Neutrino reaction in a few nucleon system

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- ✓ Neutrino reactions in supernova mechanism
  -- two nucleon system –

S. Nasu(Osaka U.), S. Nakamura(YITP Kyoto U.),K. Sumiyoshi(Numazu Col. Tech.),F. Myhrer(USC),K. Kubodera(USC),T.Sato(Osaka U.)

- ✓ Toward construction of unified model of lepton-nucleus interaction from a few hundred MeV to GeV region

Y. Hayato(ICRR, U. of Tokyo), M. Hirai(Tokyo Science U.),H. Kamano(RCNP,Osaka U.),S. Kumano(KEK),S. Nakamura(YITP,Kyoto U.),K. Saio(Tokyo Science U.),T. Sato(Osaka U.),M. Sakuda(Okayama U.)

Neutrino reactions in supernova mechanism

-- two nucleon system –

Neutrino-nucleus, nucleon reactions play central role to core collapse supernova phenomena

$$\nu_e + n \leftrightarrow e^- + p \qquad \nu + N \leftrightarrow \nu + N$$
$$\bar{\nu}_e + p \leftrightarrow e^+ + n$$

$$\nu_e + A \leftrightarrow e^- + A' \qquad \nu + A \leftrightarrow \nu + A$$
$$N + N \leftrightarrow \nu + \bar{\nu} + N + N$$

neutirno-brems

$$e^- + e^+ \leftrightarrow \nu + \bar{\nu} \qquad \nu_e + e \leftrightarrow \nu_e + e^-$$

S. W. Bruennm Astro. J. Suppl 58 (1985)771
A. Burrows,S. Reddy, T. Thompson, NPA777(2006),356.

Possible role of light cluster

Heating due to nuclear excitation from NC reactions

W.C. Haxton PRL60(1988)1999

Neutrino-4He may marginally affect supernova shock revival

N. Ohnishi,K.Kotake,S. Yamada Astrophys. J 667 (2007)375

Study of neutrino reaction rate on a few nucleon system

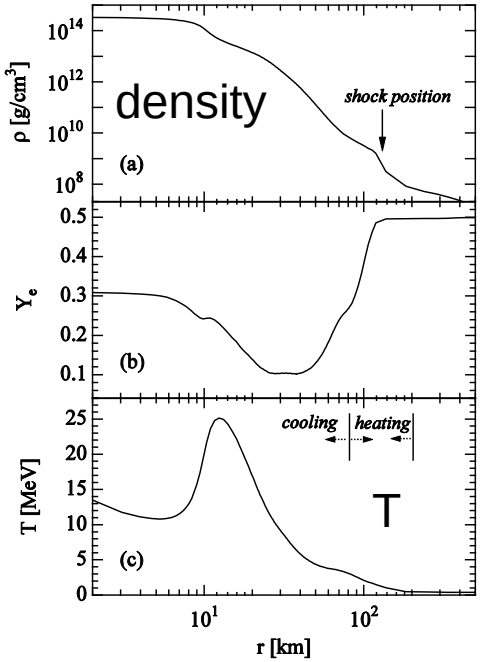
4He D. Gazit, N. Barnea PRL 98(2007)192591

