Semi-leptonic weak processes in two-nucleon systems

Impact on neutrino oscillation experiments and astrophysics

Satoshi Nakamura (JLab)

Collaborators

Toru Sato	(Osaka Univ.)	νd, supernova
Kuniharu Kubodera	(U. South Carolina)	νd
Vladimir Gudkov	(U. South Carolina)	νd
Kohsuke Sumiyoshi	(Numazu Coll. Tech.)	supernova

Introduction

Electroweak processes in few-nucleon systems

$\Rightarrow$ well-established calculational method

$$\langle \psi_f | H_{\rm ew} | \psi_i \rangle$$

$|\psi\rangle$: solution of Schröding eq. with high-precision NN (+ NNN) potential

$H_{\rm ew}$: impulse + meson exchange currents

review : Carlson and Schiavilla, Rev. Mod. Phys. 70, 743841 (1998)

cf. chiral effective field theory

Contribution to neighborhood (neutrino physics, astrophysics)

* Experiment at Sudbury Neutrino Observatory (SNO) (part 1)

  $\nu_e + d \rightarrow e^- + p + p$ (νd reaction)

* Supernova simulation (part 2)

  νd reaction

  $p + p \rightarrow d + e^+ + \nu_e$ (pp-fusion)

  $N + N \rightarrow N + N + \nu + \bar{\nu}$ (NN-bremsstrahlung)

* Solar model

  pp-fusion

Part 1

SNO experiment (neutrino oscillation, solar neutrino problem)

heavy water Cherenkov light detector :

$$\begin{aligned} \nu_e + d &\rightarrow e^- + p + p \qquad \text{(CC)} \\ \nu_x + d &\rightarrow \nu_x + p + n \qquad \text{(NC)} \end{aligned}$$

$$x = e, \mu, \tau$$

Solar neutrino fluxes of ν_e and $\sum_x \nu_x$ are separately measured.

Theoretical prediction for νd reaction is prerequisite !

Previous work

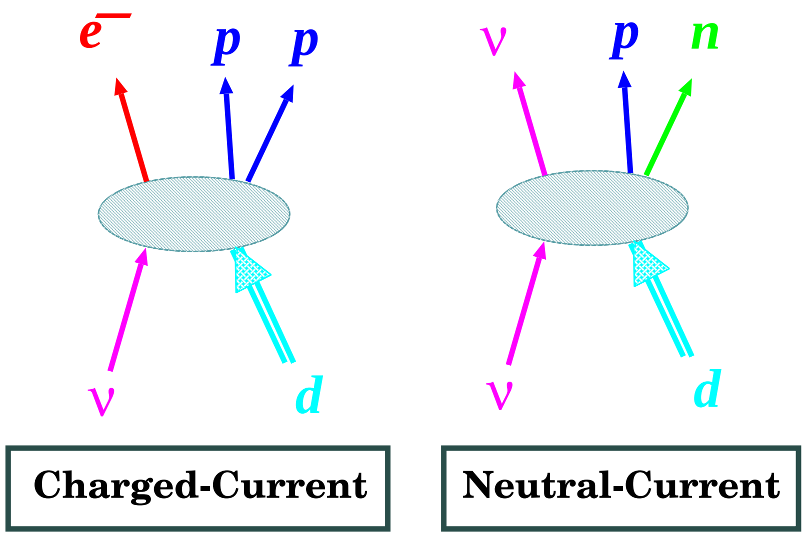
			Uncertainty	
•	Ying *et al.*	(IA)	$\sim 10\%$	(muon capture exp.)
•	Kubodera *et al.*	(IA+EXC)	a few%	

What we do SN et al., PRC **63**, 034617 (2000); NPA **707**, 561 (2002)

- Confirm the previous work
- Recent high-precision NN potential (AV18, CD-Bonn, Nijmegen)
- Exchange axial-vector current tested by tritium β-decay rate

  $\longrightarrow$ significant reduction of theoretical uncertainty ($\sim 1\%$)
- Differential cross section

Interaction Hamiltonian



$$H_W^{CC} = \frac{G'_F V_{ud}}{\sqrt{2}} \int d\boldsymbol{x} [J_\lambda^{CC}(\boldsymbol{x}) L^\lambda(\boldsymbol{x}) + \text{h. c.}] \qquad \text{for CC}$$

$$H_W^{NC} = \frac{G'_F}{\sqrt{2}} \int d\boldsymbol{x} [J_\lambda^{NC}(\boldsymbol{x}) L^\lambda(\boldsymbol{x}) + \text{h. c.}] \qquad \text{for NC}$$

$$L^\lambda(\boldsymbol{x}) = \bar{\psi}_l(\boldsymbol{x})\, \gamma^\lambda\, (1 - \gamma^5)\, \psi_\nu(\boldsymbol{x})$$

Nuclear Current

$$J_\lambda^{CC}(\boldsymbol{x}) = V_\lambda^{\pm}(\boldsymbol{x}) + A_\lambda^{\pm}(\boldsymbol{x})$$

$$J_\lambda^{NC}(\boldsymbol{x}) = V_\lambda^3 - 2\sin^2\theta_W(V_\lambda^3 + V_\lambda^s) + A_\lambda^3$$

$V(A)$: Vector (Axial) current

V^s : Isoscalar vector current

θ_W : Weinberg Angle $\sin^2\theta_W = 0.23$

J_λ = (one-body current) + (two-body exchange current)

Impulse Approximation (IA) Current

$$< p' \,|V_\lambda(0)|\, p > \quad = \quad \bar{u}(p') \left[f_V \gamma_\lambda + i \frac{f_M}{2M_N} \sigma_{\lambda\rho} q^\rho \right] u(p)$$

