Nuclear Physics studied by Neutrino induced Coherent Pion Production

Yasuhiro SAKEMI
Research Center for Nuclear Physics (RCNP)
Osaka University

Motivation from the point of view of nuclear physics ….

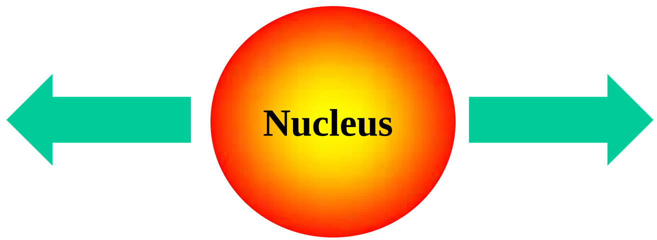
Neutrino-Nucleus scattering

1. **Neutrino oscillations ~ Detector response**
2. **Hadron physics ~ Spin structure of nucleon**
3. **Input into Astrophysics ~ Core collapse supernovae , r-process nucleosynthesis**
4. **Nuclear physics ~ π , Δ propagation in the interior of nucleus**

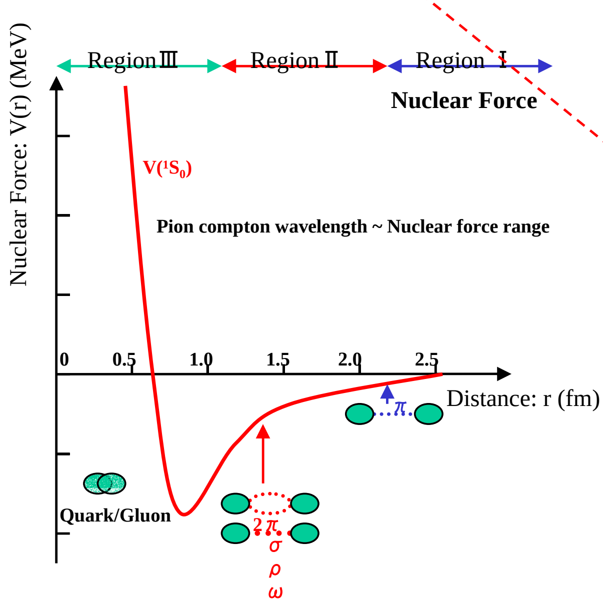
Physics motivation

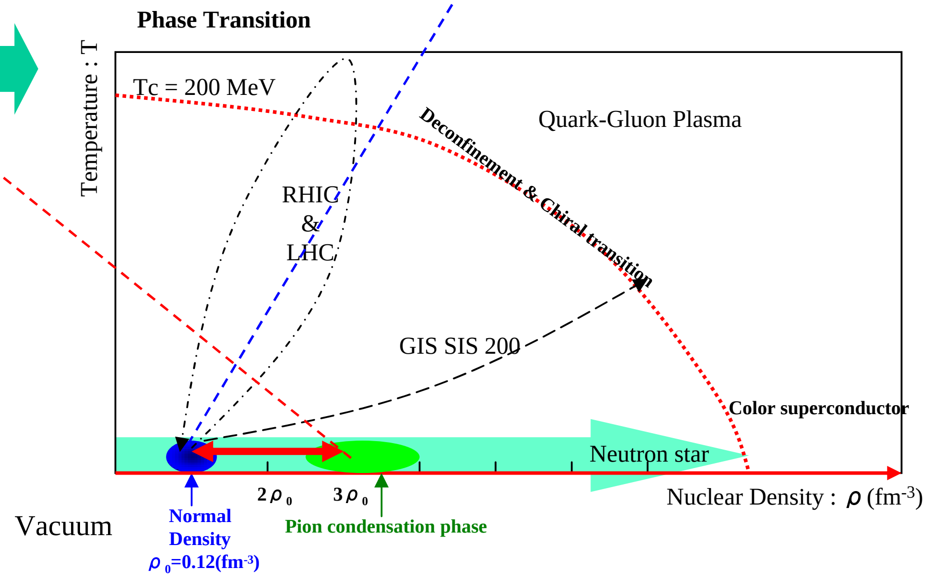
New probe ~ neutrino
Physics ~ search of nuclear interior , property of high density nuclear matter
pion, Δ propagation in the nuclear medium ~ Chiral symmetry in nuclear physics

Nuclear force
~ short range component
→ π condensation



π , Δ propagation
~ pions in nuclei
→ surface pion condensation



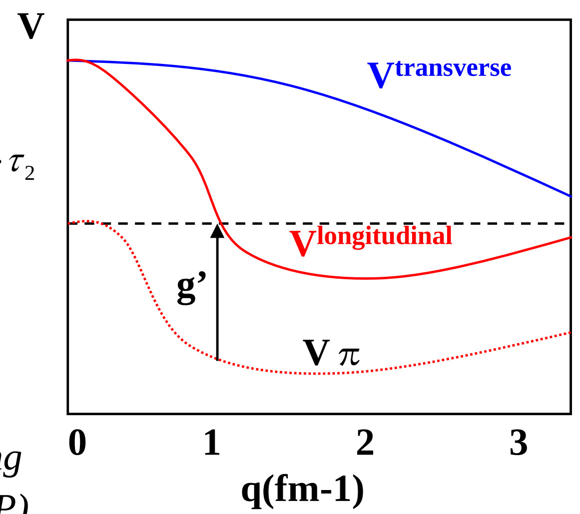


Nuclear force and short range correlation

- Nuclear force
  - short range correlation of the nuclear interaction
    $\Rightarrow$ 1 π exchange + 1 ρ exchange + g' (short range: phenomenological parameter)

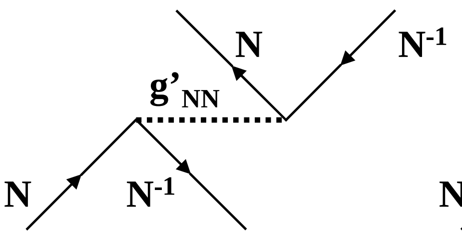
$$V_{ph}^{longitudinal} = 4\pi f^2 \left(g'_{NN} + \frac{k^2}{\omega^2 - k^2 - m_\pi^2} \right) (\sigma_1 \cdot k)(\sigma_2 \cdot k) \tau_1 \cdot \tau_2$$

$$V_{ph}^{transverse} = 4\pi f^2 \left(g'_{NN} + \frac{f_\rho^2}{f^2} \cdot \frac{k^2}{\omega^2 - k^2 - m_\pi^2} \right) (\sigma_1 \times k)(\sigma_2 \times k) \tau_1 \cdot \tau_2$$

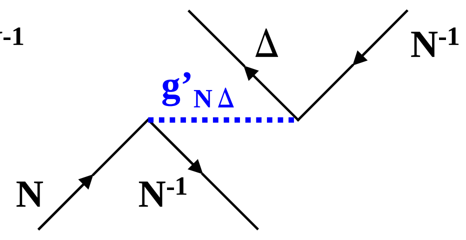


  - Critical Density of Pion Condensation
  - Finite expectation value of pion in nuclei
- Landau-Migdal parameter $g' \sim g'_{NN}, g'_{N\Delta}, g'_{\Delta\Delta}$
- *(N-h)(N-h), (Δ-h)(N-h), (Δ-h)(Δ-h) residual interaction*
- *g'_{NN}, $g'_{N\Delta}$ ~ Gamow-Teller region, $g'_{N\Delta}$ ~ quasi-free scattering*
- *$g'_{\Delta\Delta}$ ~ Δ excitation region → Coherent Pion Production (CPP)*

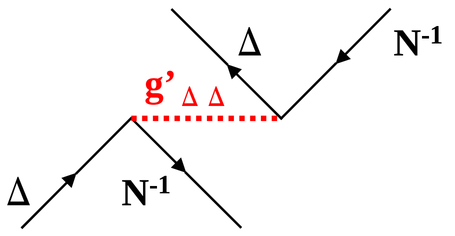
$g'_{NN}\, \sigma_1 \cdot \sigma_2\, \tau_1 \cdot \tau_2$



$g'_{N\Delta}\, \sigma_1 \cdot S_2\, \tau_1 \cdot T_2$



$g'_{\Delta\Delta}\, S_1 \cdot S_2 T_1 \cdot T_2$

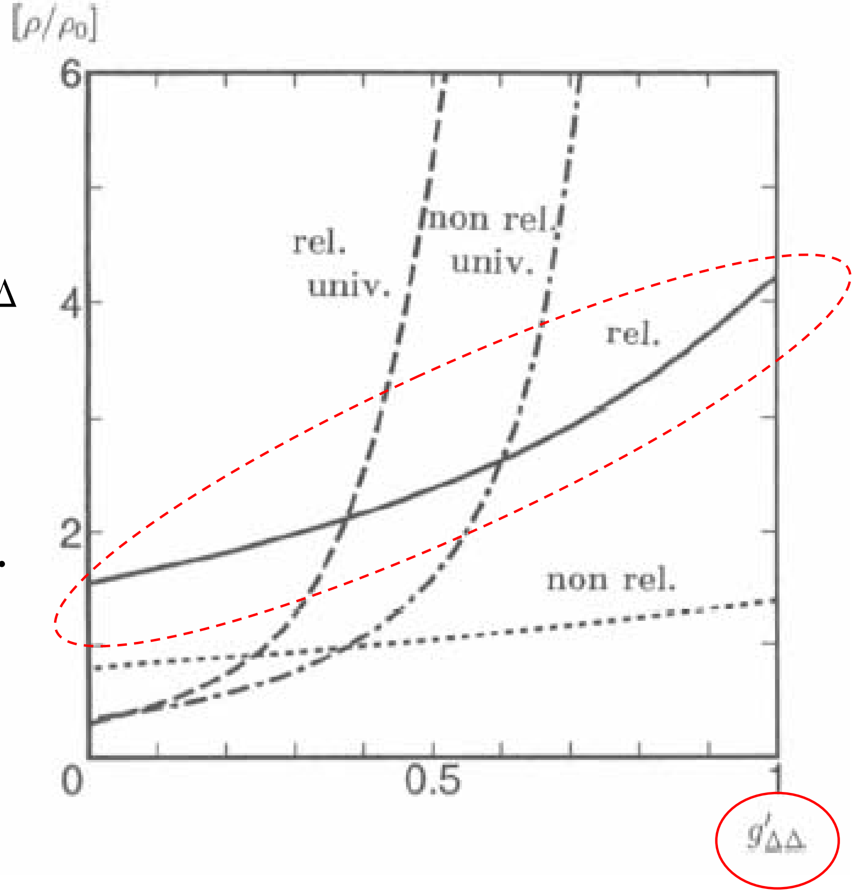


Pion condensation phase in high density nuclear matter

Short range correlation : $g'_{\Delta\Delta}$
~ sensitive to critical density ρ of pion condensation phase
~ determine the limit of ρ from the CPP measurement