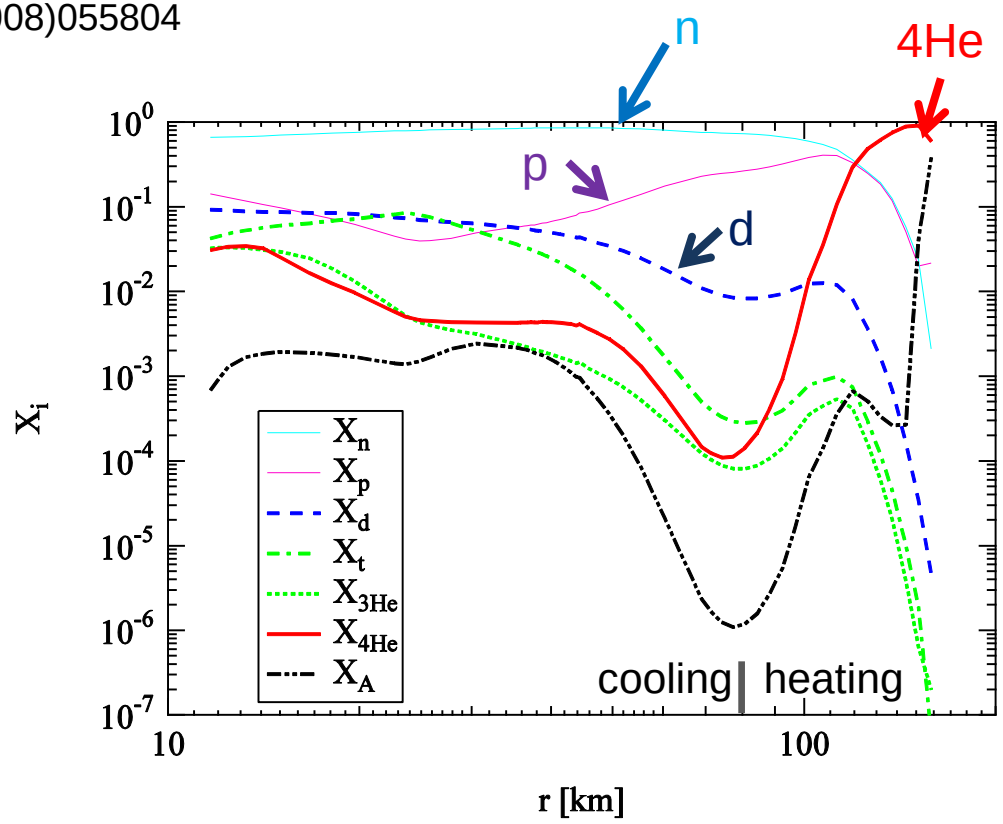
t,3He E. O'Connor, D. Gazit, C.J.Horowiz, A.Schwenk,N.Barnea PRC75(2007)055803

Possible role of the semi-leptonic reactions on few nucleon system

snap shot of supernova core, 150ms after core bounce

K. Sumiyoshi and G. Ropke PRC77 (2008)055804





mass fraction of light clusters

abundant appearance of d, triton, 3He, 4He

Also A. Arcones et al. PRC78(2008)015806

Objective:

- provide basic reaction rates of semileptonic process on two-nucleon for the supernova simulation
- examine role of semileptonic reactions of two-nucleon system

I Neutrino absorption (heating region)

S. Nakamura, K. Sumiyoshi, T. Sato (PRC80, 035802 2009)

$$\nu + d \rightarrow N + N + l$$

Energy transfer cross section $< \sigma\omega >$

II Neutrino production (cooling region)

S. Nasu, S. Nakamura, K. Sumiyoshi, F. Myhrer, K. Kubodera T. Sato(in preparation)

$$e + d \rightarrow N + N + \nu \qquad N + N \rightarrow d + e + \nu$$

Neutrino emissivity Q

Theoretical model of semi-leptonic reaction on two-nucleon

Standard nuclear physics approach developed for the analysis of SNO

S. Nakamura, T. Sato, V. Gudkov and K. Kubodera PRC63 (2001) 034617
S. Nakamura, et al., NPA707 (2002)561

- Nuclear current

  one-body impulse current up to (p/M) +
  meson exchange current(pi,rho,Delta) checked from triton beta decay

- Nuclear wave function

  from ANLV18, Bonn potential

- For low energy neutrino reaction, agreement with EFT within 1%

  M. Butler and J.-W. Chen NPA675(2000)575,PRC63(2001)035501
  S. Ando et al. PLB555 (2003)49

  For higher energy region , muon capture rate, photo reaction cross section are explained well.

I Neutrino Absorption on deuteron (heating)

CC

$$\nu_e + d \rightarrow e^- + p + p$$
$$\bar{\nu}_e + d \rightarrow e^+ + n + n$$