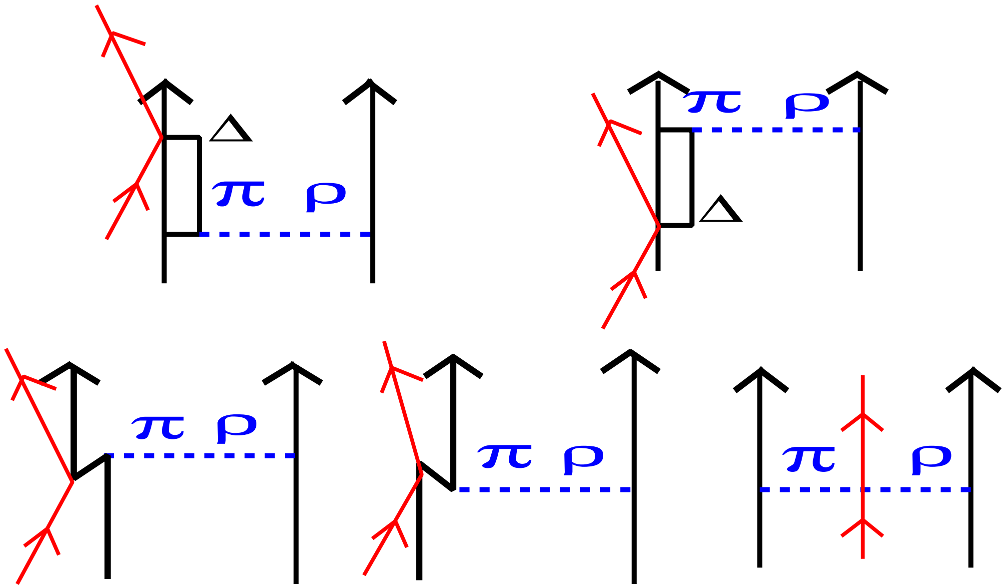
$$< p' \,|A_\lambda(0)|\, p > \quad = \quad \bar{u}(p') \left[f_A \gamma_\lambda \gamma^5 + f_P \gamma^5 q_\lambda \right] u(p)$$

$$q_\lambda \quad \equiv \quad {p'}_\lambda - p_\lambda$$

$$f_M \quad : \quad \mathrm{CVC} \qquad f_P : \mathrm{PCAC}$$

$$f_A(q_\mu^2) \quad = \quad -g_A \left(1 - \frac{q_\mu^2}{1.04\,[\mathrm{GeV}^2]} \right)^{-2}, \quad g_A = 1.2670 \pm 0.0030 \;\; (\mathrm{PDG})$$

Exchange axial-vector current R. Schiavilla et al. PRC **58**, 1263 (1998)

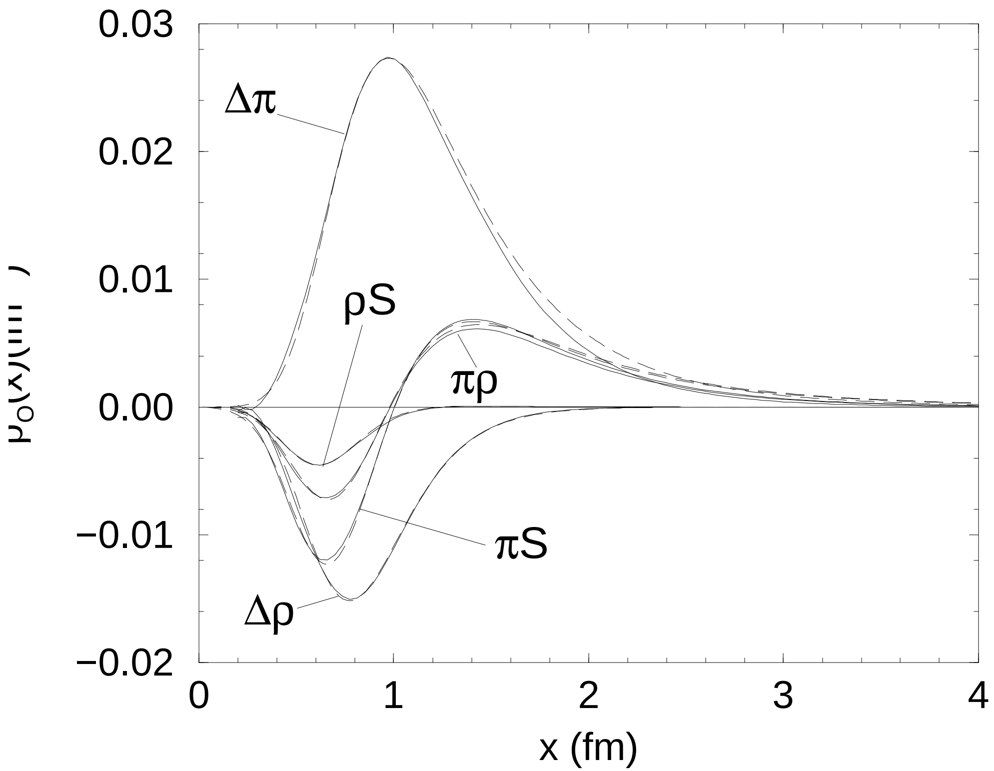


- Fit $AN\Delta$ coupling to tritium β-decay rate
- Rigorous three-body calculation

Why tritium β decay?