Universality ~ $g' = g'_{NN} = g'_{N\Delta} = g'_{\Delta\Delta}$

Relativistic H.F.

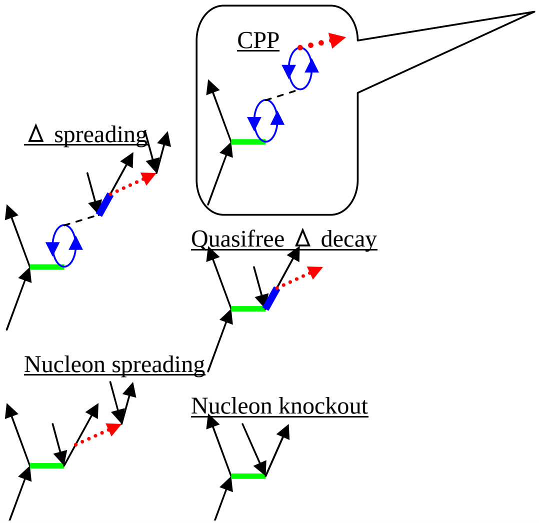


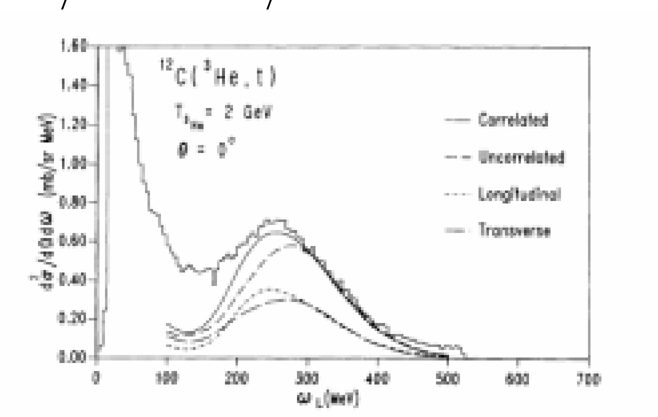
[1] M. Nakano et al., IJMP E 10-6 (2001) 459
[2] A. Onishi et al., arXiv:nucl-th/0407085

Coherent Pion Production

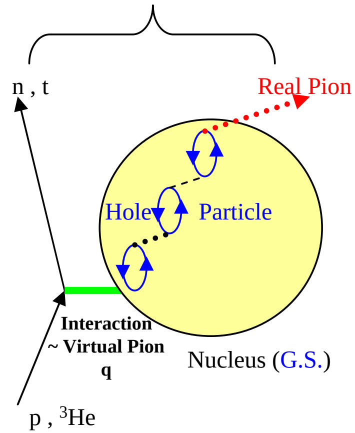
$$A(p,n\,\pi^{+})A(G.S.),\ A(\nu,\mu^{-}\pi^{+})A(G.S.)$$

Inclusive measurement





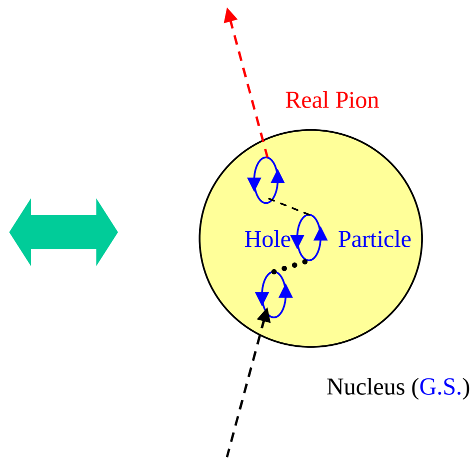
Coincidence measurement of neutron and pion



Coherent Pion Production (CPP)

- **-Virtual pion ~ emitted from incidence proton beam**
- **-Excite Δ/nucleon-particle nucleon-hole states**
- **-Propagate with mixing particle-hole states**
- **-Produce the real pion**
- **-Target nucleus is left in the Ground State (G.S.)**

Cross section ~ spin longitudinal component : dominant



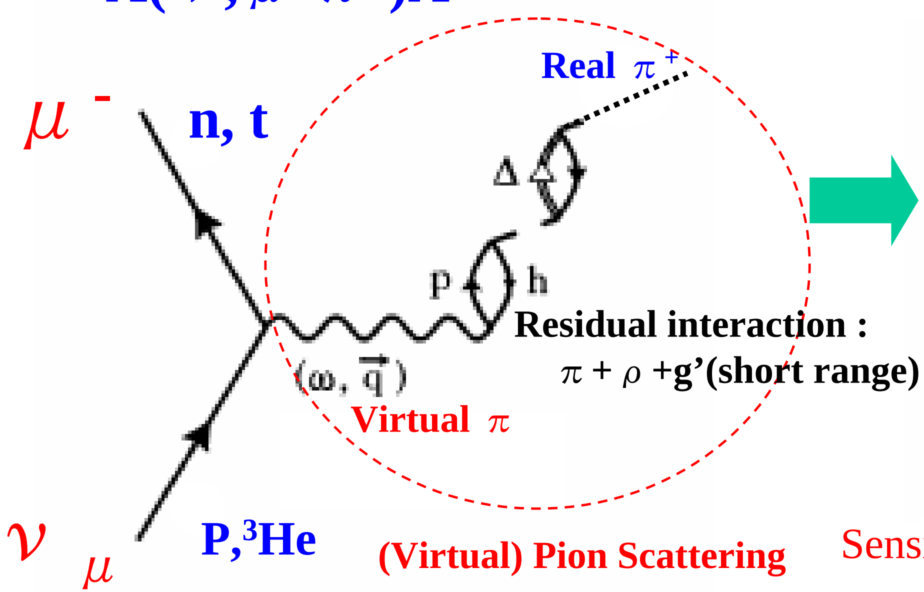
(virtual) pion scattering

Pure longitudinal mode ~ σ ・ q

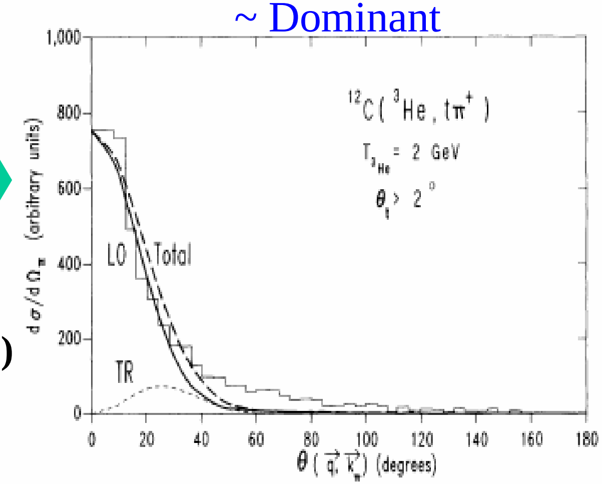
Cross section at forward angle
~ Longitudinal Response Function
→ short range correlaton : g'$_{\Delta\Delta}$
at Δ resonance region

