-elastic scattering Neutral current elastic scattering Single  $\pi$ , $\eta$ ,K resonance productions Coherent pion productions Deep inelastic scattering



 $v_{\mu} + n \rightarrow \mu^{-} + p$   $v_{\mu} + N \rightarrow \nu + N$   $v_{\mu} + N \rightarrow l + N' + \pi (\eta, K)$   $v_{\mu} + X \rightarrow l + X' + \pi$   $v_{\mu} + N \rightarrow l + N' + m\pi(\eta, K)$ (*l*: lepton, N,N': nucleon, m : integer)



## 3. Procedure of the neutrino event generation

## 1) Fix the energy of neutrino

Energy distribution of neutrino should obey

the distribution determined by

neutrino flux ( $\phi$  (E)) x total cross-section ( $\sigma_{total}$  (E))

example)

Atmospheric neutrino

(Angular distribution is also taken into account in the actual simulation.)



## 3. Procedure of the neutrino event generation

## 2) Fix the interaction mode

Interaction mode is selected

by using the each individual interaction cross-section. (In order to select one of the interactions

it is necessary to know the cross-sections for each mode.)

Example ) picked up energy in the previous step was 2.5GeV



## 3. Procedure of the neutrino event generation 3) Simulate primary interaction Fix the number of particles in the finals state Fix the types and 4-momenta (direction) of each particle. Example ) single $\pi$ production Input : Use fixed neutrino energy and direction in step 1). initial particles final particles 4) Simulate secondary interaction in nucleus Simulate the interaction in the target nucleus and fix the properties of each particle outside of the target nucleus. Example ) $\pi$ charge exchange interaction in nucleus Trace generated hadrons in nucleus until the particles exit from the nucleus.

- 4. Introduction of NEUT ~ What NEUT does
  - Neutrino energy range : ~ 100MeV to ~ TeV
  - Target nucleus :primarily proton and Oxygen. Rather well tested with Carbon ( at K2K, SciBooNE )

\*) Possible to specify heavier or lighter target nucleus. But additional approximations are used to simulate.

- Provide cross-sections to estimate the interaction rates or to select the interaction mode.
- Simulates primary neutrino interaction with nucleon and nucleus targets.
   Simulate emission of gamma from the excited state. ( only for Oxygen at this moment )
- Simulates meson interactions in the target. Especially in detail for the low momentum pions.
- Simulates nucleon re-scattering in the target nucleus.



q<sup>2</sup>: 4 momentum transfer q<sup>2</sup>  $\equiv$  (E<sub>1</sub>- E<sub>v</sub>)<sup>2</sup>- (**p**<sub>1</sub> - **p**<sub>v</sub>)<sup>2</sup> (= -Q<sup>2</sup>) *W* : Invariant Mass of N\*  $W \equiv \sqrt{E_{N^*}^2 - p_{N^*}^2}$ 

## 4. Introduction of NEUT

## ~ Summary of the interaction models

## • QE

- Llewellyn-Smith, Smith&Moniz
- M<sub>A</sub> is 1.1 or 1.2GeV/c
- Resonance production
  - Rein & Sehgal
  - M<sub>A</sub> is 1.1 or 1.2GeV/c
  - Recently  $\Delta \rightarrow N\gamma$  decay is considered.
  - Recently lepton mass effects in CC single- $\pi$  is considered.
- Coherent- $\pi$ 
  - Rein & Sehgal

(recently lepton mass correction is included.)

- DIS
  - GRV94 pdf with Bodek-Yang correction
  - GRV98 pdf with Bodek-Yang correction

## Charged current quasi-elastic



Major interaction in the low energy region

Useful interaction mode to reconstruct incident neutrino energy ~ used to measure the spectrum shape of the neutrino flux

Only the charged lepton is observed if the momentum of recoil nucleon is below 1GeV with the water Cherenkov detector.



In the original article, both vector and axial-vector form factors are assumed to be dipole. Also,  $G_E^n$  is set to 0.

Recent precise electron scattering experiments suggests deviation from the dipole assumption for vector form factor.

Still, dipole form factor is used in NEUT.  $M_A = 1.1 \text{ or } 1.2 \text{ GeV/c}^2$ 



## Quasi-elastic scattering with nucleon in nucleus

Nucleons are bound in nucleus.

- $E_v > 100 MeV$ 
  - → Fermi gas model is a good (first-order) approximation.
- Nucleon is moving in the Fermi sea.
- Nucleon is bound in the nucleus. ( "binding energy" )
- Pauli blocking is required.

(Outgoing nucleon required to have larger momentum

than Fermi surface momentum.)



$$\left( E_{v} + E_{n} + B = E_{p} + E_{\mu} \right)$$
$$\left( \rho_{p} > \text{Fermi momentum} \right)$$

To obtain the cross-section of CCQE for bound nucleons, relativistic Fermi-gas calculation by Smith and Moniz is used. (Nucl.Phys.B43 605(1972),erratum-ibid.B101 547(1975),

with additional correction.)

Assuming the simplest Fermi gas model,

Target nucleus is determined by Fermi momentum and potential







Clearly the small momentum transfer region

is suppressed due to Pauli Blocking and binding energy.

