コヒーレント中間子生成とデルタ領域のスピン・アイソスピン物理

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Introduction
(Same as summary)

- **Spin-isospin responses have been widely studied via**
  - GT at small q&ω
    - (3He,t), (p,p'), (p,n)
  - QES at large q (1-2 fm^{-1}) and medium ω (100 MeV)
    - (p,n) (as well as (p,p'))
  - Spin-longitudinal at wide q and small ω
    - (p,n), (p,p') (Dispersion matching)
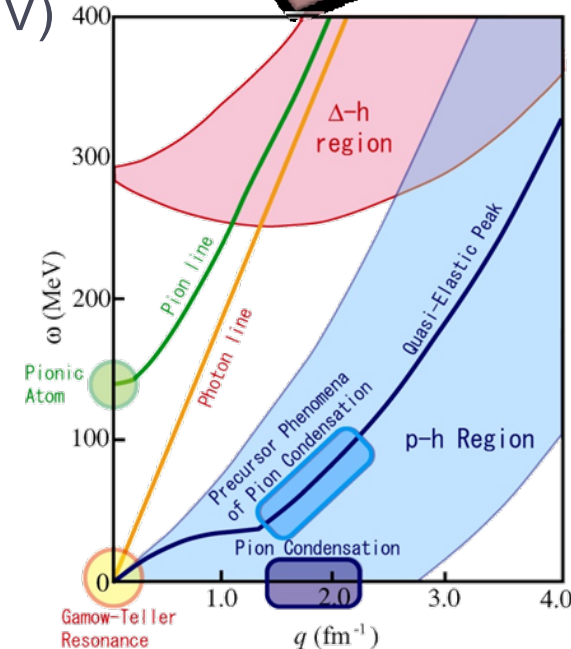 - Pionic atoms at small q and large ω (m$_\pi$)
    - (d,^{3}He), (p,^{2}He)
- **In progress**
  - GT at small q and medium ω
    - ICHO/SHARAQ at RIBF by U-Tokyo
- **NOT sufficiently explored region**
  - Δ region at large ω (200-400 MeV)

Unexplored (target) region

Goal: Understand spin-isospin responses in wide (q,ω) in a unified way
HowTo: 1. Polarization transfer observables of (p,n)
2. Coherent Pion Production (CPP) via (p,nπ^+) — **with GeV "pol." beam**

Nuclear Correlations and Δ Effects

- $\pi + \rho + g'$ model

  $$V^{\text{eff}}(\mathbf{q},\omega) = V_{\text{LM}} + V_\pi(\mathbf{q},\omega) + V_\rho(\mathbf{q},\omega)$$

- Landau-Migdal parameters: g'

$$V_{LM} = C_0 \Big[g'_{NN}(\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)$$

$$+ \Big\{ \frac{f_{\pi N\Delta}}{f_{\pi NN}} g'_{N\Delta}\big((\sigma_1 \cdot S_2)(\tau_1 \cdot T_2) + (\sigma_1 \cdot S_2^+)(\tau_1 \cdot T_2^+)\big)$$
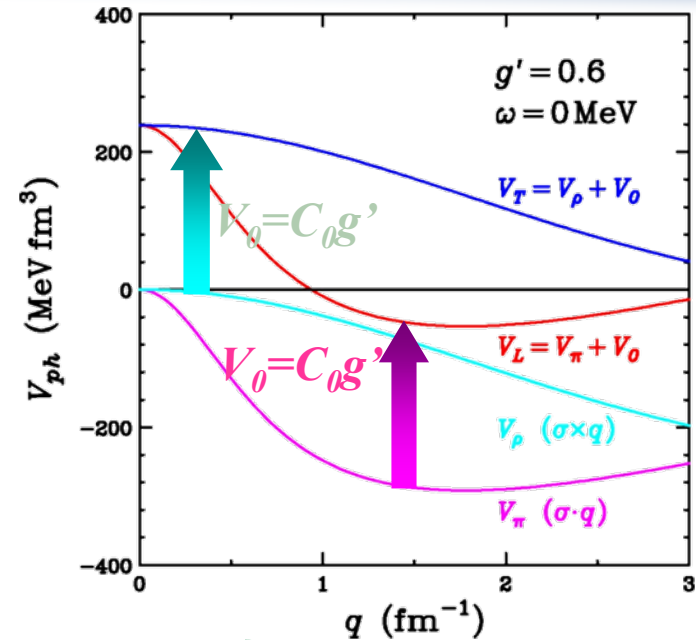
$$+ \frac{f_{\pi N\Delta}^2}{f_{\pi NN}^2} g'_{\Delta\Delta}(S_1 \cdot S_2^+)(T_1 \cdot T_2^+) \Big\} + (1 \leftrightarrow 2) \Big]$$

- g'_{NN}: Repulsion at $q=0$
  - Energy of GTGR

Exp.