Neutrino and Hadron Probes

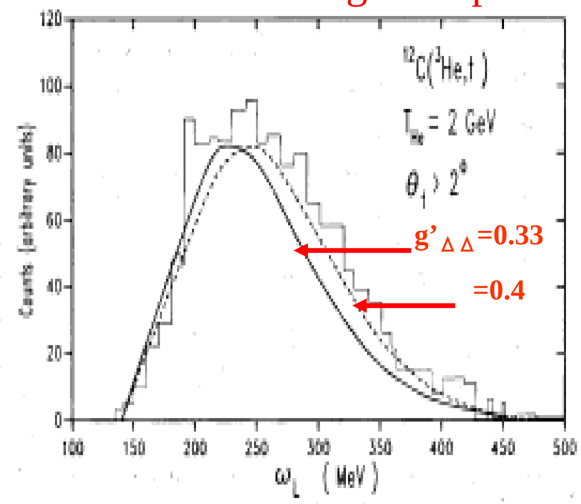
$A(\nu, \mu^- \pi^+)A$



Spin longitudinal response function ~ Dominant



Sensitive to NN short range component $g'_{\Delta\Delta}$



- **Neutrino ~ Weak interaction**

→ **No distortion, absorption**

⇒ **test the Δ, π in the interior of nucleus**

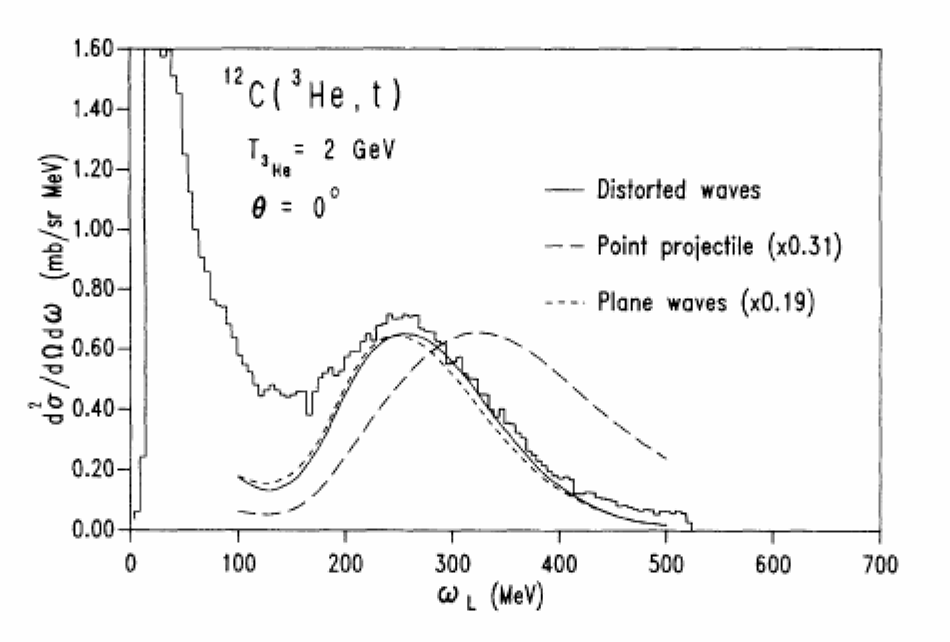
Adler's theorem : M~T(π(q)+N→X)

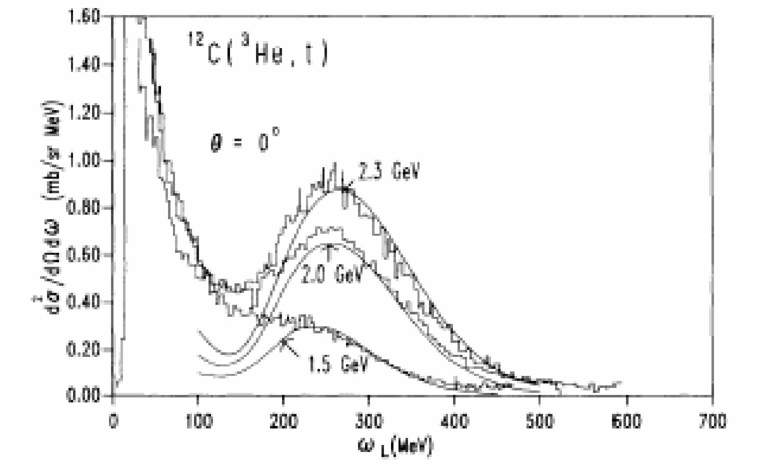
- **Hadron ~ Strong interaction**

→ **Distortion, absorption**

⇒ **peripheral reaction ~ nuclear surface**

Distortion effects

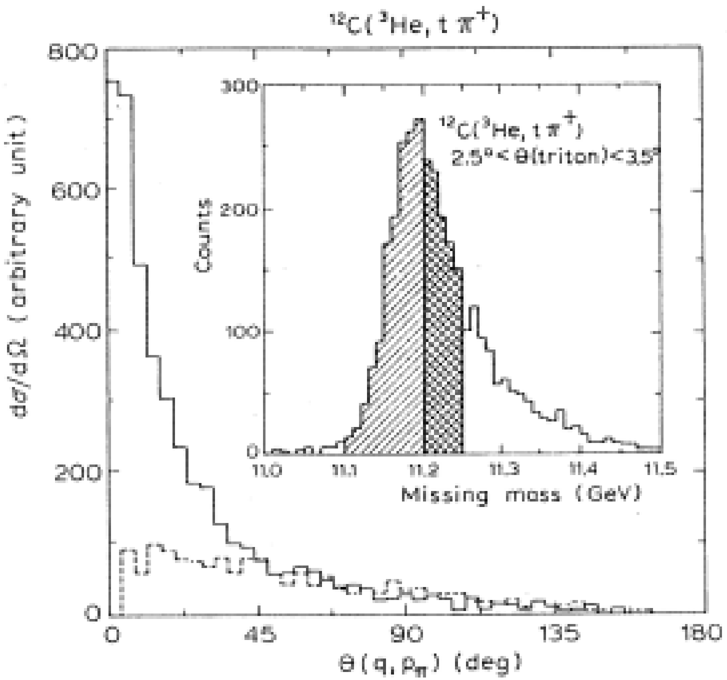




Present status

Hadron probe

- **Sacray (3He,t π^+)** **~ resolution : poor / shutdown**
- **LAMPF (p,n π^+)** **~ test experiment / shutdown**
- **RCNP (p,n π^+) (3He,t π^+)** **~ in progress**



Neutrino ~ J-PARC !

A(ν , μ^- π^+)A*

→ what should be considered

- **resolution**
- **yield**
- **…..**

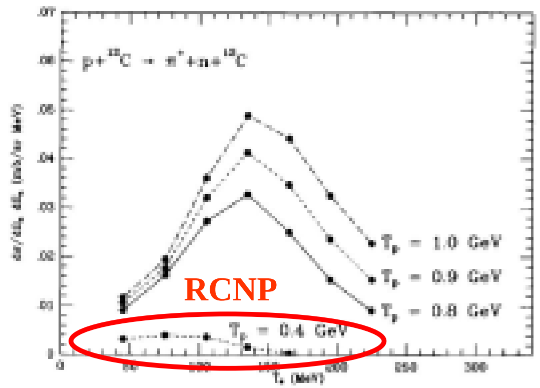
Coherent Pion Production at RCNP

- g'_{DD} extracted from Coherent Pion Production

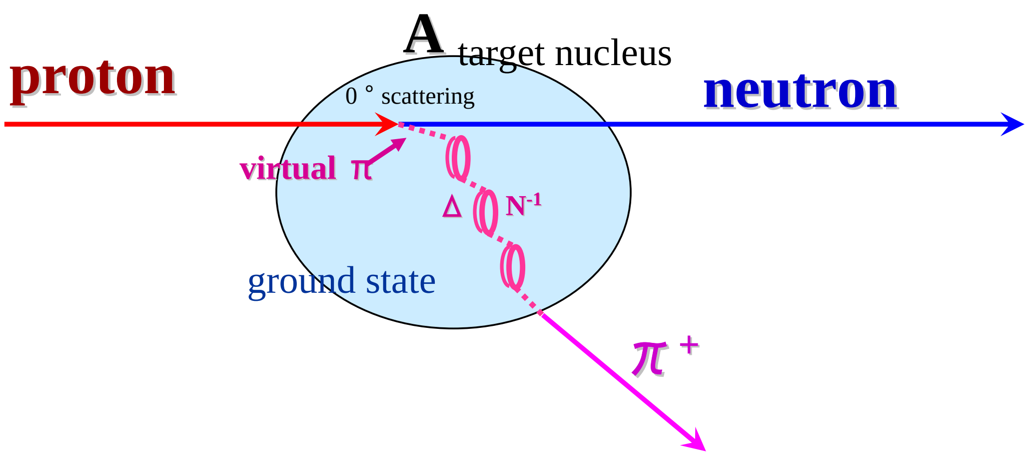
  p + A → n + π^+ + A (g.s.)

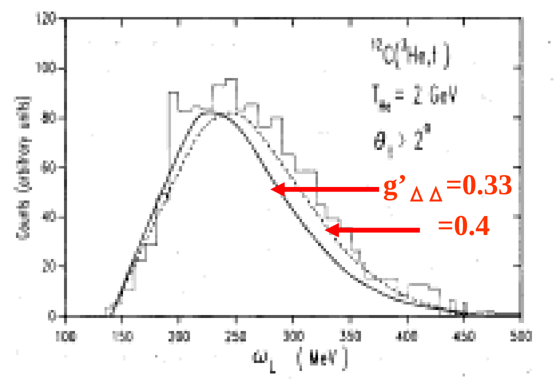
  1. *Peak shift from N-D residual interaction*
     - $\Delta E \approx g'_{\Delta\Delta}(\hbar c f_{pND}/m_p^2)\,\rho_0$
  2. *Longitudinal response function (R_L)*

     ~ dominant at 0 degree
     - $s_{cpp}(0^\circ) \to R_L \to g'\,(g'_{NN}, g'_{ND}, g'_{DD})$
- virtual pion scattering in target nucleus



coherent pion cross section[2].





correlation of cross section and $g'_{\Delta\Delta}$[3].