νd : Gamow-Teller ($^3S_1 \rightarrow {}^1S_0$) $\Rightarrow$ $\mathbf{A}_{EXC}$ is main correction

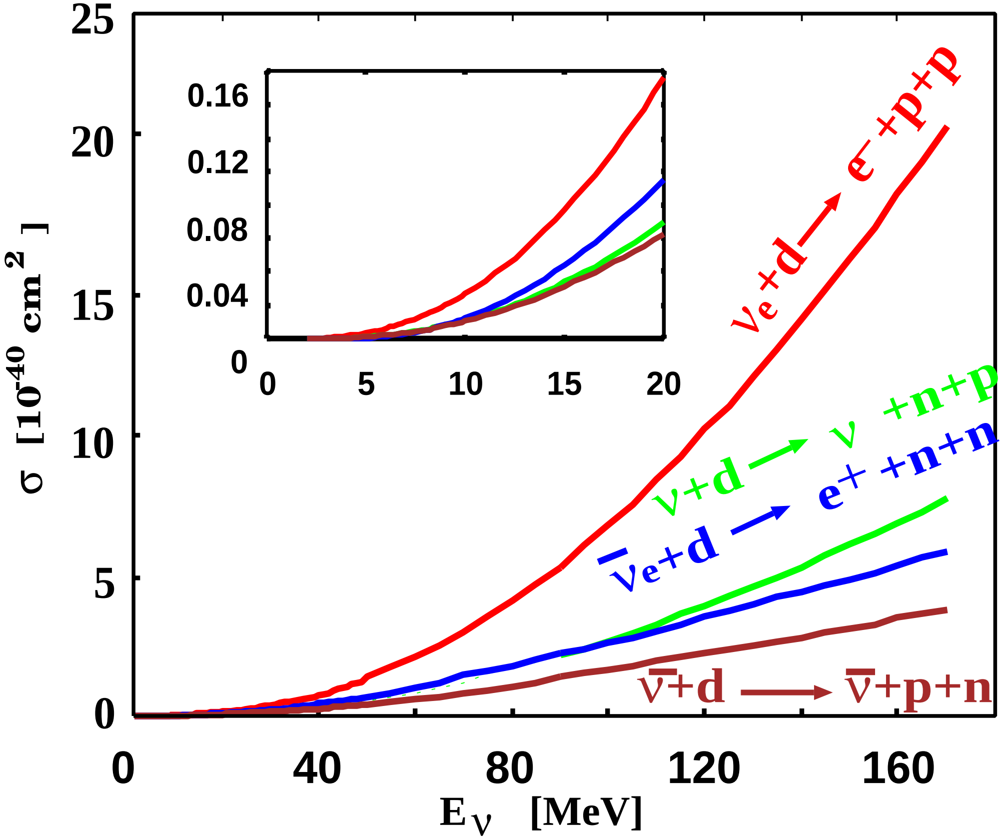
^{3}H : Fermi ($^1S_0 \rightarrow {}^1S_0$) & Gamow-Teller



Schiavilla et al., PRC**58**,1263(1998)

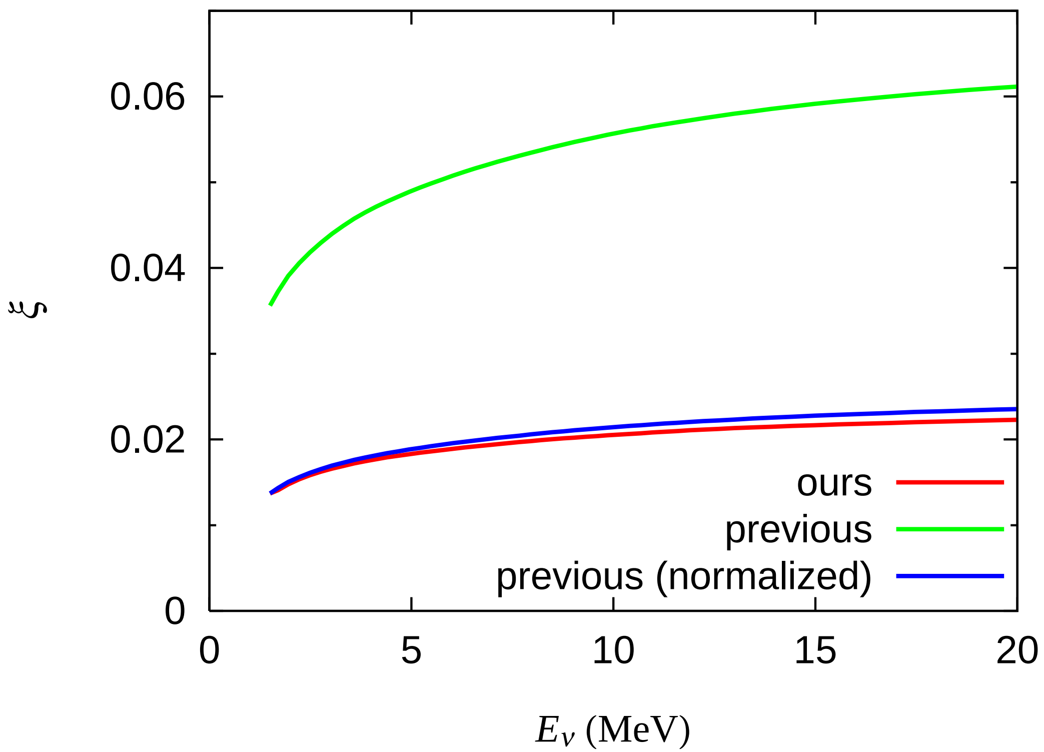
Results

Total cross sections (AV18 potential)