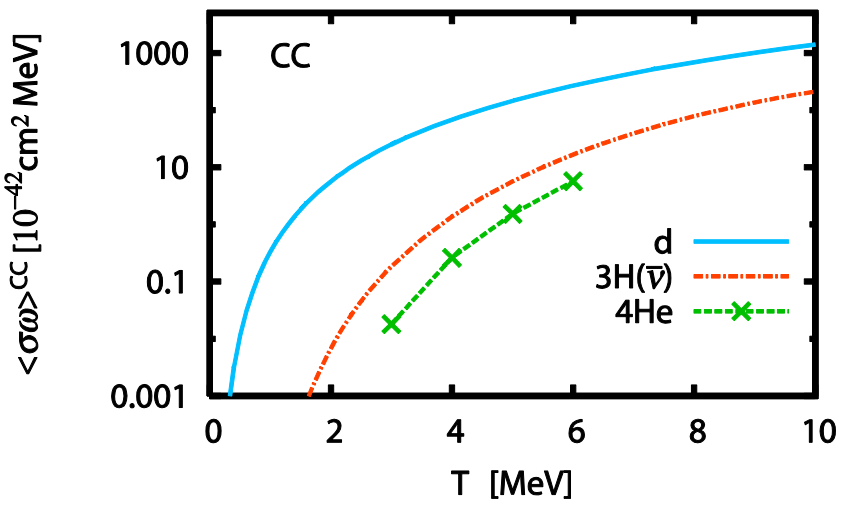
NC

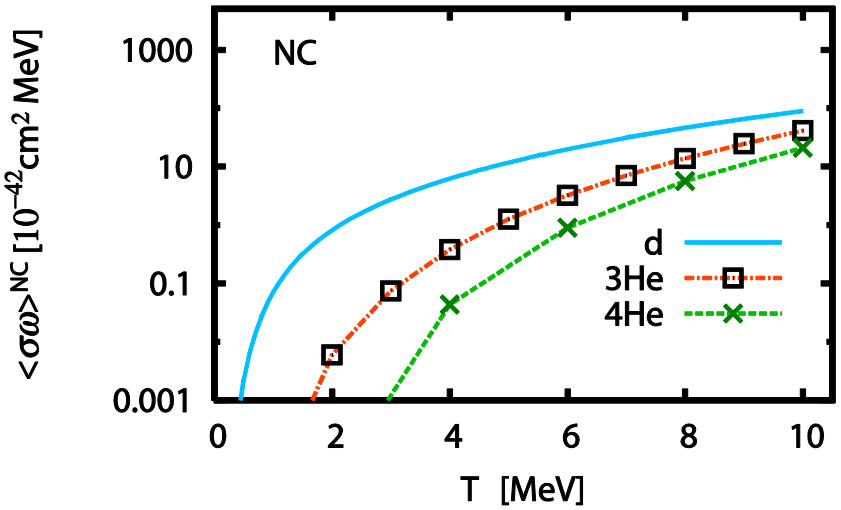
$$\nu(\bar{\nu}) + d \rightarrow \nu(\bar{\nu}) + p + n$$
$$\nu(\bar{\nu}) + d \rightarrow \nu(\bar{\nu}) + d$$

Average energy transfer cross section/ nucleon

$$< \sigma\omega >_{NC} = \frac{1}{A}[< \sigma\omega >_{\nu} + < \sigma\omega >_{\bar{\nu}}]$$

$$< \sigma\omega > = \int dE_\nu f(E_\nu)\sigma(E_\nu)\omega(E_\nu)$$





Average energy transfer cross section of nu-d is significantly larger than nu-A=3,4!

heating rate $\frac{dE}{dt} = (31.6 MeV/nucleon/s)\frac{1}{R_7^2} L_{52} \frac{5MeV}{T} \frac{A^{-1} < \sigma\omega >}{10^{-40} cm^2 MeV}$

deuteron 99.1 for $T_{\nu_e} = T_{\bar{\nu}_e} = 5MeV$

55.6 for $T_{\nu_\tau} = 10MeV$

nucleon 223 for $T_{\nu_e} = T_{\bar{\nu}_e} = 5MeV$ (Haxton)

$[MeV/nucleon/s]$

radius $R = 10^7 cm$, neutrino luminosity $10^{52} ergs/sec$

II Neutrino production (Emissivity)

NN -> d

$$p + p \rightarrow d + e^{+} + \nu_e$$
$$n + n \rightarrow d + e^{-} + \bar{\nu}_e$$
$$n + p \rightarrow d + \nu + \bar{\nu}$$

$\leftrightarrow$ $N + N \rightarrow N + N + l + \bar{l}$

electron capture

$$e^{-} + d \rightarrow \nu_e + n + n$$
$$e^{+} + d \rightarrow \bar{\nu}_e + p + p$$

