Coherent Pion Production
induced by neutrino and hadron beam

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• Neutrino beam at J-PARC
• Summary
$\Delta \Delta$ interaction in the nuclear medium
~ short range correlation of $\Delta$-hole: $g'_{\Delta \Delta}$

Density dependence of $g'_{\Delta \Delta}(\rho)$
$\Delta \Delta$ interaction in high density

Hadron beam ~ Low density
Neutrino beam ~ Saturated density
Coherent Pion Production

Coincidence measurement of pion and external probe

Virtual pion prove the pion correlation in the nucleus

Virtual Pion: $\pi^+^*$ ~ interaction ($\omega, q$)

Beam (p, ν)

Real Pion

Virtual pions in the nucleus (G.S.)

Coherent Pion Production
Spin Response in Nuclei

\[ \sigma \cdot q \]

\[ (q, \omega) \rightarrow \pi^+ \]

\[ \pi^{++} \]

n, \mu^- 

p, \nu

Spin Longitudinal Response ~ Pion correlation

Maximum

M. Ericson

\[ \Delta-h \] region

Pion line

Photon line

Pre-see Pion of Pion Condensation

Pion Condensation

\[ q (\text{fm}^{-1}) \]

\[ \omega (\text{MeV}) \]

Long response (MeV/1)
**Longitudinal Response**

- Longitudinal Response ~ Enhancement and Softening

\[ R_L \propto \left| \langle n | \sigma \cdot q | 0 \rangle \right|^2 \]

- Representing $\pi NN$ and $\pi N\Delta$ couplings

- Transverse Response ~ Quenching and Hardening

\[ R_T \propto \left| \langle n | \sigma \times q | 0 \rangle \right|^2 \]

- Transverse Response ~ Quenching and Hardening

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**Diagram**

- **p-h interaction**
  - p-h and $\Delta$-h attractive force from OPE
  - $g' = 0.8$
  - $\pi = 0 \text{MeV}$
  - $V_T = V_p + V_\rho$

- **$\Delta$-h interaction**
  - $N\Delta$ channel
  - $g'_{N\Delta} = 0.4$
Hadron induced CPP Data

Nuclear Structure Model (RPA,...)

R_L~Extraction

Spin Response Function

Input for the analysis of neutrino induced CPP ~ detailed study on reaction mechanism

Effective Interaction: $\pi+\rho+g'$ model

g'_{\Delta\Delta}$ ~ determine

Neutrino induced CPP Data

g'_{\Delta\Delta}$ in saturated density
Effective Interaction

\( \pi + \rho + g' \) model

\[ V_{\text{eff}}(q, \omega) = V_{LM} + V_\pi(q, \omega) + V_\rho(q, \omega) \]

- Landau-Migdal parameters \( \sim \) short range correlation

\[
V_{LM} = \frac{f_{\pi NN}^2}{m_\pi} \left( g'_{NN} \sigma_1 \cdot \sigma_2 \tau_1 \cdot \tau_2 \right) + \frac{f_{\pi \Delta}^2}{f_{\pi NN}} \left( g'_{NN} \left((\tau_1 \cdot T_2)\sigma_1 \cdot S_2 + (\tau_1 \cdot T_2)\sigma_1 \cdot S_2\right) + h.c.\right)
\]

\[
+ \left( \frac{f_{\pi \Delta}^2}{f_{\pi NN}} \right) \left( g'_{NN} \left((T_1 \cdot T_2)S_1 \cdot S_2 + (T_1 \cdot T_2)S_1 \cdot S_2\right) + h.c.\right) \delta(r_1 - r_2)
\]

\( g'_{NN} \quad \boxed{\text{well known from Gamow-Teller resonance}} \)

\( g'_{NN} \quad \boxed{\text{known from Quasi-free scattering}} \)

\( g'_{NN} \quad \boxed{\text{unknown}} \)
Polarization transfer experiment: Quasi-free $^{12}$C(p,n)