- $d \rightarrow ^1S_0$ dominance in low-energy region
- confirmation of the past work

$\mathbf{A}_{\rm EXC}$ contribution



$$\xi \equiv \frac{\sigma(\mathrm{IA} + \mathbf{A}_{\rm EXC}) - \sigma(\mathrm{IA})}{\sigma(\mathrm{IA})}$$

- 2% contribution of $\mathbf{A}_{\rm EXC}$
- 0.2% model dependence on $\mathbf{A}_{\rm EXC}$ (insensitive to detailed structure)

Comparison with EFT results

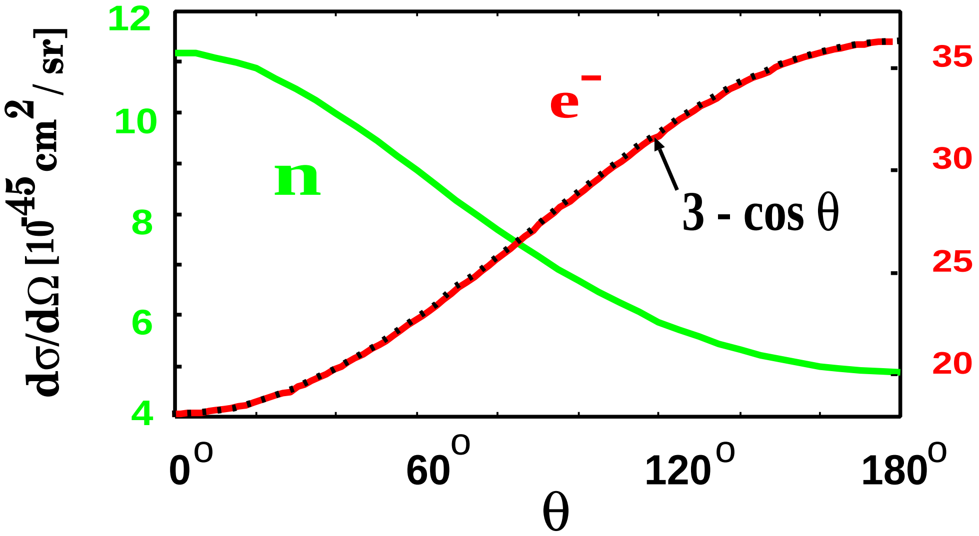
- EFT* (Ando *et al.*, PLB **555**, 49 (2003))

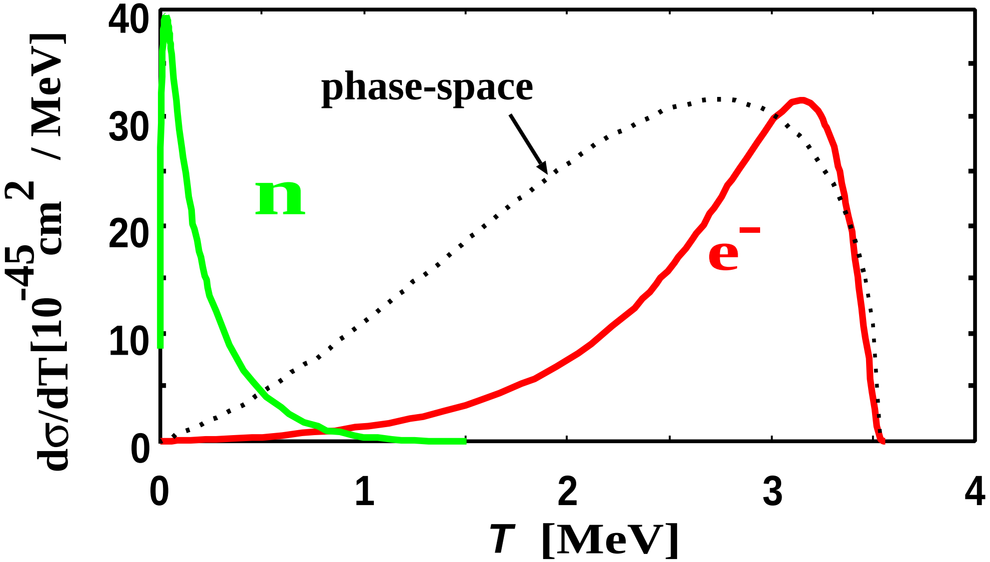
σ(EFT*)/σ(this work)		
E_ν (MeV)	$\nu_e d \to e^- pp$	$\nu d \to \nu pn$
5	1.003	1.004
10	1.001	1.003
20	0.998	1.001

- KSW-counting scheme (Butler *et al.*, PRC **63**, 035501 (2001))