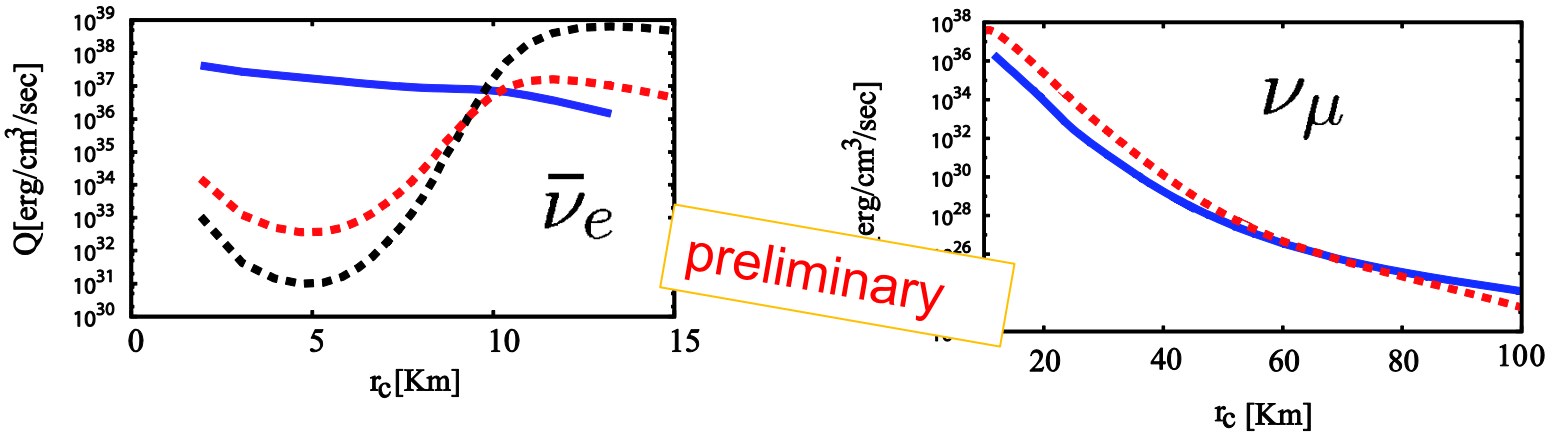
$e + N \rightarrow \nu + N$

emissivity Q

$$Q = \sum_{i,f} \prod_{i,f} \int \frac{d\vec{p}}{(2\pi)^3} f_i (1 - f_f) |M_{fi}|^2 E_\nu \delta^4 (P_f - P_i)$$

Analysis using ‘snap shot’ of supernova (by Sumiyoshi-Ropke)

- NN->d < electron capture on deuteron < electron capture on nucleon [CC]
- NN-> d ~ NN-> NN [NC]
- Inner region np->d [NC] can be very important



$n + p \rightarrow \bar{\nu} + \nu + d[NC]$

$N + N \rightarrow N + N + \nu + \bar{\nu}$

$e^+ + n \rightarrow \bar{\nu}_e + p$

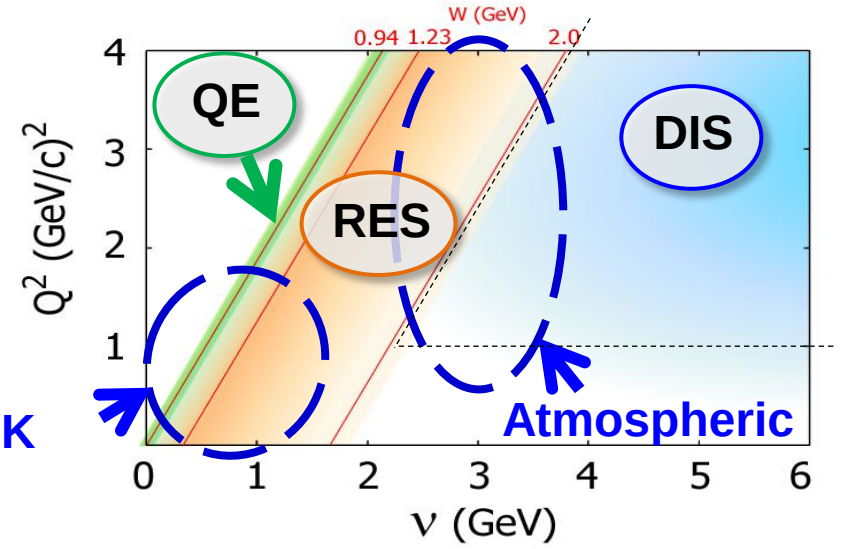
Toward construction of unified model of lepton-nucleus interaction from a few hundred MeV to GeV region

Y. Hayato(ICRR, U. of Tokyo), M. Hirai(Tokyo Science U.),H. Kamano(RCNP,Osaka U.),S. Kumano(KEK),S. Nakamura(YITP,Kyoto U.),K. Saio(Tokyo Science U.),T. Sato(Osaka U.),M. Sakuda(Okayama U.)