RCNP: $T_p=346$ MeV

LAMPF: $T_p=494$ MeV
*T.N.Taddeucci et al., Phys.Rev.Lett.73,3516 (1994)*

$g'_{NN} \sim 0.7$, $g'_{N\Delta} \sim 0.3$

$g'_{NN}=0.7$  
$m^*=0.7m$

$g'_{N\Delta}=0.3$  
$m^*=0.7m$

$g'_{NN}=0.7$  
$g'_{N\Delta}=0.3$
$g'_{\Delta \Delta}$ and pion condensation

$g'_{\Delta \Delta} \sim$ No experimental information

$g'_{\Delta \Delta} \sim$ Sensitive to

- Critical density of pion condensation
- Cooling mechanism of neutron star
- $\Delta$ propagation in the high density matter

$\pi^0$ condensation ($Z=0, g'_{NN}=0.6$)

calculations by Tatsumi et al.

$g'_{\Delta \Delta}$

$\rho_a/\rho_0$

$g'_{\Delta \Delta}$
Inclusive process

- **Proton/³He induced CPP**: $p(³He) + A \rightarrow n(t) + \pi^+ + A_{g.s.}$
- **Neutrino induced CPP**: $\nu + A \rightarrow \mu^- + \pi^+ + A_{g.s.}$

Quasifree $\Delta$ decay  Nucleon knockout  $\Delta$ spreading  Nucleon spreading  CPP

Information on Spin response

Osterfeld, Udagawa
Spin longitudinal response

CPP ~ forward peaked:
Amplitude ~
\((S^+ \cdot q)(S \cdot k_\pi) \sim qk_\pi \cos \theta_\pi\)

\(\theta_\pi = 0\) degree
~ cross section: maximum
~ Spin longitudinal component
\(\text{Dominant}\)

0 degree measurement

Osterfeld, Udagawa
g'_{\Delta\Delta} extraction from CPP

Interaction ~ Virtual Pion

Hole ~ Particle

Nucleus (G.S.)

Observables

- Cross section
- Spectrum shape
- Peak position:

\[ \Delta E \approx \Delta g'_{\Delta\Delta} \frac{h c f_{\pi N\Delta}}{m_\pi^2} \rho_0 \]

Depend on \( g'_{\Delta\Delta} \)

Coincidence measurement of neutron and pion

\( q, p, ^3\text{He} \)
CPP experiments

Hadron probe
• Saclay \((^3\text{He},t^+\)\) ~ resolution: not enough to separate ground state
• LAMPF \((p,n^+\)\) ~ test experiment: shutdown
• RCNP \((p,n^+\) \((^3\text{He},t^+\)\) ~ in progress
  □ study residual interaction with high resolution measurement

Neutrino
\(\Lambda(\bar{s},\bar{d}\cdot\bar{d}^+\)\)A
□ a few GeV region ~ Data: poor
➢ K2K ~ first data at <1.3 GeV>
➢ J-PARC!
Experiment

- $^{12}$C(p,n$\pi^+$)$^{12}$C(g.s.)
- Beam ~ proton 400MeV
- Beam energy resolution ~ $\Delta E$~100keV
- Current ~ 1 nA
- Target ~ $^{12}$C (100mg/cm²)
- Detector
  - Neutron detector ~ $\Delta E$~300 keV
  - $\pi$ detector ~ $\Delta E$~1 MeV
- Identification of CPP
  - select the ground state of residual nucleus
Experimental setup

Charged particle detector in the sweeping magnet

Neutron Counter

Position sensitive Neutron Counter (liq Sci.)
TOF length ~ 70 m
Energy resolution : 300 keV
Detection efficiency : 15 % @150~400 MeV

Multi-anode PMT
~ set far from magnet through WLS fiber

Tracking detector : GEM

Neutron to TOF Counter

Swinger Magnet

Proton to Beam Damp

10 cm

80 cm

scintillator

WLS fiber
Tracking Detector

1. Gas Electron Multiplier detector (GEM)
2. Charged particle (π..) detection in the magnet
3. Detector components
   - Three layers of GEM foil ~ high gain
   - 2dimensional Readout board ~ high resolution
4. Specification
   - high position resolution~ 100μm
   - Effective area~ 300x50 mm
   - radiation tolerance
5. Readout ~ high speed with parallel processing :
   - SpaceWire