In the determination of the kinematics,

NEUT uses the classical (simple) energy and momentum conservations.

There are several recent models

Here is a coparison with the model by Nieves et al.



**NEUT(Smith-Moniz)** Nieves et al. solid: v, dashed:  $\overline{v}$ Nieves model is lower than S-M by 10% at 500MeV for both in  $v_e, v_\mu$ Ratio (Nieves to S-M) is within +/-25% above 200MeV. Currently, this model is applicable up to 500MeV, and not used in neut. Authors are trying to extend the energy range up to  $\sim 1$ GeV.

Comparison between the models Smith-Moniz and Nieves et al.

$$\nu_{\mu} + n \rightarrow \mu^{-} + p$$



More detailed model by Nieves et al. shows larger suppression in small q<sup>2</sup> region.

Forward going particles are suppressed.

## Single pion production



Major background of the nucleon decay

Particles in the final state are same as the ones from nucleon decay.

Major background of the  $\nu_{e}$  appearance search at T2K

 $\gamma$  from asymmetric decay of  $\pi^0$ 

might be misidentified as  $v_e$  appearance signal.

Major contamination to the energy spectrum measurement. If pions are absorbed,

> event shape is similar to the CCQE in the water Cherenkov detector.

Without the detection of the recoil-nucleon track,

it is difficult to discriminate single pion and CCQE.

#### 6. Single meson production via resonances $\nu + N \rightarrow I + N' + \pi (K, \eta)$ Based on D.Rein, and L.M.Sehgal, Ann. of Phys. 133(1981) $\nu + N \rightarrow I + \Delta (N^*)$ $\Delta(N^*) \rightarrow \pi + N'$ Resonances up to 2GeV are taken into account. $W^+$ In NEUT, only $\Delta$ absorption and Pauli blocking $\pi^+$ decky, Phys.Rev.D 25, 1161 (1982 are also considered rish Phys Rev D 19 2521 (197) (Effect : Delta absorption ~ 20%) Pauli blocking $\sim$ a few %) Ilen Nucl Phys B 176, 269 (1980 Allasia Nucl Phys B 343 285 (1990 σ(v<sub>µ</sub>)(10<sup>-38</sup> cm<sup>2</sup>) 2.0 0 <sub>5</sub>( ۷<sub>"</sub>)(10<sup>-38</sup> cm<sup>2</sup> Kitagaki Phys.Rev.D 34, 2554 (1986 $\nu_{\mu}$ + p $\rightarrow$ $\mu^{-}$ + p + $\pi^{+}$ $v_{\mu}$ + n $\rightarrow \mu^{-}$ + n + $\pi^{+}$ 1.2 0.9 FNAL Bell Phys.Rev.Lett. 41, 1008 (1978) I 0.8 F Ī 0.8 0.5 0.6 0.4 0.4 0.3 0.2 0.2 0.1 10 Ev (GeV) 10 Ev (GeV)

## 6. Single meson production via resonances



7. Single meson production via resonances

K and the other meson productions via resonances Used to estimate the background of nucleon decay. Basically same for the  $\pi$  production.

 $\nu + N \rightarrow I + N^*$ 

Use appropriate resonances and branching ratios.

In NEUT, we use upper limit of each branching ratio.

(for the background estimation)

 $\bullet \Delta(\mathsf{N}^*) \to \mathsf{K} + \Lambda$ 



## 8. $\Delta \rightarrow N\gamma$ decay

 $\Delta$  resonance can decay into gamma (Br ~<0.5%) This branching ratio is small,

but NC  $\Delta \rightarrow N\gamma$  can be background

in searching for the  $v_{\mu} \rightarrow v_{e}$  appearance.

 $\rightarrow \Delta(N^*) \rightarrow \gamma + N'$ 

This mode is added to NEUT, assuming

– Kinematics are basically same as  $\Delta \rightarrow N\pi$ 

- Three reactions are considered
  - CC :  $v + n \rightarrow l + p + \gamma$

 $\nu + N \rightarrow I + \Delta (N^*)$ 

- NC :  $v + n \rightarrow v + n + \gamma$
- NC :  $v + p \rightarrow v + p + \gamma$



8.  $\Delta \rightarrow N\gamma$  decay



 $E_v$  is randomly selected between 200MeV and 3000MeV

## Deep inelastic scattering

Dominant interaction in the high energy region ( > several GeV )

### Understood as neutrino quark interaction.

Parton distribution function of nucleon is obtained from the high energy lepton nucleon (nucleus) scattering experiments.

Thus, important in estimating the energy of neutrino above several GeV. ( measure momentum of lepton together with the total energy deposit

to estimate the energy of neutrino.)

## 9. Deep Inelastic scattering $\nu + N \rightarrow I + hadrons$ Dominant interaction in the high energy region (> several GeV )



Parton distribution functions (F2 and xF3) are extracted from the accelerator experiments. However, major parton distribution functions can not be used not applicable in the small W or q2 region. (If we use the PDF as-is, excess was observed in the small q<sup>2</sup> region.)