  1% level agreement if $L_{1,A}$ is appropriately chosen

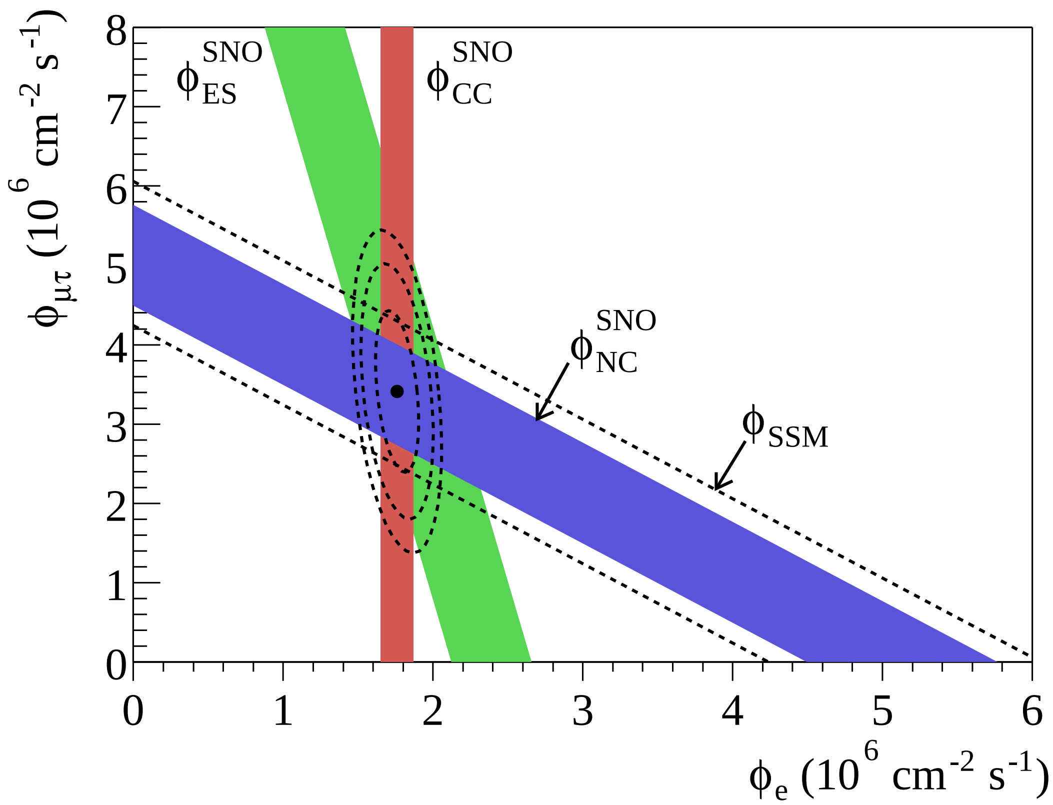
Angular & energy distributions of electron(neutron) in CC(NC) (E_ν=5MeV)





SNO result

PRL 89, 011301 (2002)



- Strong evidence for neutrino oscillation
- Long-standing solar neutrino problem resolved
- Theoretical νd cross sections played essential role

Summary for Part 1 : νd reactions

- $*$ confirmation of existing work
- $*$ update
  - high-precision NN-potential (AV18, CD-Bonn, Nijmegen)
  - exchange axial-vector current tested by tritium β-decay rate
- $*$ differential cross sections
- $*$ theoretical uncertainty : $\delta\sigma_{\nu d} \lesssim 1\%$ ($\boldsymbol{A}_{EXC}$, NN-model, etc.)
- $*$ good agreement with EFT results ($< 1\%$)

Part 2

Neutrino-deuteron reaction as heating mechanism in Supernova

SN et al., PRC 80, 035802 (2009)

In most simulations, supernova doesn't explode !

$\Rightarrow$ extra assistance needed for re-accelerating shock-wave

- $*$ neutrino absorption on <u>nucleon</u> (main)
- $*$ neutrino scattering or absorption on <u>nuclei</u> (extra agent)

Heating through neutrino-nucleus scattering

- ^{4}He, ^{56}Fe   Haxton, PRL 60, 1999 (1988)

  $\Rightarrow$ small effect on supernova dynamics

- ^{3}He, ^{3}H   O'Connor et al. PRC 75, 055803 (2007)

  more effective heating than ^{4}He

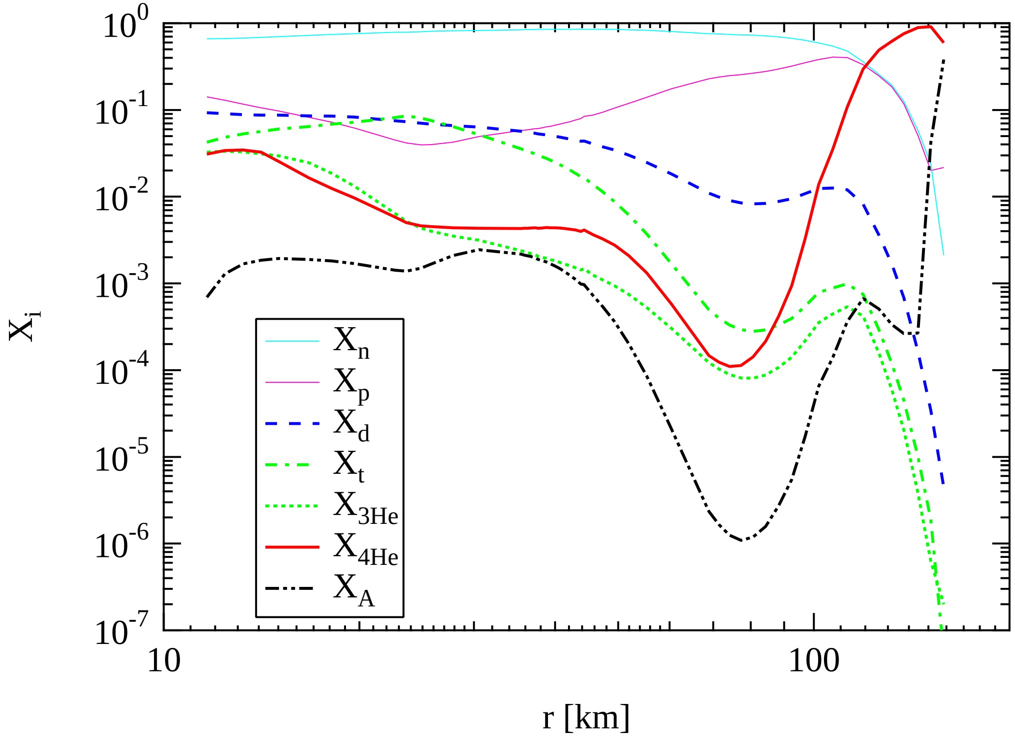
  Arcones et al. PRC 78, 015806 (2008)