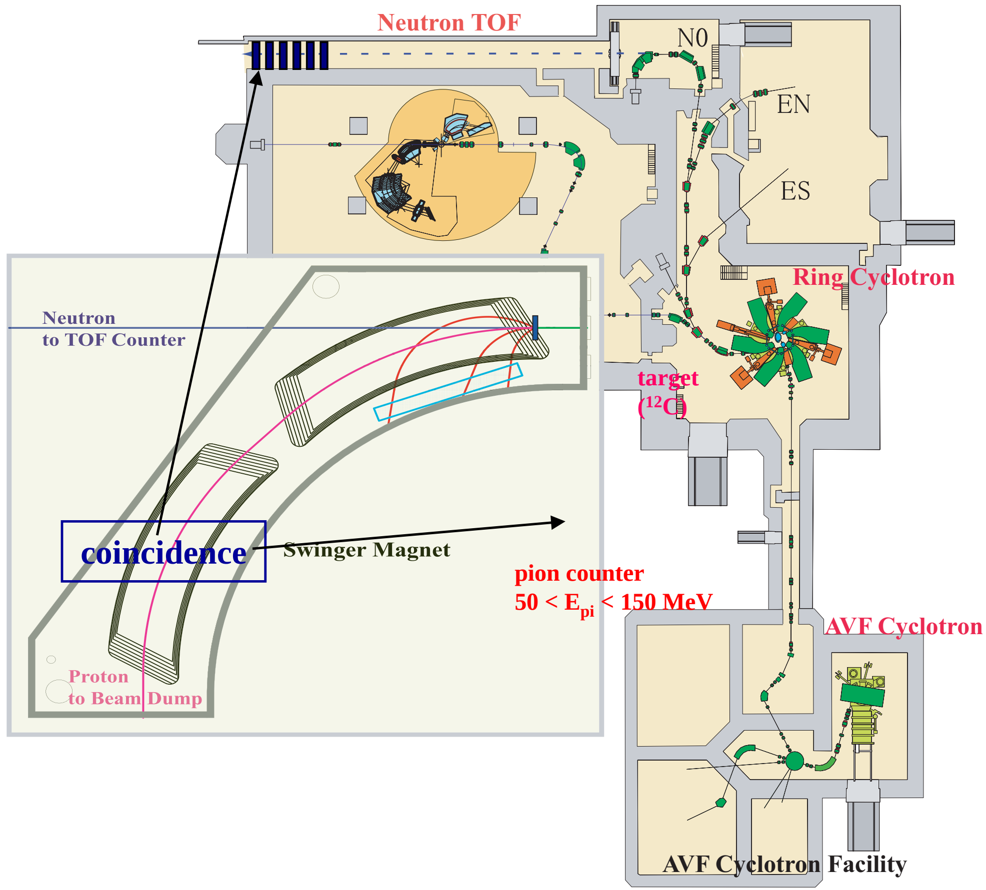
[2] E. Oset, Nucl. Phys. A 592 (1995) 472.
[3] T. Udagawa et al., Phys. Rev. C 49 (1994) 6.

Experiment

- Beam ~ proton 400MeV un-polarized
- Target ~ ^{12}C ($100 mg/cm^2$)
- True Event 100nA → ~ 0.15 cps
- Observables
  - *pion energy and angle*
    - *position counter (developed newly)*
  - *neutron energy*
    - *Neutron Counter NTOF*

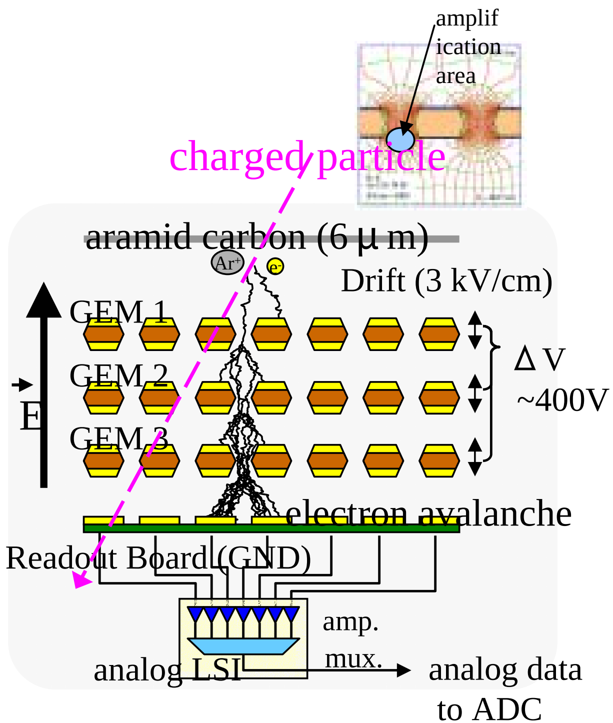
      ↓ *coincidence*
    - *missing mass spectra*
- Requirements
  - *high spatial and angle resolution*
    - *Dx < 100mm*
    - *Dq < 1 mrad*
  - *counting rate ~ 100kcps*
  - *High magnetic field ~ 0.5 T*
  - *space boundary*

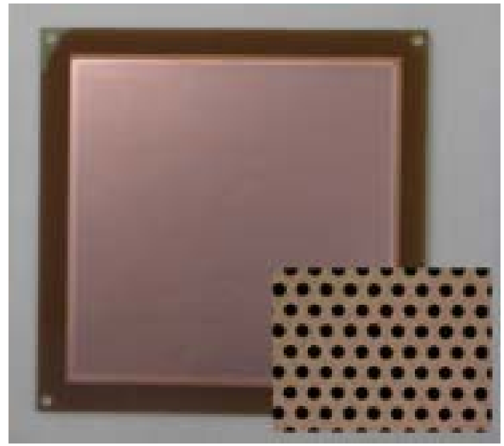
➢ GEM detector



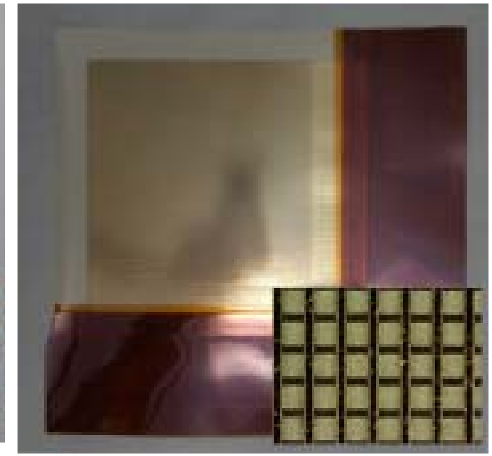
Schematic layout of the GEM+NTOF experiment