Use experimental results of neutrino scattering in that region.
 Apply corrections to the parton distribution functions.

9. Deep Inelastic scattering  $\nu + N \rightarrow I + hadrons$ Avoid double counting : the resonance region to the DIS region W < 2GeV : Restrict # of mesons to be larger than 1 Exclude 1 meson production by using multiplicity function <n>(W)Because non-resonant background is already included in the single  $\pi$  production. Multiplicity is determined based on the experimental result. Current version: S. J. Barish et al. Phys. Rev D.17,1 (1978) (There are recent reports from CHORUS collaboration. Eur.Phys.J.C51:775-785,2007)  $\langle n_{\pi} \rangle = 0.09 + 1.83 \ln(W^2)$ W > 2GeV : Use PYTHIA to generate vectors. W < 2GeV W > 2GeV# of  $\pi = 1$ Rein & Sehgal PDF + Custom kinematics (Bodek & Vang Corr.)

# of π > 1	Use PDF + PYTHIA	Use PDF + PYTHIA
	(Bodek & Yang Corr.)	(Bodek & Yang Corr.)

As for the parton distribution function,

we use the correction suggsted by Bodek and Yang.

## 9. Deep Inelastic scattering

1. Modified scaling variable

$$\xi_w = x \frac{Q^2 + B}{0.5Q^2(1 + [1 + (2Mx)^2/Q^2]^{1/2}) + Ax}$$

2. Correction factor for the PDF ( K-factor ) to describe low  $q^2$ 

$$\begin{split} K_{valence} &= \frac{[1-G_D^2(Q^2)][Q^2+C_{2v}]}{Q^2+C_{1v}} \\ & 1-G_D^2(Q^2) = \frac{Q^2}{Q^2+C} & \text{A=0.419} \\ K_{sea} &= \frac{Q^2}{Q^2+C_{sea}} & \text{C}_{1v} = 0.544 \\ C_{2v} = 0.431 \end{split}$$

3. Correction to Callan-Gross relation

$$2xF_1 = F_2 \frac{1 + 4Mx^2/Q^2}{1+R}$$

R: Fitted function

 $C_{sea} = 0.380$ 

4. d/u ratio

$$u_v \to u'_v(d_v, u_v) \quad d_v \to d'_v(d_v, u_v)$$

9. Formation zone

In determining the location of the interaction, the simple Woods-Saxon density function is used. In order to pick up the location of the production point of hadrons, Formation Zone is taken into account. The idea of formation zone: Hadronization does not occur at the interaction point Distance from the neutrino interaction point to the production point of hadron is proportional to the momentum of hadron. Actual interaction position Generated position of hadron Formation Zone (L) is defined as follows:  $L = p / \mu^2$ p: Momentum of hadron Ammosov et al.  $\mu^2$ : fitted constant = 0.08  $\pm$  0.04 GeV<sup>2</sup>

## 9. Deep Inelastic scattering

(G. Mitsuka)



## 9. Deep Inelastic scattering

## Two examples of basic distributions (Atmospheric neutrino flux was used as input)





Recently, cross-section of **charged current** coherent pion production was found to be very small in ~<GeV region. M. Hasegawa et al.(K2K collaboration) ( hep-ex/0506008 )

## 10. Coherent pion productions

Low energy charged current coherent pion production seems to be small. (Results from the K2K and the SciBooNE experiments.)



12. Nuclear effects (Final state interactions of hadrons ) Large fraction of the  $\pi$  from single  $\pi$  production are coming from the decay of  $\Delta$ . Cross-section of those  $\pi$  is large. Interaction probability of  $\pi$  in nucleus

generated by the single  $\pi$  production is large.



Momentum of  $\pi$ from p  $\rightarrow e^+ \pi^0$ is ~460<MeV/c.

re-scattering of pion, kaon, eta, omega and nucleon in nucleus

Different models are used in each simulation program.

Implementation in NEUT

Cascade model is used.

Each particle is tracked in the nucleus until it escapes from the nucleus.

For low momentum pion ( < 500MeV/c , so-called ∆ region ) Mean free paths of absorption and inelastic-scattering are calculated based on a model by L.Salcedo et al. . (Nucl. Phys. A484(1998) 79)

\* These mean free paths are position and momentum dependent.\* The Fermi surface momentum also has radius dependence.

For the higher momentum pion ( > 500MeV/c), kaons, eta, omega and nucleons Parameters are taken from various experiments. 11. Nuclear effects (Final state interactions of hadrons) Low momentum pion ( < 500MeV/c , so-called ∆ region ) (L.L.Salcedo et al. Nucl. Phys. A484(1998) 79)

Calculate interaction probability using  $\Delta h$  model and  $\pi \& \Delta$  self-energy.

**Pion scattering**  $\pi + N \rightarrow \Delta \rightarrow \pi + N$ (2 body)Pion absorption  $\pi + N + N \rightarrow \Delta + N \rightarrow N + N$  (2 body) (3 body)π  $\pi + N + N \rightarrow \Delta + N \rightarrow N + \Delta \rightarrow N + N$  (3 body)

(Note: There are several other diagrams. See reference.)