  $\bar{\nu}$ spectrum can be changed

- deuteron ?

  can be abundant in supernova, $\sigma_{\nu d} \gg \sigma_{\nu ^3\mathrm{He}}, \sigma_{\nu ^3\mathrm{H}}$

Abundance of light elements in supernova



Sumiyoshi and Röpke, PRC 77, 055804 (2008)

$*$ Nuclear statistical equilibrium is assumed

Quantities of interest for supernova

Thermal average of energy transfer cross section

$$< \sigma\omega >_{T_\nu} = \int dE_\nu f(T_\nu, E_\nu) \sigma\omega(E_\nu)$$

Fermi-Dirac distribution for the neutrino

$$f(T_\nu, E_\nu) = \frac{N}{T_\nu^3} \frac{E_\nu^2}{e^{E_\nu/T_\nu} + 1}$$

Energy transfer cross section for CC (absorption)

$$\sigma\omega(E_\nu) = \int dE'_l \frac{d\sigma}{dE'_l} E_\nu$$

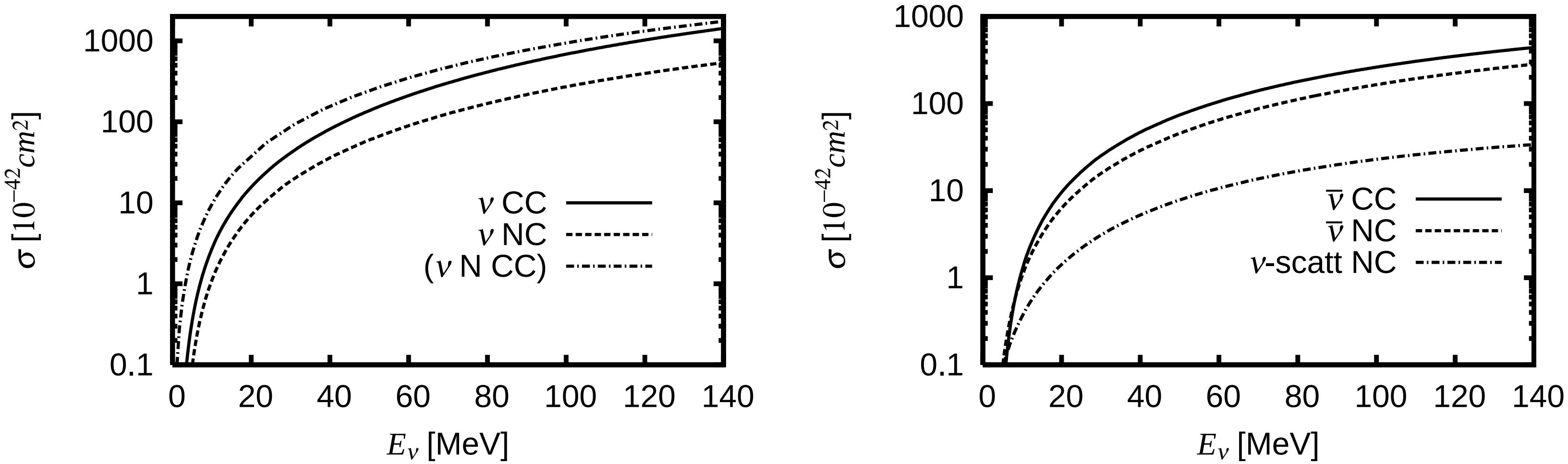
for NC (scattering)