Tracking Detector: Gas Electron Multiplier

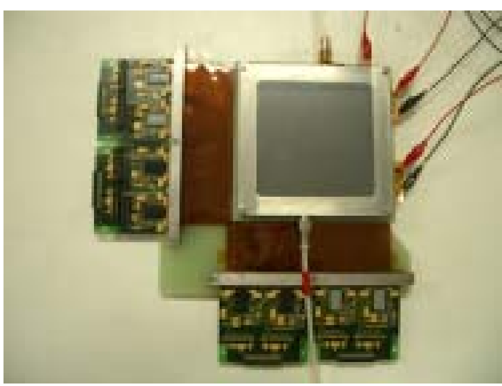


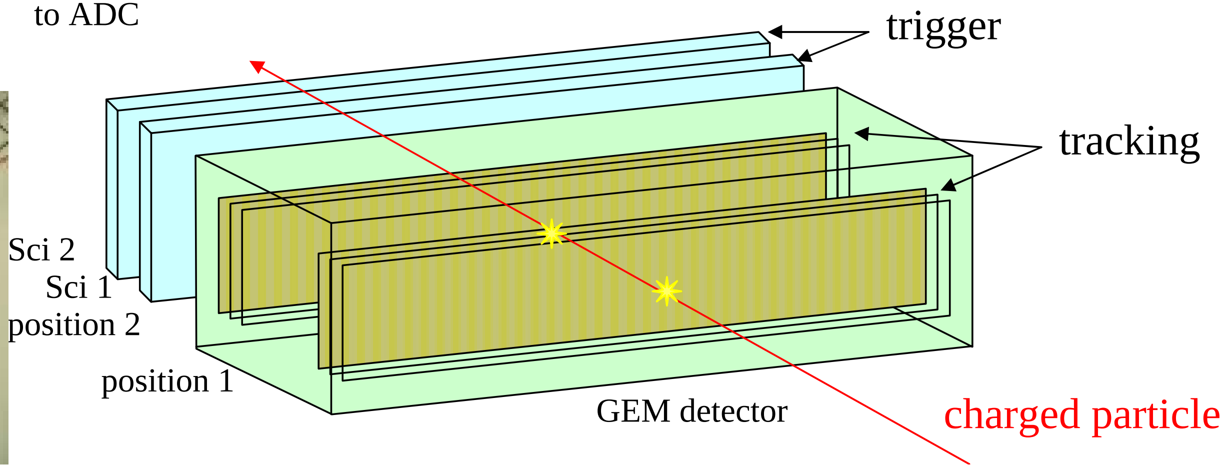


GEM



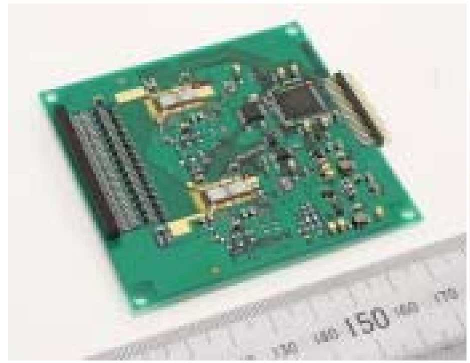
Readout Board

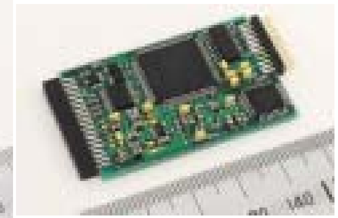


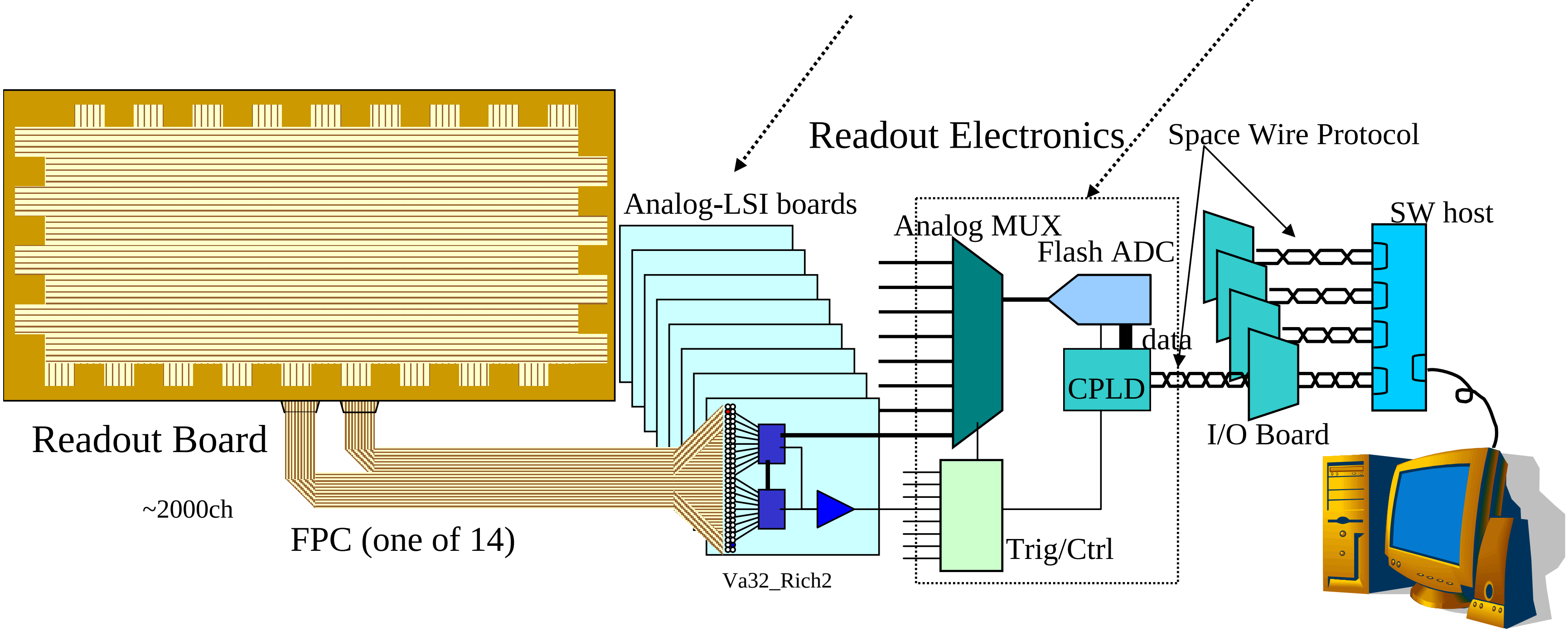


Readout System

- Present Status of Production
  - *hardware*
  - *DAQ system*
- Specification
  - *high speed data transfer*

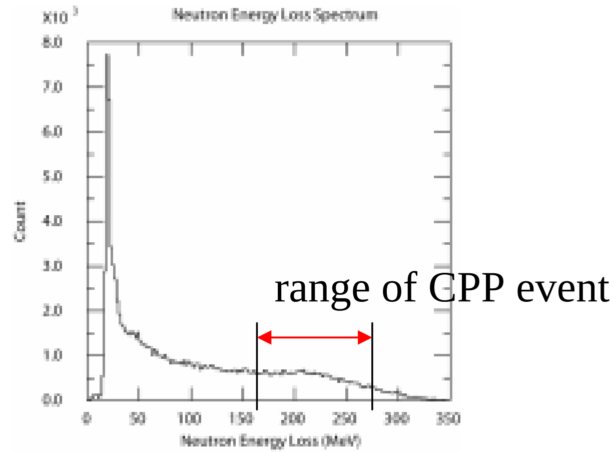






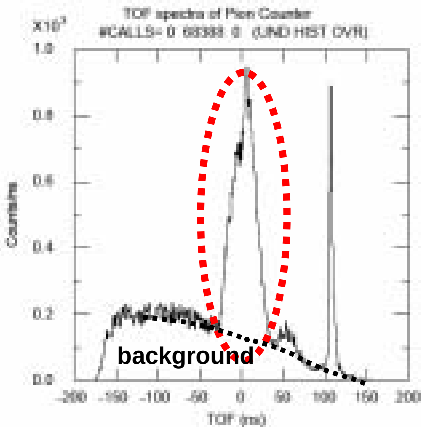
Experimental status

- Hardware
  - *Trigger scintillator with WLS fiber*
  - *GEM detector ~ prototype*
- Experiment and analysis Status
  - *Beam: proton (392MeV, <30nA)*
  - *Target: ^{12}C (113mg/cm^2)*
  - *Event rate: 2kcps (p + n event)*
  - *proton background ~ not separated clearly*
    - *True/B.G. < 1/60*
- Improvements
  - *TOF & shield*
    - *longer path length*
    - *shielding around the beam-line*
  - *tracking detector*
    - *precise b information*
    - *reconstruction with high position resolution*

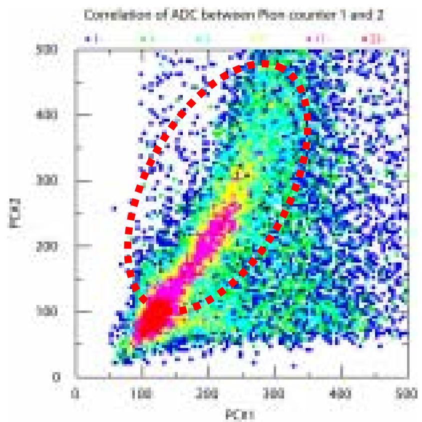


energy spectrum of neutron

Feasibility check ~ this year
Data production run ~ this year/next year



TOF spectrum of pion counter



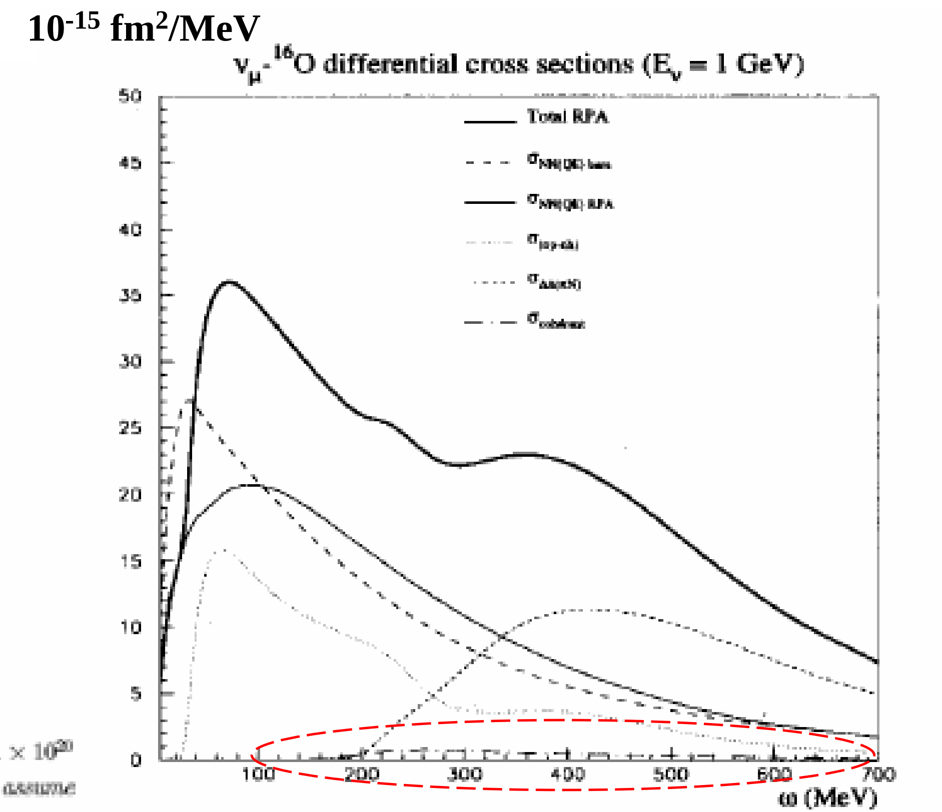
ADC histogram

Neutrino induced CPP

E=1 GeV → Δ resonance region ~ π , Δ propagation in the interior of nucleus

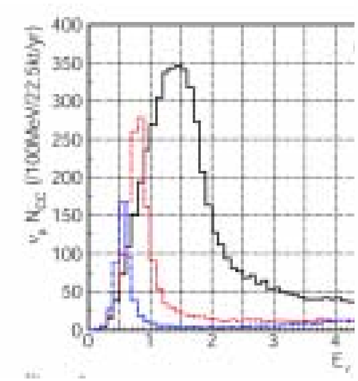
ν interaction type	ν_μ 10^{20} POT 1 ton	$\overline{\nu_\mu}$ 10^{20} POT 1 ton	$\nu_e + \overline{\nu_e}$ 10^{20} POT 1 ton
CC QE, $\nu_\mu n \to \mu^- p$	11,395	184	56
NC EL, $\nu_\mu N \to \nu_\mu N$	4,903	86	22
CC π^+, $\nu_\mu p \to \mu^- p \pi^+$	3,293	24	24
CC π^0, $\nu_\mu n \to \mu^- p \pi^0$	725	11	6
CC π^+, $\nu_\mu n \to \mu^- n \pi^+$	646	10	6
NC π^0, $\nu_\mu p \to \nu_\mu p \pi^0$	606	10	5
NC π^+, $\nu_\mu p \to \nu_\mu n \pi^+$	370	6	3
NC π^0, $\nu_\mu n \to \nu_\mu n \pi^0$	454	8	3
NC π^-, $\nu_\mu n \to \nu_\mu p \pi^-$	290	5	2
CC DIS, $\nu_\mu N \to \mu^- X$	176	0	1
NC DIS, $\nu_\mu N \to \nu_\mu X$	64	0	0
CC coh π^+, $\nu_\mu A \to \mu^- A \pi^+$	539	22	3
NC coh π^0, $\nu_\mu A \to \nu_\mu A \pi^0$	349	14	2
other	464	14	1
total	24,364	394	134