![Gain as a function of biased voltage to GEM](image)

![2 dimensional Readout Board](image)
Test Experiment

Neutron Energy Loss Spectrum

CPP event selection
~ need GEM detector for pion tracking

range of CPP event

TOF spectrum of pion counter

Energy loss of two sci.
The present status includes:

- Neutron energy spectrum
  - CPP region ~ enhancement ? ~ detailed analysis continued
  - need much more statistics to confirm CPP
- Background ~ study in progress
  - beam halo
  - Transmission efficiency of the primary beam ~ bad
  - beam optics tuning ~ considered now
- To identify CPP
  - Separate ground state of residual nucleus by missing mass spectrum
  - Tracking information ~ GEM detector is needed next step

Neutrino Beam

- Weak interaction
- Can prove the interior of nucleus
- Cross section ~ behave volume like
- No distortion/absorption
- Adler’s theorem: $M \sim T(\mathcal{K}(q) + N X)$

**Neutrino**
- Good Probe to study the interior of the nucleus
- keep the information of nuclear interior

**Hadron**
- Can not transmit...
- Can investigate residual interaction and response function with high accuracy

- Strong interaction
- Reaction ~ peripheral
- Sensitive to nuclear surface
- Distortion/Absorption effects
Density dependence of $g'$

$S(b) \sim \lambda \sim (A\rho\sigma)^{-1}$

Neutrino

Light ions
Neutrino induced CPP

J. Marteau

Total response per nucleon at $q = 200 \text{ MeV}/c$.

Quasi-free

- Longitudinal $\vec{\rho}$
  - attractive
- Transverse $\vec{\rho}$
  - repulsive

$g'_{NN} = 0.7$, $g'_{N\Delta} = 0.5$, $g'_{\Delta\Delta} = 0.5$

- Peak $g'_{\Delta\Delta}$
- Strength $g'_{\Delta\Delta}$ response function

$\nu_\mu^{16}\text{O}$ differential cross sections ($E_\nu = 1 \text{ GeV}$)

- Total RPA
- $\sigma_{\text{NN}(Q)}$
- $\sigma_{\text{NN}(Q) \text{ RPA}}$
- $\sigma_{\text{NN} (Q)}$
- $\sigma_{\text{NN} (Q)}$
- $\sigma_{\text{NN} (Q) \text{ RPA}}$

We report the result from a search for charged-current coherent pion production induced by muon neutrinos with a mean energy of 1.3 GeV. The data are collected with a fully active scintillator detector in the K2K long-baseline neutrino oscillation experiment. No evidence for coherent pion production is observed and an upper limit of $0.60 \times 10^{-2}$ is set on the cross section ratio of coherent pion production to the total charged-current interaction at 90% confidence level. This is the first experimental limit for coherent charged pion production in the energy region of a few GeV.

PACS numbers: 13.15.+g,25.30.Pt,95.55.Vj
Neutrino induced CPP

Coherent Pion Production data ~ not so much data
First data from K2K ~ GeV energy region  ⏯ NO evidence of CPP
Beam energy ~ 1 GeV
- suitable for Nuclear Physics in the Δ resonance region

Detector ~ LOI(AGS neutrino beam) ~ Liquid Sci. with W.L.S Target
- Proton
- Carbon
- Heavy Nucleus

Detector design in LOI@AGS ν beam
Neutrino induced CPP

E~1 GeV \[\Delta\] resonance region \[\sim \Delta \Delta\] interaction in the nuclear medium
\[\sim \pi \Delta\] propagation in the interior of nucleus