# 11. Nuclear effects (Final state interactions of hadrons) $\pi^+ p \rightarrow \pi^+ p$ Interaction probability $P(\pi^+ p \rightarrow \pi^+ p) = \frac{1}{\omega} 2 \int \frac{d^3 k}{(2\pi)^3} n(\mathbf{k}) \frac{2}{3} \left(\frac{f^*}{m_-}\right)^2 \mathbf{q}^2_{c.m.} |G_{\Delta}(q+k)|^2 \frac{1}{2} \widetilde{\Gamma}(q+k)$

 $\Delta$  propagater

Corrected width of  $\Delta \qquad \frac{1}{2}\widetilde{\Gamma}(q+k) =$ 

Use local density to determine  $k_F$ when considering Pauli blocking effect.

$$\int \frac{1}{3} \left( \frac{s}{m_{\pi}} \right) \mathbf{q}^{2} c.m. |G_{\Delta}(q+k)|^{2} \frac{1}{2} \Gamma(q+k)$$

$$G_{\Delta} = \left( \sqrt{S} - M_{\Delta} + \frac{1}{2} i \Gamma \right)^{-1}$$

$$\frac{1}{2} \widetilde{\Gamma}(q+k) = \frac{1}{2} \Gamma \times \frac{1}{4} (\overline{\mu}^{3} c.m. + \overline{\mu}_{c.m.} + 2)$$

$$\overline{\mu}_{c.m}^{2} = \begin{cases} -1 \quad (\text{ if } \mu^{0} < -1) \\ \mu^{0} \quad (\text{ if } -1 \le \mu^{0} \le 1) \\ 1 \quad (\text{ if } \mu^{0} > 1) \end{cases}$$
effect.
$$\mu^{0} = \frac{E_{\Delta} E^{N} c.m. - E_{F} W}{|\mathbf{q} + \mathbf{k}|| \mathbf{q}_{c.m.}|}$$

$$E_{\Delta} = q^{0} + k^{0}$$

$$E_{c.m.} = \sqrt{q^{2} c.m. + M^{2}}$$

$$W = \sqrt{s}$$

11. Nuclear effects (Final state interactions of hadrons) Absorption probability

$$P = \frac{1}{\omega} \frac{4}{9} \left( \frac{f^*}{m_{\pi}} \right)^2 \mathbf{q}^2 c_{.m.} \left| \widetilde{G}_{\Delta} (\overline{q+k}) \right|^2 \left( \frac{1}{2} \widetilde{\Gamma} - \operatorname{Im} \Sigma_{\Delta} \right) \rho$$
$$\operatorname{Im} \Sigma_{\Delta} (\omega) = -\left[ C_Q (\rho / \rho_0)^{\alpha} + C_{A2} (\rho / \rho_0)^{\beta} + C_{A3} (\rho / \rho_0)^{\gamma} \right]$$

$$C(T_{\pi}) = ax^2 + bx + c \qquad x = T_{\pi} / \mu$$

E.Oset et al. Nucl. Phys. A468 (1987) 631

	C <sub>Q</sub> (MeV)	C <sub>A2</sub> (MeV)	C <sub>A3</sub> (MeV)	α	β
а	-5.19	1.06	-13.46	0.382	-0.038
b	15.35	-6.64	46.17	-1.322	0.204
C	2.06	22.66	-20.34	1.466	0.613

γ**=2**β

Interaction probability (mean free path) depends on the  $\pi$  momentum and location (radius ~ density).



Fermi surface momentum depends on the local density.

Smaller q<sup>2</sup> interaction is allowed at the peripheral region

Kinematics of the scattered particles

Use the results of phase shift analysis of  $\pi$ -N scattering

Also, the medium correction is applied to each phase shift. (R.Seki et al., Phys. Rev. C27 (1983) 2817)

$$f = \sum_{T} C_{T} \sum_{l} \{ [lf_{2T,2l-1}^{l} + (l+1)f_{2T,2l+1}^{l}] \\ \times P_{l}(\cos \theta) - i\sigma \cdot n[f_{2T,2l-1}^{l} - f_{2T,2l+1}^{l}] \\ \times P_{l}^{\prime}(\cos \theta) \}.$$

Here,  $f'_{2T, 2J}$  is an amplitude with orbital angular momentum *l*, isospin *T*, and total angular momentum *J*.  $C_T$  is the isospin factor written with Clebsch-Gordan coefficients,

$$C_{T} = \left(1t_{\pi'} \frac{1}{2} t_{N'} | Tt_{\pi} + t_{N}\right) \left(1t_{\pi} \frac{1}{2} t_{N} | Tt_{\pi} + t_{N}\right),$$

( $t_N$ ,  $t_\pi$ ,  $t_{N'}$ ,  $t_{\pi'}$  are initial and final Z component of  $\pi$ , N isospin.)