$$\sigma\omega(E_\nu) = \int dE'_\nu \frac{d\sigma}{dE'_\nu} (E_\nu - E'_\nu)$$

Only neutrino is treated separately, others are regarded as matter

Results

Neutrino-deuteron cross sections

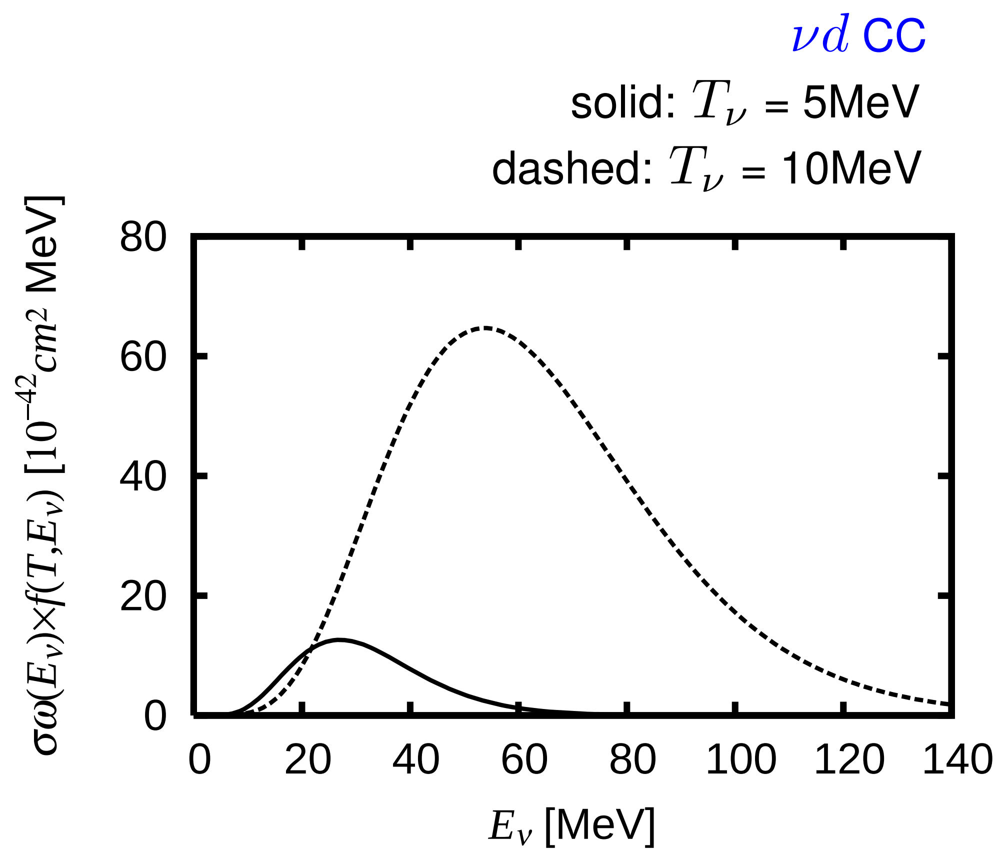


$* \, \sigma(\nu d\, CC) \sim \sigma(\nu N\, CC)/3$ at E_ν = 10 MeV

$* \, \sigma(\nu d\, CC) \sim \sigma(\nu N\, CC)/2$ at E_ν = 50 MeV

$* \, \sigma(\mathrm{elastic}\ \nu d)$ is very small

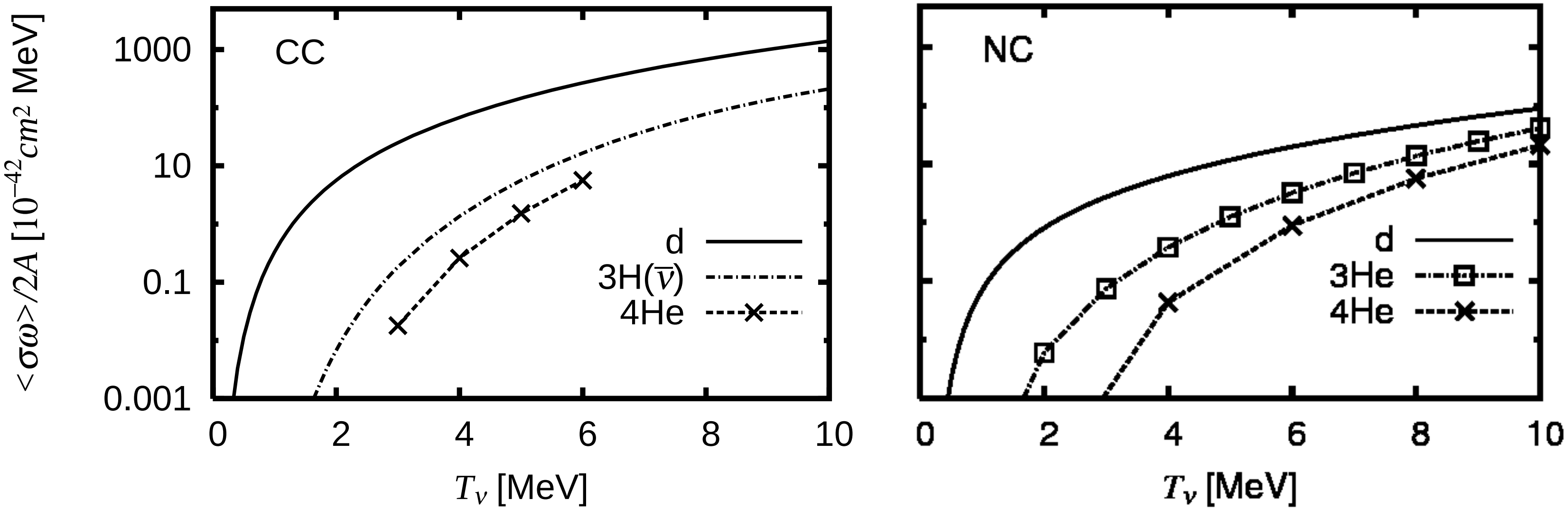
E_ν-dependence of energy transfer cross section



$*$ Main contribution is from E_ν = 20 (60) MeV for T_ν = 5 (10) MeV

$*$ High energy tail of $\sigma\omega \times f$ is appreciable

Thermal average of energy transfer cross section



$*$ $< \sigma\omega >$ for the deuteron is much larger than those of ^{3}H, ^{3}He, ^{4}He

$*$ Small binding energy $\Rightarrow$ rapid increase of $< \sigma\omega >$ at low T_ν

$*$ $< \sigma\omega >_{\nu_e d} / < \sigma\omega >_{\nu_e N} \sim$ 0.44 at T_{ν_e} = 5MeV

$*$ $< \sigma\omega >_{\nu_\mu d} / < \sigma\omega >_{\nu_e N} \sim$ 0.25 at T_{ν_e} = 5MeV and T_{ν_μ} = 10MeV

Neutrino emissivity from deuteron (in progress)

Emission of neutrino in supernova

- $*$ cooling of matter (99% of total cooling)
- $*$ flux and spectrum of neutrino (SN1987A)
- $*$ neutrino heating

Abundance of light elements on surface of protoneutron star

$\Rightarrow$ Careful consideration of ν-emission from deuteron (and other light nuclei)

