Nuclear Physics studied by
Neutrino induced Coherent Pion Production

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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 ~ $\pi, \Delta$ propagation in the interior of nucleus
Physics motivation

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

Nuclear force
~ short range component
$\rightarrow$ pion condensation

$\pi$, $\Delta$ propagation
$\rightarrow$ pions in nuclei
$\rightarrow$ surface pion condensation
Nuclear force and short range correlation

- Nuclear force
  - short range correlation of the nuclear interaction
    \[ \Rightarrow 1\pi \text{ exchange } + 1\rho \text{ exchange } + g' \text{ (short range: phenomenological parameter)} \]

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

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

- Critical Density of Pion Condensation
- Finite expectation value of pion in nuclei

- Landau-Migdal parameter
  \[ g' \sim g'_{NN}, g'_{N\Delta}, g'_{\Delta\Delta} \]

- \((N-h)(N-h), (\Delta-h)(N-h), (\Delta-h)(\Delta-h)\) residual interaction

- \(g'_{NN}, g'_{N\Delta} \sim \text{Gamow-Teller region, } g'_{N\Delta} \sim \text{quasi-free scattering}\)

- \(g'_{\Delta\Delta} \sim \text{excitation region } \rightarrow \text{Coherent Pion Production (CPP)}\)
Pion condensation phase in high density nuclear matter

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

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

Relativistic H.F.

Coherent Pion Production

$A(p,n\,\pi^+\!\rightarrow\!A(G.S.),\; A(\nu,\mu^-\pi^+\!\rightarrow\!A(G.S.))$

Coherent Pion Production (CPP)
- Virtual pion emitted from incidence proton beam
- Excite $\Delta$/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.)

Coexistence measurement of neutron and pion

Inclusive measurement

Cross section – spin longitudinal component : dominant

(virtual) pion scattering

Pure longitudinal mode $\sim \sigma \cdot q$

Cross section at forward angle
$\sim$ Longitudinal Response Function
$\rightarrow$ short range correlation $: g'_{\Delta\Delta}$
$\Delta$ resonance region
Neutrino and Hadron Probes

\[ A(\nu, \mu - \pi^+)A \]

**Neutrino ~ Weak interaction**

→ No distortion, absorption

⇒ test the \( \Delta, \pi \) in the interior of nucleus

Adler’s theorem : \( M \sim T(\pi(q) + N \rightarrow X) \)

**Hadron ~ Strong interaction**

→ Distortion, absorption

⇒ peripheral reaction ~ nuclear surface

\[ g'_{\Delta} = 0.33 \]

\[ g'_{\Delta} = 0.4 \]
Distortion effects

\[ \frac{d\sigma}{d\Omega \cdot d\omega} \text{ (mb/ sr MeV)} \]

\[ ^{12}\text{C}(^{3}\text{He}, t) \]
\[ T_{3\text{He}} = 2 \text{ GeV} \]
\[ \theta = 0^{\circ} \]

- Distorted waves
- Point projectile (x0.31)
- Plane waves (x0.19)
Present status

**Hadron probe**
- Sacray \((3\text{He},t\pi^+)\) ~ resolution: poor / shutdown
- LAMPF \((p,n\pi^+)\) ~ test experiment / shutdown
- RCNP \((p,n\pi^+)\) \((3\text{He},t\pi^+)\) ~ in progress

**Neutrino ~ J-PARC !**
\[ A(\nu,\mu\pi^+)A^* \]
→ what should be considered
  • resolution
  • yield
  •.....
**Coherent Pion Production at RCNP**

- $g'_{DD}$ extracted from Coherent Pion Production
  \[ p + A \rightarrow n + \pi^+ + A \text{ (g.s.)} \]

1. **Peak shift from $N$-$D$ residual interaction**
   - $\Delta E = g'_{\Delta\Delta} (\hbar f_{\rho ND} m_{\rho^2}) \square_0$
2. **Longitudinal response function ($R_L$)**
   - dominant at 0 degree
   - $s_{cpp}(0 \square) \rightarrow R_L \rightarrow g' \left( g'_{NN}, g'_{ND} g'_{DD} \right)$
3. virtual pion scattering in target nucleus

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Experiment

- Beam ~ proton 400MeV un-polarized
- Target ~ $^{12}$C (100mg/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
    - $Dx < 100\,$mm
    - $Dq < 1\,$mrad
  - counting rate ~ 100k cps
  - High magnetic field ~ 0.5 $T$
  - space boundary
- GEM detector

Schematic layout of the GEM+NTOF experiment
Tracking Detector: Gas Electron Multiplier