<table>
<thead>
<tr>
<th>(\nu) interaction type</th>
<th>(\nu_\mu n \rightarrow \mu^- p)</th>
<th>(\bar{\nu}_\mu n \rightarrow \mu^- p)</th>
<th>(\nu_\tau + \bar{\nu}_\tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC QE, (\nu_\mu n \rightarrow \mu^- p)</td>
<td>11.395</td>
<td>184</td>
<td>56</td>
</tr>
<tr>
<td>NC El, (\nu_\mu N \rightarrow \nu_\mu N)</td>
<td>4.903</td>
<td>86</td>
<td>22</td>
</tr>
<tr>
<td>CC (\pi^+, \nu_\mu p \rightarrow \mu^- p \pi^+)</td>
<td>3.293</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>CC (\pi^0, \nu_\mu n \rightarrow \mu^- p \pi^0)</td>
<td>725</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>CC (\pi^-, \nu_\mu n \rightarrow \mu^- n \pi^+)</td>
<td>646</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>NC (\pi^0, \nu_\mu p \rightarrow \nu_\mu p \pi^0)</td>
<td>606</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>NC (\pi^-, \nu_\mu p \rightarrow \nu_\mu n \pi^+)</td>
<td>370</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>NC (\pi^0, \nu_\mu n \rightarrow \nu_\mu n \pi^0)</td>
<td>454</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>NC (\pi^-, \nu_\mu n \rightarrow \nu_\mu p \pi^-)</td>
<td>290</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>CC DIS, (\nu_\mu N \rightarrow \mu^- X)</td>
<td>175</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>NC DIS, (\nu_\mu N \rightarrow \nu_\mu X)</td>
<td>64</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CC coh (\pi^+, \nu_\mu A \rightarrow \mu^- A \pi^+)</td>
<td>539</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>NC coh (\pi^0, \nu_\mu A \rightarrow \nu_\mu A \pi^0)</td>
<td>349</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>other</td>
<td>464</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>total</td>
<td>24,364</td>
<td>394</td>
<td>134</td>
</tr>
</tbody>
</table>

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

Nuclear physics with Coherent Pion Production

- \( \Delta\Delta \) interaction in the nuclear medium
- Short range correlation : \( g'_{\Delta\Delta} \)
- Spin longitudinal response function : \( R_L \)

- **Hadron(Proton/3He) Beam** ~ Prove the surface, low density region
  - Detailed study of reaction mechanism, response function
  - Input for the accurate analysis of neutrino induced CPP data
  - proton induced CPP experiment @RCNP ~ test experiment ~ done

- **Neutrino Beam** ~ Prove the interior of the nucleus
  - J-PARC neutrino beam ~ 1 GeV ~ suitable for the \( \nu \)-nucleus physics

- CPP ~ important to know neutrino detector response ~ RICH Particle ID
- Physics discussion, Detector design ~ needed

*Strange Quark Content in the Nucleon by T.-A. Shibata, N.Saito, Y.Miyachi*

*Nuclear Physics ~ \( \Delta\Delta \) interaction in the nuclear matter*

~ pion condensation, cooling mechanism of neutron star

Neutrino Beam
Electron/Photon induced CPP

Suggested by Prof. M. Sakuda

- **Longitudinal Response**
  \[ R_L \propto |\langle n | \sigma \cdot q | 0 \rangle|^2 \]
  - Enhancement and Softening

- **Transverse Response**
  \[ R_T \propto |\langle n | \sigma \times q | 0 \rangle|^2 \]
  - Quenching and Hardening

Can extract Longitudinal response strength by reducing the Transverse component measured by e/\(\gamma\) induced CPP
Tracking Detector: Gas Electron Multiplier

- GEM detector
- Sci 1
- Sci 2
- position 1
- position 2
- trigger
- tracking
- size: 70um
- pitch: 140um
- 200um separation

- charged particle
- aramid carbon (6 μm)
- Drift (3 kV/cm)
- electron avalanche
- Readout Board
- GND
- analog data to ADC

- amp.
- mux.
- analog LSI
- divide

- 307.2
- 50.2
- ~400V
- 200um separation