ν-emission previously considered

- $p + e^- \longrightarrow n + \nu_e$
- $n + e^+ \longrightarrow p + \bar{\nu}_e$
- $n + n \longrightarrow p + n + e^- + \bar{\nu}_e$ cooling of neutron star
- $p + p \longrightarrow p + n + e^+ + \nu_e$
- $N + N \longrightarrow N + N + \nu + \bar{\nu}$ dominant source of ν_μ, ν_τ

ν-emission previously considered	Other, possibly significant processes
* $p + e^- \longrightarrow n + \nu_e$	$d + e^- \longrightarrow n + n + \nu_e$
* $n + e^+ \longrightarrow p + \bar{\nu}_e$	$d + e^+ \longrightarrow p + p + \bar{\nu}_e$
* $n + n \longrightarrow p + n + e^- + \bar{\nu}_e$	$n + n \longrightarrow d + e^- + \bar{\nu}_e$
* $p + p \longrightarrow p + n + e^+ + \nu_e$	$p + p \longrightarrow d + e^+ + \nu_e$
* $N + N \longrightarrow N + N + \nu + \bar{\nu}$	$p + n \longrightarrow d + \nu + \bar{\nu}$

Previous calculation of bremsstrahlung : IA, Born Approx. $\Rightarrow$ Full calculation

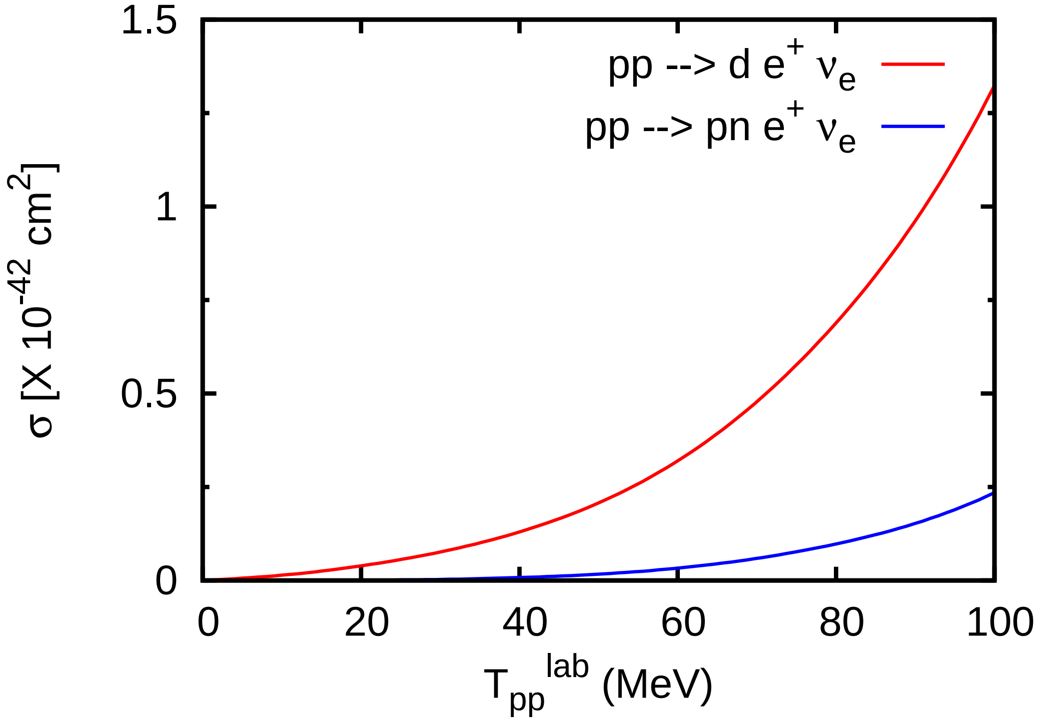
Emissivity Q

for, e.g., $N_1 + N_2 \rightarrow N_1' + N_2' + \nu + \bar{\nu}$

$$
\begin{aligned}
Q &= \int \frac{d\boldsymbol{p}_{N_1}}{(2\pi)^3} \frac{d\boldsymbol{p}_{N_2}}{(2\pi)^3} \frac{d\boldsymbol{p}_{N_1'}}{(2\pi)^3} \frac{d\boldsymbol{p}_{N_2'}}{(2\pi)^3} \frac{d\boldsymbol{p}_{\nu}}{(2\pi)^3} \frac{d\boldsymbol{p}_{\bar{\nu}}}{(2\pi)^3} \\
&\times \quad (2\pi)^4 \delta^{(4)}(p_f - p_i) \sum_{spin} |M|^2 F_{N_1} F_{N_2} (1 - F_{N_1'})(1 - F_{N_2'})
\end{aligned}
$$

F_N : nucleon distribution function

Total cross sections for $pp \to pne^+\nu_e$, $pp \to de^+\nu_e$



$*$ Much larger cross section for $pp \to de^+\nu_e$

$*$ A_{EXC} increases σ by 5, 20, 30% at T_{pp} = 10, 50, 100 MeV

Summary for Part 2 : ν heating and emissivity in supernova

Abundance of light elements in supernova

$\Rightarrow$ Careful consideration of ν-emission and absorption on the light elements

Deuteron can play an important role !

- $\ast$ ν-heating much more effective than A=3,4 nuclei
- $\ast$ $\sigma(NN \to d\nu\bar{\nu})$ (emissivity) much larger than $\sigma(NN \to NN\nu\bar{\nu})$

$\Rightarrow$ Supernova simulation with mixture of light elements and ν-nucleus interactions