Diagram showing the components of a GEM detector:
- Aramid carbon
- GEM layers (GEM 1, GEM 2, GEM 3)
- Drift field (3 kV/cm)
- Potential difference \( \Delta V \approx 400 \text{V} \)
- Electron avalanche
- Amplification area
- Analog LSI to ADC
- Trigger and tracking

Images depict the physical setup of the GEM detector and readout board.
Readout System

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

Readout Electronics

- Analog-LSI boards
- FPC (one of 14)
- ~2000ch

I/O Board
- Flash ADC
- Analog MUX
- CPLD
- Trig/Ctrl

Sw host

Space Wire Protocol

Va32_Rich2

SW host
Experimental status

- **Hardware**
  - Trigger scintillator with WLS fiber
  - GEM detector ~ prototype
- **Experiment and analysis Status**
  - Beam: proton (392MeV, <30nA)
  - Target: $^{12}$C (113mg/cm²)
  - 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 $\delta$ information
    - reconstruction with high position resolution

**Feasibility check ~ this year**
**Data production run ~ this year/next year**
Neutrino induced CPP

$E = 1 \text{ GeV} \rightarrow \Delta$ resonance region $\sim \pi, \Delta$ propagation in the interior of nucleus

$10^{-15} \text{ fm}^2/\text{MeV}$
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

Quasi-free

Longitudinal → attractive

Transverse → repulsive

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

$g' \Delta \Delta$

Critical density of pion condensation

M. Nakano et al.
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

**Appeared Phenomena**

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

2. Nuclear force mediated by pion
~ Strong tensor force

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

Include pion exchange explicitly in the mean field

**Simple transition to study the pion behavior in the nucleus**

1. Gamow-Teller states (GT):
\[
\Delta S=1, \Delta L=0 \text{ ~ interaction from pi/rho-meson exchange}
\]
Polarized \(^1\)He beam \(\Rightarrow\) separate \(\pi/\rho\) response to GT

2. Pion-like 0\(^-\) states:
Carry a quantum number of pion
Polarized \(^3\)He/\(^6\)Li beam \(\Rightarrow\) 0\(^-\) state search/identify
Pions in nuclei

Volume type or Surface type distribution?

![Graph showing intrinsic energy of $^{12}$C as a function of pion number expectation.](image)

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

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

Spin Observables = Tool for $0^-$ state Search/Identification
1. Spin transfer
2. High resolution charge exchange reaction

$$D_{nn} = \frac{-1}{1 + 2 \frac{\sigma_f}{\sigma_i}} \rightarrow -1$$

If longitudinal character ~ dominant

H. Orihara et al., PRL 49, 1318 (1982)  
K. Hosono et al., PRC 36, 746 (1984)
Microscopic structure of Gamow-Teller states

Motivation:
1. Microscopic structure of Gamow-Teller States ~ observed in high resolution (³He,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

\[ \sigma(q = 0) \propto |V_{aa}(q = 0)|^2 \propto B(GT) \]

300 MeV

\[ q \approx 0 \]

Parity Mixing State

At large \( q \neq 0 \),
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

Identify spin flip (\( \Delta S=1, \Delta L=0 \)) states with Polarization Transfer \( D_{nn} \) at 0 degree

\[ D_{nn} = \frac{\sigma'(\hat{n}) - \sigma'(\hat{Q}) - \sigma'(\hat{q})}{\sigma'(\hat{n}) + \sigma'(\hat{Q}) + \sigma'(\hat{q})} = \frac{-1}{1 + 2\sigma'/\sigma'} \]

Determine transition density:

\[ \frac{\sigma'}{\sigma'} = \left| \frac{\rho'_{\mu,r} \cdot V'_{r}(q)}{\rho'_{\mu,r} \cdot V'_{r}(q)} \right|^2 \]

Discuss the parity mixing state and pion distribution

\[ \rho'_{\mu,r} = \left( I, M_{f} \left| \sum_{r} \exp[i q \cdot r] \sigma_{r} \cdot q_{r} I, M_{i} \right. \right) \]

\[ \rho'_{\mu,r} = \frac{1}{\sqrt{2}} \left( I, M_{f} \left| \sum_{r} \exp[i q \cdot r] \sigma_{r} \times q_{r} I, M_{i} \right. \right) \]
CPP reaction mechanism

\[ \sigma \sim \mu^- \rightarrow n, t \rightarrow (\omega, \pi) \rightarrow P, {}^3\text{He} \rightarrow \text{(Virtual) Pion Scattering} \]

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

Real pion

Virtual pion in nuclei

Offshell pion to onshell
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 ….