 $\sigma$  is the Pauli matrix and  $n=(k \times k')/(|k \times k'|)$ , with k, k' being pion initial and final momenta. We consider 8 resonances,  $S_{11}$ ,  $S_{31}$ ,  $P_{11}$ ,  $P_{13}$ ,  $P_{31}$ ,  $P_{33}$ ,  $D_{13}$ ,  $D_{15}$  for this amplitude. The resonance parameters are taken from the phase shift analyses of  $\pi - N$  scattering.<sup>25)</sup> Pion interaction in oxygen is

$$f_{2T,2J}(^{16}\text{O}) = f_{2T,2J} \times \left\{ 1 - \frac{2f_{2T,2J}^l}{\pi} \times C \times \int k^2 \, \mathrm{d}k Q_0(k,K) G_0(k,E) \right\}^{-1}.$$

$$C = 1 + (k^{2} + m_{\pi}^{2})^{1/2} / (k^{2} + m_{N}^{2})^{1/2},$$

$$Q_{0}(k, K) = \begin{cases} 1 & \text{if } \xi K + k < P_{F}, \\ 0 & \text{if } |\xi K - k| > P_{F}, \\ [P_{F}^{2} - (\xi K - k)] / 4\xi K k & \text{otherwise}, \end{cases}$$

$$G_{0}^{-1}(k, E) = \left(E - \frac{k^{2}}{2M}\right)^{2} - k^{2} - m_{\pi}^{2} + i\varepsilon,$$

$$\xi = 1 / \left(1 + \frac{W}{m_{N}}\right),$$

Higher momentum (  $p_{\pi} \ge 500 \text{MeV/c}$  ),

 $\pi$  - N interaction cross-section is used.



 $\pi^{+} p$  1.94 + 0.28 \* log (s) + 0.130 \* (log (s))<sup>2</sup>

 $\pi^{-} p = 0.59 + 0.81 * \log (s) + 0.074 * (\log (s))^{2}$ 

Actual multiplicity is calculated from

s : Total energy

J.Whitmore Phys. Rep. 27C (1976) 187.





# 11. Nuclear effects ( Final state interactions of hadrons ) Interactions of $\eta$

 $\eta + N \rightarrow N^* \rightarrow N + X \qquad X : \eta, \pi, \pi\pi$ 

Interaction cross-section : Use Breit - Wigner formula

$$\sigma(k) = \frac{\pi}{k^2} \cdot \frac{\Gamma_{\eta N} \Gamma_X}{\left(W - M_N\right)^2 + \Gamma_{tot}^2 / 4}$$

 $\Gamma_{\text{tot}}$  : Total width of  $\mathbf{N^{*}}$ 

 $\Gamma_{\eta \mathsf{N}}$  : Partial decay width of  $\mathsf{N}^{\star} \rightarrow \eta + \mathsf{N}$ 

 $\Gamma_{\eta X}$  : Partial decay width of  $N^* \rightarrow X$ 

As the intermediate resonance  $(N^*)$ , N(1535) and N(1650) are considered.

The direction of the scattered  $\eta$  is isotropic in the resonance rest frame.

 $\omega$  is also simulated in the same manner as  $\eta$ .

## 11. Nuclear effects (Final state interactions of hadrons) Nucleon re-scattering

Originally prepared by the members of IMB group. (W. Gajewski for K2K)

Nucleon re-scattering is also simulated by using the cascade model.

Elastic scattering, single  $\pi$  and two  $\pi$  productions are considered.

(Original ref. S.J.Lindenbaum and R.M.Sternheimer, Phys.Rev. 105 (1957), Modifications in MECC7 and GCALOR have been taken into account.)

 $N + N \rightarrow N + N$   $N + N \rightarrow N^* + N \rightarrow N^* \rightarrow N' + \pi$   $N + N \rightarrow N^* + N^* \rightarrow N' + \pi$ 

Interaction probabilities ( tables of each interaction mean free path ) and direction of nucleons or intermediate resonances are taken from MECC7 and GCALOR.

(Basic parameters are taken from various experiments.)

Decay of the intermediate resonances

Isotropic in the resonance rest frame.

Nucleon re-scattering

Some distributions (results of the simulation)

Target : <sup>16</sup>O

Momentum dependence of the interaction probabilities of proton

Scattering angle of the outgoing nucleon ( most energetic one ) Incident momentum of proton 0.5 ~ 1.0 GeV / c ( uniform )



## 12. Remaining Issues

## Nucleon emission after pion absorption

From the experience of SciBooNE, we realized that the nucleon emission after the pion absorption seems to be visible with the full active detectors.

## Need to incorporate various recent precise models.

From dipole form factors to more precise ones.

Use spectrum functions instead of the simplest Fermi gas mode.

More proper treatment of resonances in meduim.

Nuclear medium correction

in the meson production via resonance.

Another resonance production models.

Improved treatments of the higher momentum pion in nuclear medium.

#### Fin.

## Sample program of NEUT

## neut\_ntpl [ CARD FILE ] [ output NTUPLE file ]

The card file controls the energy distribution, direction, target etc..

In the following pages, there are some information how to control the program.