Table 3.1: *Number of events expected at 50 m with a 25 m decay length for 1×10^{20} POT per ton detector. These predictions do not include final state effects and assume 100% detection/reconstruction efficiency.*



Neutrino Beam Line

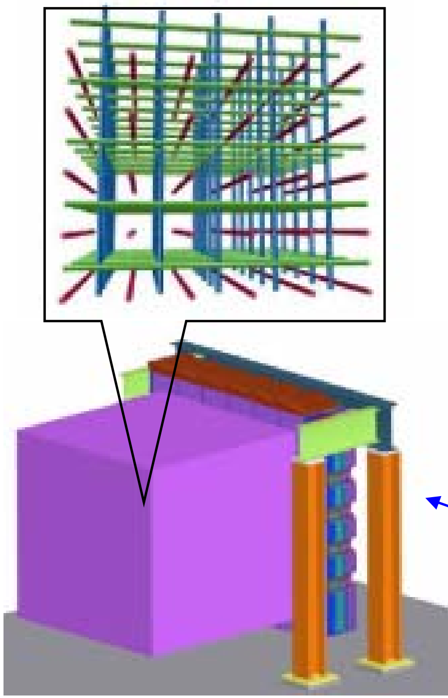
Beam energy ~ 1 GeV



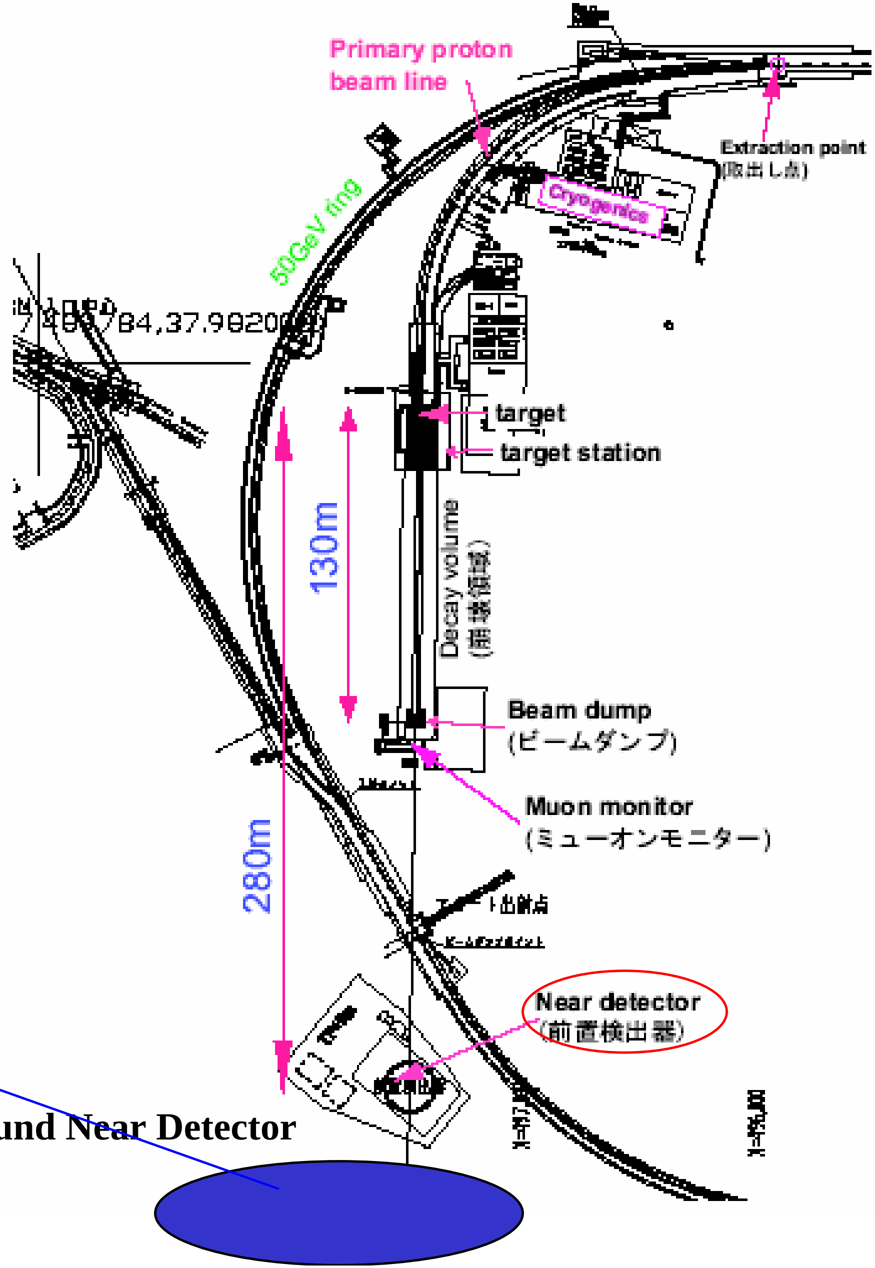
Detector
~ BNL case

Liquid Sci.
With W.L.S

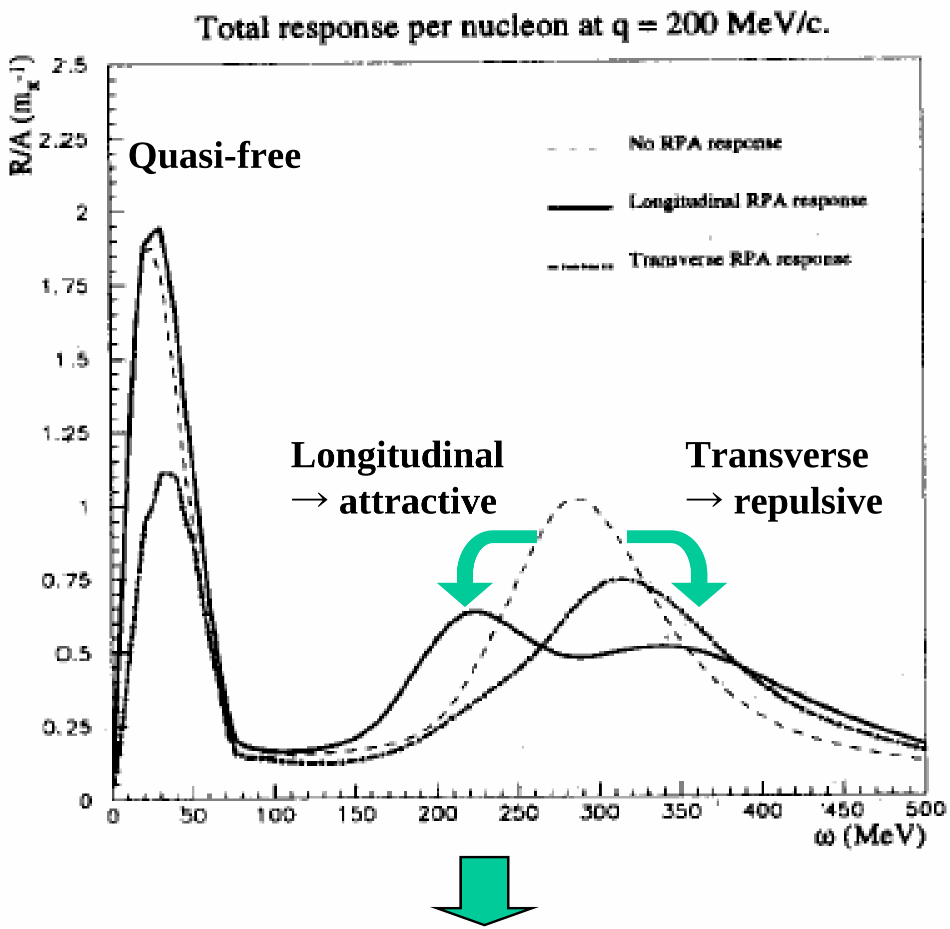
Target
- **Proton**
- **Carbon !**
- **Nucleus**



Around Near Detector



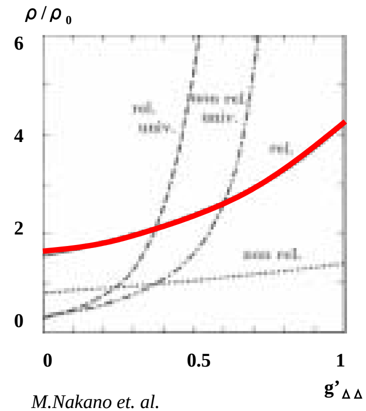
Predicted response function



g' Δ Δ
Critical density of pion condensation

Nuclear density dependence ~ g'
•Neutrino ~ interior of nucleus
~ saturated density
•Hadron ~ surface of nucleus
~ low density

•Pion condensation phase
•Neutron star structure
•Cooling mechanism of neutron star



M.Nakano et. al.
Int. J. of Mod. Phys. E10(2001) 459

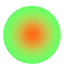
Pion distribution in nuclei

Nuclear structure ~ pion distribution
Surface pion condensation ~ finite expectation value of pions in the nuclear surface !