Lepton-nucleus interactions in the new era of large θ_{13}

Need for precise knowledge of lepton-nucleus interactions:

- **Less than 10% accuracy of the neutrino cross sections is required for the determination of precise value of θ_{13} and CP-phase δ.**
- **Neutrino experiments probe *overlapping region* among Quasi-elastic(QE), Resonance(RES), and Deep-inelastic scattering (DIS).**



T2K

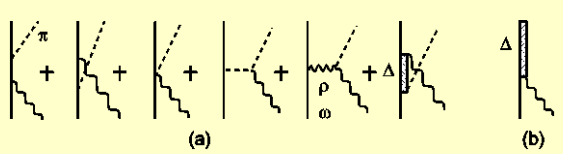
Combining our *baseline models*, we develop an improved model for the overlapping regions !!

➔ **A new collaboration at J-PARC branch of KEK theory Center**

http://j-parc-th.kek.jp/html/English/e-index.html

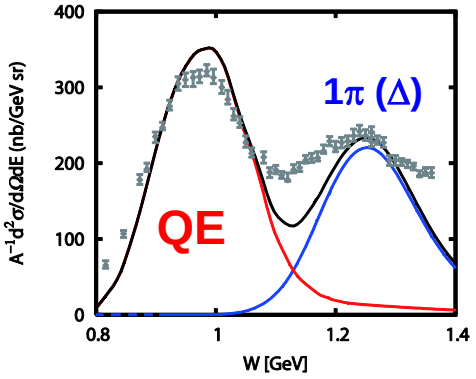
Base line of our model (resonance reaction)

Model of single pion production (Uno et al. 2003)

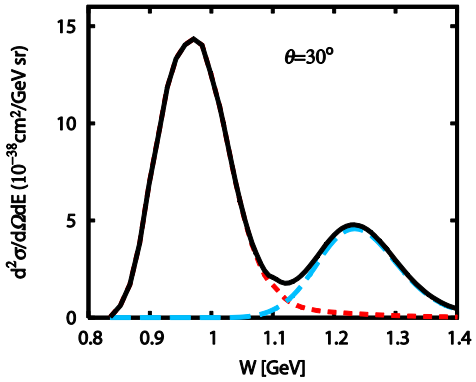


$$\left(+ \sum_{\text{Res}} \right) \times (1 + G\_0 \; T(\pi N))$$

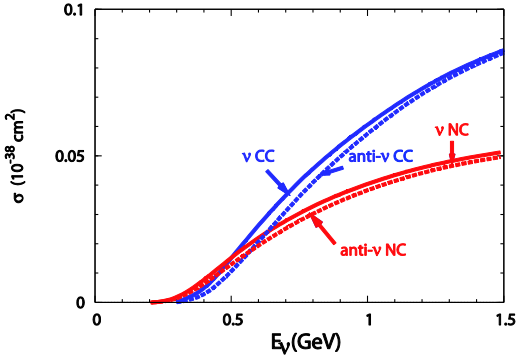
e-12C



nu-12C



Inclusive lepton-12C (Szczerbinska et al. 2007)

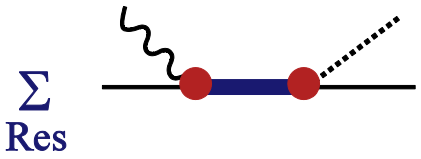


Coherent CC,NC pion production
(Nakamura et al. 2010)

spectral function: ground state correlation
Delta-hole model: pion rescattering, absorption