## NEUT card file

C Number of events : EVCT-NEVT EVCT-NEVT 1000 C-----C Particle Code : EVCT-IDPT EVCT-IDPT 14 C-----C fixed VERTEX ; EVCT-MPOS 1 C random VERTEX ; EVCT-MPOS 2 С C EVCT-MPOS 1 C VECT-POS 100.0.0. С EVCT-MPOS 2 EVCT-RAD 100. C-----C fixed DIRECTION ; EVCT-MDIR 1 C random DIRECTION ; EVCT-MDIR 2 С EVCT-MDIR 1 EVCT-DIR 0. 0. 1. C-----C fixed MOMEMTUM ; EVCT-MPV 1 C random MOMEMTUM ; EVCT-MPV 2 С C EVCT-MPV 1 C EVCT-PV 1000.

EVCT-MPV 2

EVCT-PV 0. 10000.

C \*\*\*\* TARGET INFORMATION \*\*\*\* С C NUMBNDN : total number of neutron (e.g. CH => 6, H2O => 8, Ar => 22, Fe => 30) С **NEUT-NUMBNDN 8** С C NUMBNDP : total number of bound proton (e.g. CH => 6, H2O => 8, Ar => 18, Fe => 26) С С **NEUT-NUMBNDP 8** С C NUMFREP : total number of free proton (e.g. CH => 1, H2O => 2, Ar => 0, Fe => 0) С С **NEUT-NUMFREP 2** С C NUMATOM : atomic number of atom heavier than hydrogen (e.q. CH => 12, H2O =>16, Ar => 40, Fe => 56) С С **NEUT-NUMATOM 16** С NEUT-PFSURF 0.225 NEUT-PFMAX 0.225 С

# NEUT card file

```
C **** NEUTRINO INTERACTION ****
С
C FERM : Fermi motion 0 : on ( default ) 1 : off
С
NEUT-FERM 0
С
C PAUL : Pauli blocking 0 : on (default) 1 : off
С
NEUT-PAUL 0
С
C NEFF : Nuclear effect in O16 0 : on (default) 1 : off
С
NEUT-NEFF 0
С
C IFORMLEN : Formation zone 1: on (default) 0: off
С
NEUT-IFORMLEN 1
С
C Nucleon rescattering
С
C NUCRES-RESCAT 1: on (default) 0: off
С
NUCRES-RESCAT 1
С
C NUCRES-XNUCFACT
  cross-section factor to study uncertainty default = 1.
С
NUCRES-FACT 1.
```

```
С
C PDF for DIS is set in this section
C (GRV94DI -> 7, GRV98 LO -> 12)
NEUT-PDF
            12
C PDF Correction is used?
          (original=0, modified=1)
NEUT-BODEK 1
C Select Coherent pion model
          Rein & Sehgal
                               =0(default)
С
          Kartavtsev et al.
С
                               =1
NEUT-COHEPI 0
С
```

```
C RAND : random seed
```

C 0 : Read RANDOM number from FILE

```
C 1 : Generating RANDOM SEED from the time
C
```

```
NEUT-RAND 1
```

## NEUT card file

C MODE : Interaction mode С 0 : normal ( default ) С -1 : input cross section by NEUT-CRS / NEUT-CRSB С n : sellect one mode (n > 0) С **NEUT-MODE 0** С C CRS : Multiplied factor to cross section on each mode. (neu) C CSRB: Multiplied factor to cross section on each mode. (neu-bar) С С 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 С nub nu C 1 CC Q.E. C 2-4: CC 1pi C 5: CC DIS 1320 C 6-9: NC 1pi C 10: NC DIS 1320 C 11-13 NC els 11-14:NC els C 14,15: coherent 15,16: C 16: CC eta 17: C 17,18: NC eta 18,19 C 19: CC K 20: C 20,21: NC K 21,22: C 22: dummy C 23: CC DIS C 24: NC DIS

## Interaction modes used in NEUT

- -- ELASTIC --1 : NEU,N --> LEPTON-,P
- -- SINGLE PI FROM DELTA RESONANCE --11 : NEU,P --> LEPTON-,P,PI+ 12 : NEU,N --> LEPTON-,P,PI0 13 : NEU,N --> LEPTON-,N,PI+
- 16 : NEU,O(16) --> LEPTON-,O(16),PI+
- -- SINGLE GAMMA FROM DELTA RESONANCE --17 : NEU,N --> LEPTON-,P,GAMMA

-- MULTI PI (1.3 < W < 2.0 GeV) --21 : NEU,(N OR P) --> LEPTON-,(N OR P),MULTI PI

- -- SINGLE ETA FROM DELTA RESONANCE --(added 97/12/01 J.Kameda) 22 : NEU,N --> LEPTON-,P,ETA0
- -- SINGLE K FROM DELTA RESONANCE --(added 98/02/25 J.Kameda) 23 : NEU,N --> LEPTON-,LAMBDA,K+

-- DEEP INELASTIC (2.0 GeV < W , JET set) --26 : NEU,(N OR P) --> LEPTON-,(N OR P),MESONS \*\*\*\*\* NEUTAL CURRENT \*\*\*\*\*