Chiral Symmetry ~ Pion

Vacuum : Spontaneously broken ~ Pion as Goldstone boson → **Nucleus (finite density) : Partially restored** → **High Density Matter : Restored**

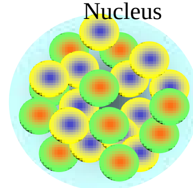
Nucleon



$$\partial^\mu A^i_\mu(x) = m_\pi^2 f_\pi \pi^i(x) \neq 0$$

$$\langle 0|\bar{q}q|0\rangle \approx (-250MeV)^3 \neq 0$$

Nucleus

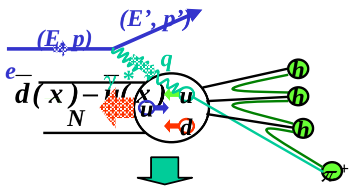


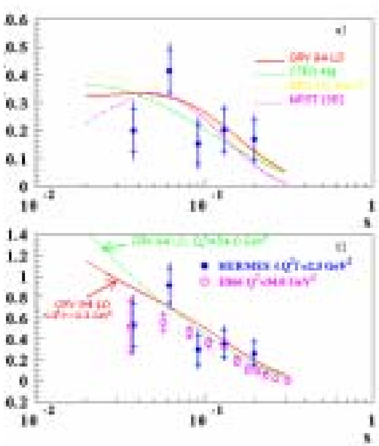
Appeared Phenomena

Simple transition to study the pion behavior in the nucleus

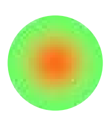
1. Gamow-Teller states (GT) :
   $\Delta S=1, \Delta L=0$ ~ interaction from pi/rho-meson exchange
   Polarized ^{3}He beam ⇒ separate pi / rho response to GT
2. Pion-like 0^- states :
   Carry a quantum number of pion
   Polarized ^{3}He/^{6}Li beam ⇒ 0^- state search/identify

1. Meson Cloud in Nucleon : Sea Quark Flavor Asymmetry
~ Drell-Yan process / lepton-DIS



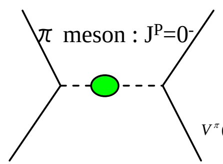


Meson Cloud



$P \rightarrow n + \pi^+$

2. Nuclear force mediated by pion
~ Strong tensor force



$$H_{(N.R.)}^{pv} = -\frac{f_p}{u_p}(\psi^+ \sigma \psi) \cdot \nabla \phi$$

$$V^\pi(1,2) = -\sum_{a=1}^{3}\left(\frac{f}{\mu_\pi}\tau_a^1 \sigma_1 \cdot \nabla_1\right)\left(\frac{f}{\mu_\pi}\tau_a^2 \sigma_2 \cdot \nabla_2\right)\frac{e^{-u_\pi r_{12}}}{4\pi r_{12}}$$

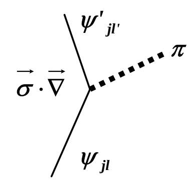
$$V^{OPEP}(1,2) = -m_\pi c^2 f^2 (\tau_1 \cdot \tau_2)[(\sigma_1 \cdot \sigma_2)Y(x) + S_{12}Z(x)]$$

$$\vec{\sigma} \cdot \vec{\nabla}$$

Pion Distribution In Nuclear ?

3. Mean field theory with pion-nucleon coupling
~ Finite pion density in the nuclear surface

Include pion exchange explicitly in the mean field

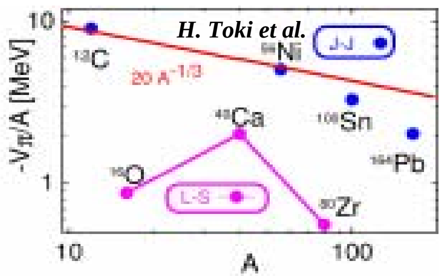


$$\psi_{jl} \Rightarrow \xi \psi_{jl} + \zeta \psi'_{jl'}$$

$$\psi'_{jl'} \propto (\vec{\sigma} \cdot \vec{\nabla})\psi_{jl}$$

$$(l' = l \pm 1)$$

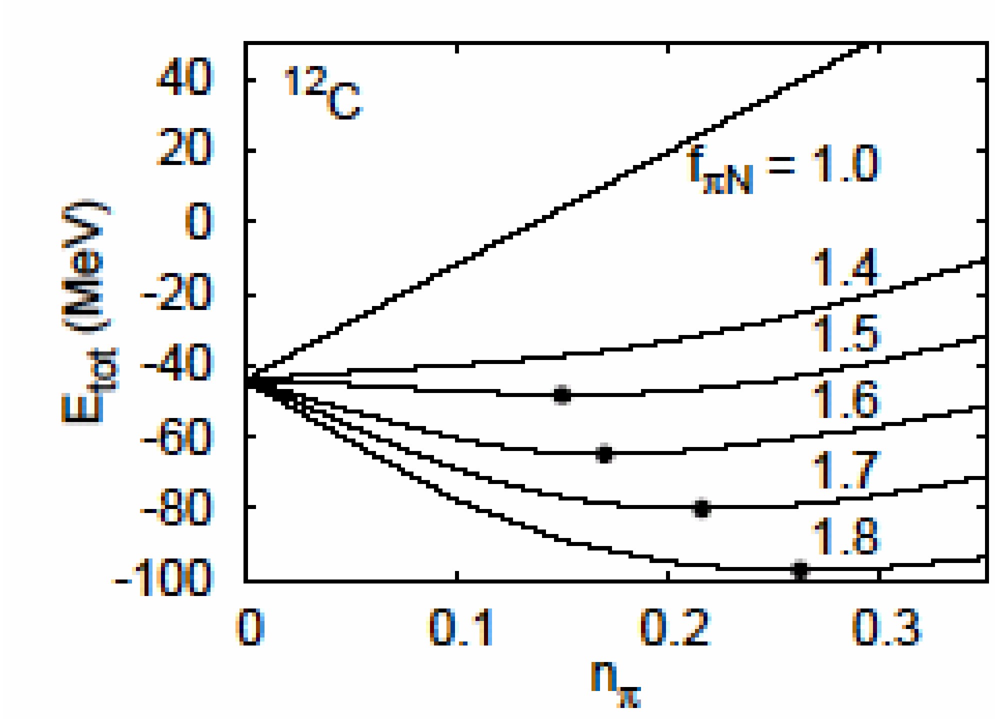
$$\left[i\alpha \cdot \nabla + \gamma_0 (M + g_\sigma) + \frac{f_\pi}{m_\pi}\gamma_0 \gamma_5 \gamma \cdot \tau^a \nabla \pi^a + g_\omega \omega + g_\rho \tau^a \rho^a + e\frac{1+\tau_3}{2}A \right]\psi = E\psi$$



Pion energy ~ Surface like : V~A$^{-1/3}$

Pions in nuclei

Volume type or Surface type distribution ?



Intrinsic energy of ^{12}C as a function of pion number expectation [1].

[1] A. Onishi et al., arXiv:nucl-th/0407085

Search for 0^- state with Polarized ^{3}He Beam

Motivation

1. $J^P=0^-$ excitations : carry the simple Pion-like quantum number ⇒ will have a pion correlation in the nucleus
2. 0^- state is not clearly separated ⇒ poor data , limited
3. (p,n) data by Orihara et al. ~ low incident energy ⇒ large difference between data and DWBA at large q ~ signature of pionic field ?

Physics Goal

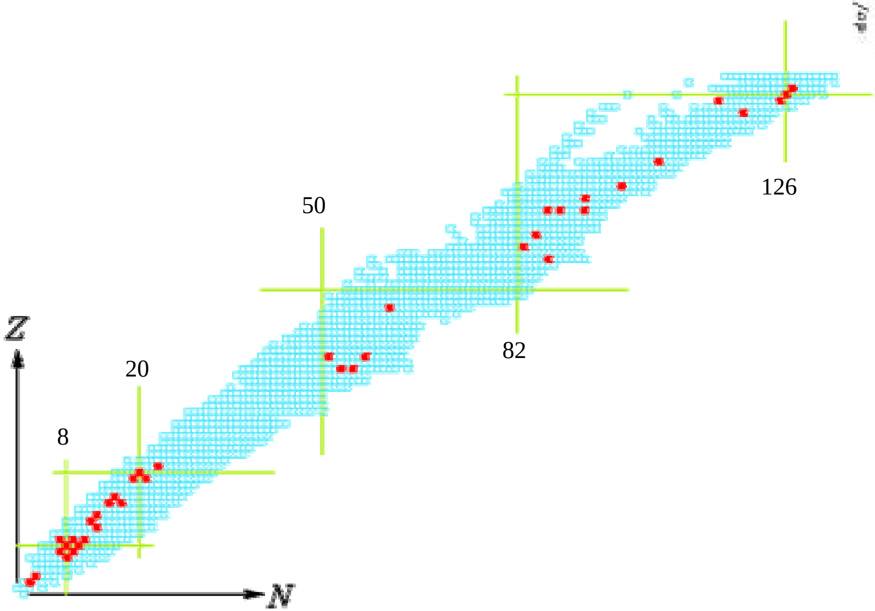
1. 0^- states search with high resolution charge exchange reaction (^{3}He,t) and (^{6}Li,^{6}He)
2. Polarized beam ~ Powerful tool to identify 0^- states with spin observables
3. Pion correlation in the nucleus

$$D_{nn} = \frac{-1}{1+2\,{\sigma_t}/{\sigma_l}} \rightarrow -1$$

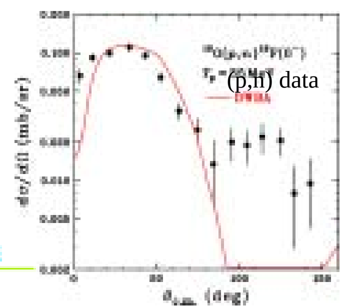
If longitudinal character ~ dominant

Spin Observables = Tool for 0- state Search/Identification

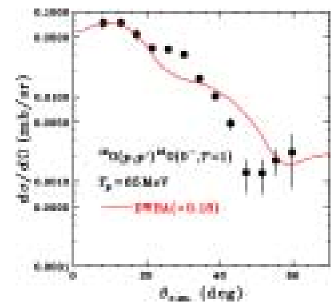
1. Spin transfer
2. High resolution charge exchange reaction