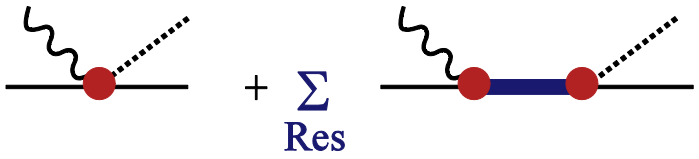
Weak one-pion production: brief summary of model

resonance



Rein Sehgal AP133(80)
Alvarez-Ruso et al. PRC57(98)
Lin et al. PRC52(95)
Paschos et al. PRD65(02)
Lalakulich et al. PRD71(05), PRD74(06)
Leitner et al. PRC79(09)

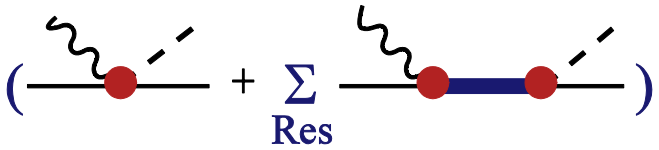
+ non-resonance



Hernandez et al. PRD76 (07),PRD81(10)
Lalakulich et al. arXiv 1007.0925

No model other than single pion production in N* region

+ rescattering



$$\times\ (1 + G\_0\ T(\pi N))$$

SL PRC67(03),PRC72(05)

N* resonance region toward DIS:

lepton induced meson production reaction on nucleon

* W<2GeV main meson production are pi,eta,K,omega and two-pion

* significant efforts on the understanding of electron,photon-nucleon reactions in nucleon resonance physics

- **Combined analysis of available single pion,eta, kaon production incorporating two pion final state with Coupled-Channels approach**
- **Extraction of resonance parameters(Mass, transition form factor) from the partial wave amplitudes**

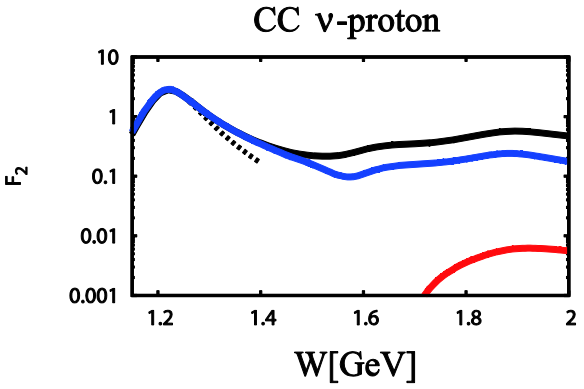
The model can be extended for neutrino reaction in N* region

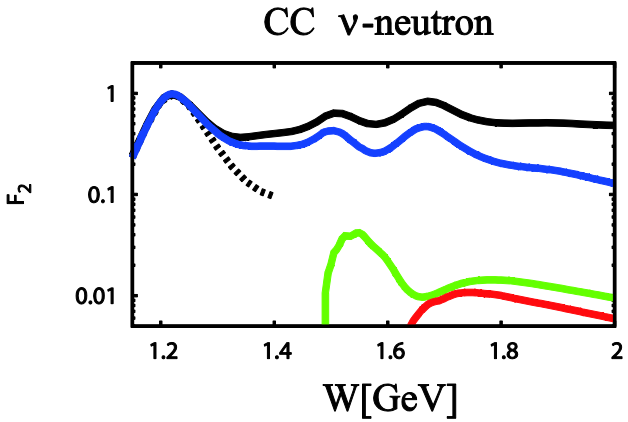
Forward neutrino induced meson production reaction in nucleon resonance region : the first application of coupled channel approach

Objective: * benchmark for the future full meson production model
* eta,kaon production rate for back ground estimation of proton decay analysis

Use PCAC for $Q^2 = 0, m_l = 0$

$$\frac{d\sigma_\nu}{dE'd\Omega} = \frac{G_F^2 V_{ud}^2}{2\pi^2} \frac{E'^2}{E - E'} F_2 \quad , \quad F_2 = \frac{2f_\pi^2}{\pi} \sigma(\text{virtual}\pi + N)$$





SL model (single pi via Delta)

Tot (including 2pi)
single pi
eta
K

Summary

- ✓ Neutrino production and absorption reactions in two-nucleon system have been studied in standard nuclear physics approach
- ✓ Neutrino reaction via deuteron has potential of significant effects in both heating and cooling mechanisms
- ✓ Neutrino reaction beyond delta resonance has been investigated by using coupled channel model of meson production reaction in the N*(W<2GeV) resonance region.
- ✓ Forward neutrino induced meson production cross sections in N* region were predicted using DCC approach for the first time.