-- SINGLE PI FROM DELTA RESONANCE --

- 31 : NEU,N --> NEU,N,PI0
- 32 : NEU,P --> NEU,P,PI0
- 33 : NEU,N --> NEU,P,PI-
- 34 : NEU,P --> NEU,N,PI+
- 36 : NEU,O(16) --> NEU,O(16),PI0
- -- SINGLE GAMMA FROM DELTA RESONANCE --38 : NEU,N --> NEU,N,GAMMA 39 : NEU,P --> NEU,P,GAMMA

-- MULTI PI (1.3 GeV < W < 2.0 GeV) --41 : NEU,(N OR P) --> NEU,(N OR P),MULTI PI

- -- SINGLE ETA FROM DELTA RESONANCE --(added 97/12/01 J.Kameda)
- 42 : NEU,N --> NEU,N,ETA0
- 43 : NEU,P --> NEU,P,ETA0
- 52 : NEU,N --> NEU,N
  - -- SINGLE K FROM DELTA RESONANCE --(added 98/02/20 J.Kameda)
- 44 : NEU,N --> NEU,LAMBDA,K0
- 45 : NEU,P --> NEU,LAMBDA,K+
- -- DEEP INELASTIC (2.0 GeV < W , JET set) --46 : NEU,(N OR P) --> NEU,(N OR P),MESONS

-- ELASTIC --51 : NEU,P --> NEU,P

## Interaction modes used in NEUT

\*\*\*\*\* CHARGED CURRENT \*\*\*\*\*

-- ELASTIC --

-1 : NEUBAR,P --> LEPTON+,N

-- SINGLE PI FROM DELTA RESONANCE ---11 : NEUBAR,N --> LEPTON+,N,PI--12 : NEUBAR,P --> LEPTON+,N,PI0 -13 : NEUBAR,P --> LEPTON+,P,PI-

-16 : NEUBAR,O(16) --> LEPTON+,O(16),PI-

-- SINGLE GAMMA FROM DELTA RESONANCE ---17 : NEUBAR,P --> LEPTON+,N,GAMMA

-- MULTI PI (W > 1.4 GEV) --

-21 : NEUBAR, (N OR P) --> LÉPTON+, (N OR P), MULTI PI

-- SINGLE ETA FROM DELTA RESONANCE --(added 97/12/01 J.Kameda) -22 : NEUBAR,P --> LEPTON+,N,ETA0

-- SINGLE K FROM DELTA RESONANCE --(added 98/02/25 J.Kameda) -23 : NEUBAR,P --> LEPTON+,LAMBDA,K0

-- DEEP INELASTIC (2.0 GeV < W , JET set) ---26 : NEUBAR,(N OR P) --> LEPTON+,(N OR P),MESONS \*\* NEUTAL CURRENT \*\*

-- SINGLE PI FROM DELTA RESONANCE --

- -31 : NEUBAR,N --> NEUBAR,N,PI0
- -32 : NEUBAR,P --> NEUBAR,P,PI0
- -33 : NEUBAR, N --> NEUBAR, P, PI-
- -34 : NEUBAR,P --> NEUBAR,N,PI+

-36 : NEUBAR,O(16) --> NEUBAR,O(16),PI0

-- SINGLE GAMMA FROM DELTA RESONANCE --

-38 : NEUBAR, N --> NEUBAR, N, GAMMA

-39 : NEUBAR,P --> NEUBAR,P,GAMMA

-- MULTI PI (W > 1.4 GEV) ---41 : NEUBAR,(N OR P) --> NEUBAR,(N OR P),MULTI PI

-- SINGLE ETA FROM DELTA RESONANCE --(added 97/12/01 J.Kameda) -42 : NEUBAR,N --> NEUBAR,N,ETA0 -43 : NEUBAR,P --> NEUBAR,P,ETA0

-- SINGLE K FROM DELTA RESONANCE --(added 98/02/20 J.Kameda) -44 : NEUBAR,N --> NEUBAR,LAMBDA,K0 -45 : NEUBAR,P --> NEUBAR,LAMBDA,K+

-- DEEP INELASTIC (2.0 GeV < W , JET set) ---46 : NEUBAR,(N OR P) --> NEUBAR,(N OR P),MESONS

-- ELASTIC ---51 : NEUBAR,P --> NEUBAR,P -52 : NEUBAR,N --> NEUBAR,N

## Meanings of the variables in ntuple

MODE NUMNU IPNU ABSPNU PNU	: Interaction mode : Number of particles ( includir : Particle Code : Absolute momentum of partic : Momentum of particle ( GeV	ng initial neut cle ( GeV / c / c )	rino and nucleon) )	
NPAR IPV IORGV	: Number of particles (after the : Particle code : Parent particle	final state ir	iteractions)	
ICRNV	: Tracking flag ( set to 0 if the particle was interacted,			
	absorbed or disappeared)			
IFLGV		e alleady int	this flag is set	
	0		Not interacted vet	
	1		Decayed to the other particles	
	2		N/A	
	-3		Absorbed	
	4	:	Charge exchanged	
	5	:	Stopped	
	6	:	N/A	
	7	:	Particle production	
	8	:	Scattered	
ABSPV	: Absolute momentum of particl	e		
PMOMV	: Momentum of particle			

## Water Chernkov detector

High efficiency in detecting electrons

low momentum neutral pi0

Relatively low threshold in detecting muon and charged pion

#### Cherenkov Analysis threshold radiation electron 0.57 (MeV/c) 100 (MeV/c) 118 (MeV/c) 200 (MeV/c) muon (GeV/c)1 proton

Momentum threshold

Precise particle type identification

showering (e-like) electron, gamma non-showering (mu-like) muon, charged pions, etc.