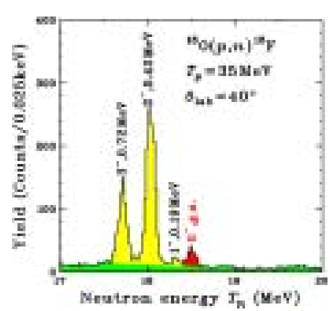


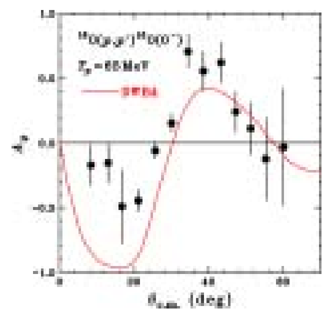
(p,n) data



(p,p') data







H. Orihara et al., PRL 49, 1318 (1982)

K. Hosono et al., PRC 30, 746 (1984)

Microscopic structure of Gamow-Teller states

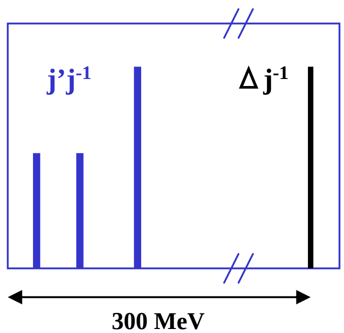
Motivation :

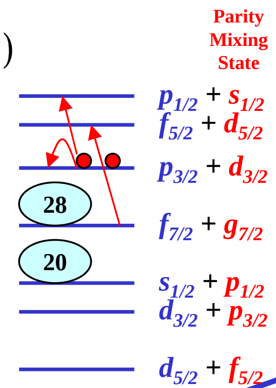
1. Microscopic structure of Gamow-Teller States ~ observed in high resolution (^{3}He,t) : Can not explain with usual shell model
2. Parity mixing state due to pion field in the nuclear medium ~ possible explanation ?

Physics Goal :

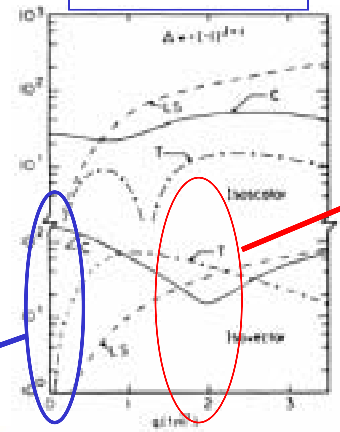
1. Determine the pion response (contribution) to Gamow-Teller states ⇒ obtain the information on parity mixing state
2. Pion distribution in nucleus ~ Surface pion condensation

$$\sigma(q=0) \propto |V_{\sigma\tau}(q=0)|^2 \propto B(GT)$$

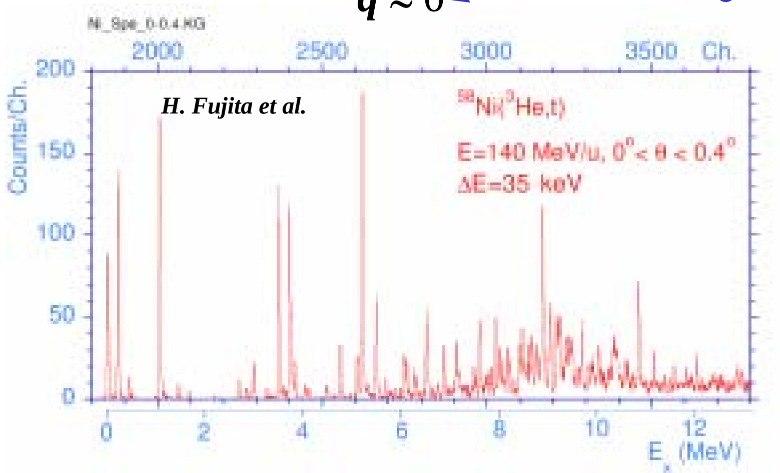




Nuclear Interaction



$q \approx 0$



Simple transition

At large q ≠ 0 ,

1. **Tensor interaction ~ dominant**
2. **Pion correlation ~ large**
3. **Sensitive to pion behavior in nuclei**

Spin transfer measurement

1. **Separate pion / rho-meson contribution**
2. **Identify GT states at 0 degree**

① Identify spin flip (ΔS=1, ΔL=0) states with Polarization Transfer D_{nn} at 0 degree

② At large q, measure the spin transfer :

$$D_{nn} = \frac{\sigma^t(\hat{n}) - \sigma^t(\hat{Q}) - \sigma^l(\hat{q})}{\sigma^t(\hat{n}) + \sigma^t(\hat{Q}) + \sigma^l(\hat{q})} = \frac{-1}{1 + 2\sigma^t / \sigma^l}$$

③ Determine transition density :

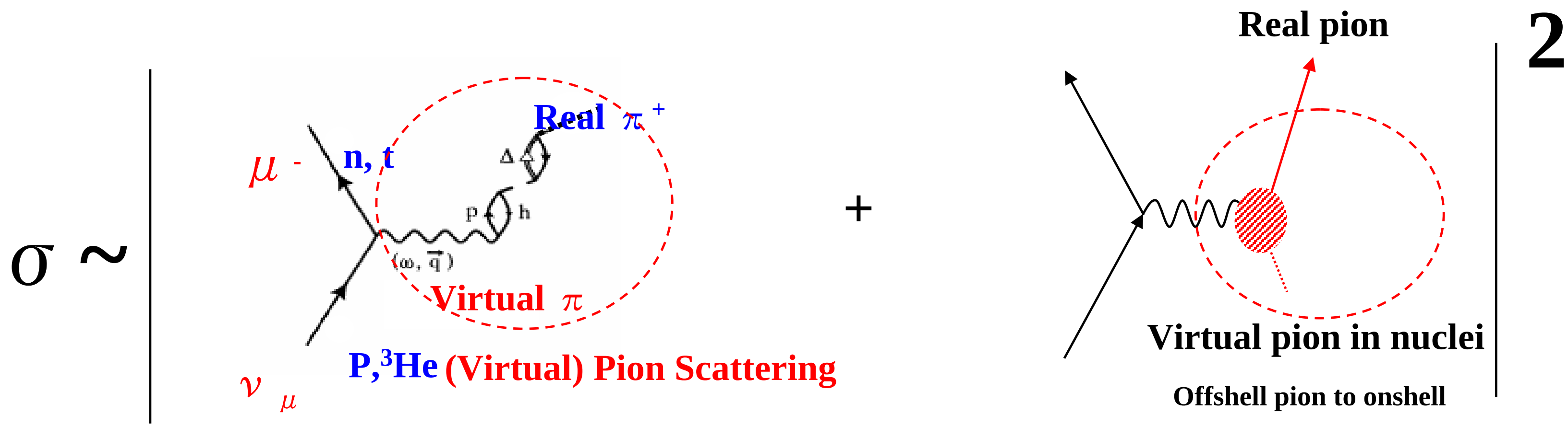
$$\frac{\sigma^t}{\sigma^l} = \left| \frac{\rho^t{}_{fi,\tau}}{\rho^l{}_{fi,\tau}} \cdot \frac{V^t{}_\tau(q)}{V^l{}_\tau(q)} \right|^2$$

④ Discuss the parity mixing state and pion distribution

$$\rho^l{}_{fi,\tau} = \left\langle I_f M_f \left| \sum_j \exp[iq \cdot r_j] \sigma_j \cdot q \tau_j \right| I_i M_i \right\rangle$$

$$\rho^t{}_{fi,\tau} = \frac{1}{\sqrt{2}} \left\langle I_f M_f \left| \sum_j \exp[iq \cdot r_j] \sigma_j \times q \tau_j \right| I_i M_i \right\rangle$$

CPP reaction mechanism



- Neutrino probe ~ can penetrate interior of nucleus ~ volume type
- Hadron probe ~ sensitive to surface

What should be done next

- $g'_{\Delta\Delta}$ ~ measurement accuracy
- pions in nuclei ~ theoretical calculation ~ what should be observed
- Neutrino beam ~ Coherent Pion Production ~ separation difficult
  → measured observables and extracted physics
- MC preparation ~ physics/detector study
- Required specification for the detector
- Detector design

Summary

Nuclear physics with Neutrino Beam

- New probe ~ Neutrino at J-PARC
  - ✓Coherent Pion Production
  - ✓Interior of nucleus ~ Spin response function
- Short range correlation of nuclear force g' ~ phase transition of nuclear matter
- Pions in Nuclei
- Natural extension of Spin-Isospin Physics at RCNP

- Physics discussion, Detector design …..