# **PID** performance

Detection threshold is high for the massive particles like proton

Charge Identification is not possible

Table 1. Proton and neutron Fermi momenta and binding energies (in MeV) for selected nuclei.

Nucleus	$p_F^p$	$\epsilon^p_b$	$p_F^n$	$\epsilon_b^n$
$^{12}_{6}\mathrm{C}$	221	25.6	221	25.6
$^{14}_{7}{ m N}$	223	26.2	223	26.1
$^{16}_{8}{ m O}$	225	26.6	225	26.6
$^{19}_{9}{ m F}$	233	28.4	233	28.3
$^{20}_{10}{ m Ne}$	230	27.8	230	27.8
$^{27}_{13}{ m Al}$	239	29.5	239	29.4
$^{40}_{18}\mathrm{Ar}$	242	30.7	259	35.0
$^{56}_{26}\mathrm{Fe}$	251	33.0	263	36.1
$^{80}_{35}\mathrm{Br}$	245	31.5	270	38.1





# 6. Deep Inelastic scattering $\nu + N \rightarrow I + hadrons$

Corrections proposed by Bodek and Yang

1. Bjorken scaling  $x \rightarrow x_w$ 

$$x_w = x \frac{Q^2 + B}{Q^2 + Ax}$$

A : target mass effect higher twist effect B : photoproduction limit(Q<sup>2</sup>=0)

2. Correction to the structure function  $F_2$ 

$$F_2(x) \to \frac{Q^2}{Q^2 + C} F_2(x_w)$$

to fit both intermediate-x and low-x

(hep-ex/0203009, hep-ex/0308007)

3. d/u ratio

$$d_{v} \rightarrow d'_{v}(d_{v},u_{v})$$
$$u_{v} \rightarrow u'_{v}(d_{v},u_{v})$$

Correction to the conversion from  $F_2^d$  to  $F_2^n$ 

4. Longitudinal R

$$2xF_1 = F_2 \frac{1 + 4Mx^2/Q^2}{1 + R}$$

Corrections for the spin of the target.

These correction parameters are obtained by fitting various existing experimental results.

# 4. Single meson production via resonances (G.Mitsuka) Simulation result -Integrated cross section-

Berger and Sehgal add the pion-pole term in the hadronic current. This effect is the almost same as in the coherent- $\pi$  production hep-ph/0709.4378



An amount of reduction depends on lepton flavor and energy These values are consistent with the description in references

# 4. Single meson production via resonances (G.Mitsuka) Simulation result -Kinematics-



Lepton momentum has no significant change Lepton scattering angle has suppression in forward direction Pion and nucleon kinematics are not changed

$$\frac{\sigma(\nu N \to \nu X)}{\sigma(\nu N \to \mu^{-} X)} = \begin{cases}
0.26 & (E_{\nu} < 3 \,\text{GeV}) \\
0.26 + 0.04 (E_{\nu}/3 - 1) & (3 \,\text{GeV} \le E_{\nu} < 6 \,\text{GeV}) \\
0.30 & (E_{\nu} \ge 6 \,\text{GeV})
\end{cases}$$

$$\frac{\sigma(\bar{\nu}N \to \bar{\nu}X)}{\sigma(\bar{\nu}N \to \mu^{+}X)} = \begin{cases}
0.39 & (E_{\nu} < 3 \,\text{GeV}) \\
0.39 - 0.02 (E_{\nu}/3 - 1) & (3 \,\text{GeV} \le E_{\nu} < 6 \,\text{GeV}) \\
0.37 & (E_{\nu} \ge 6 \,\text{GeV})
\end{cases}$$
(4.21)

The kinematics of the hadronic system is simulated by two different methods according to the range of invariant mass. In the region of  $1.3 \text{ GeV}/c^2 < W < 2.0 \text{ GeV}/c^2$ , only pions are considered as outgoing mesons. The mean multiplicity of pions is estimated from the result of Fermilab 15-foot hydrogen bubble chamber experiment [129]:

$$\langle n_{\pi} \rangle = 0.09 + 1.83 \ln(W^2)$$
 (4.23)

The number of pions in each event is determined by using KNO (Koba-Nielsen-Olsen) scaling. Since the range of W overlaps with that in single pion production,  $n_{\pi} \geq 2$  is required in this W region. The forward-backward asymmetry of pion multiplicity in the hadronic center of mass system is included using the results from BEBC experiment [130]:

$$\frac{n_{\pi}^{F}}{n_{\pi}^{B}} = \frac{0.35 + 0.41 \ln(W^{2})}{0.5 + 0.09 \ln(W^{2})}$$
(4.24)