- $g'_{N\Delta}$: Coupling between N and Δ at $q=0$
  - GT quenching

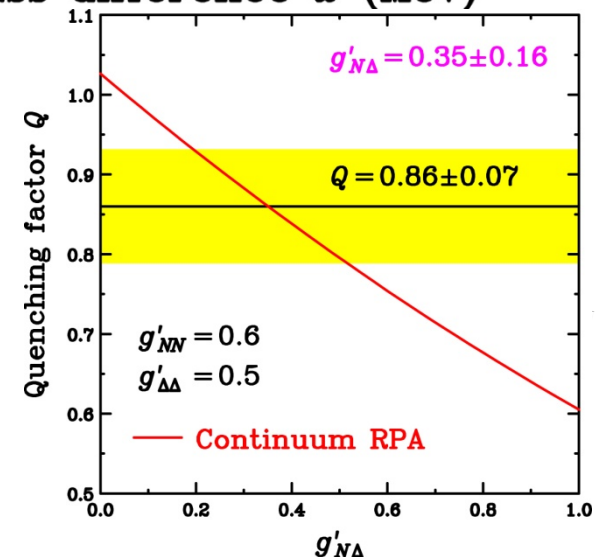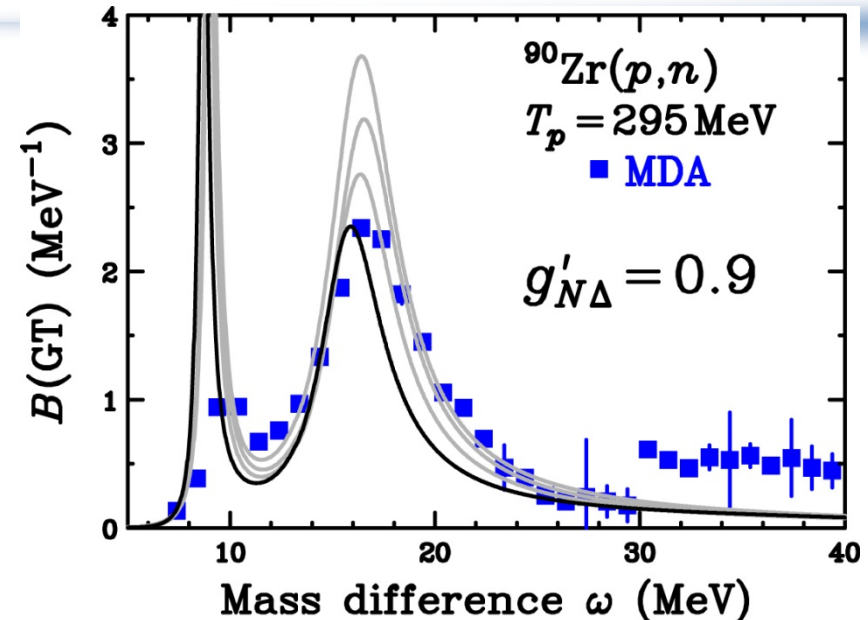*Exp.*

- $g'_{\Delta\Delta}$: Few experimental information
  - PT and CPP measurements are sensitive to $g'_{\Delta\Delta}$

$g' = 0.6$
$\omega = 0 \, \text{MeV}$

$V_0 = C_0 g'$

$V_0 = C_0 g'$

$V_T = V_\rho + V_0$

$V_L = V_\pi + V_0$

$V_\rho \;(\sigma \times q)$

$V_\pi \;(\sigma \cdot q)$

V_{ph} (MeV fm^3)

q (fm^{-1})

g's affect V^{eff} at large q

# GT Strength and Landau-Migdal Parameters

- g′ Dependence of GTGR
  - RPA(1p1h) by Ichimura group
  - GTGR peak position
    - **Strongly depends on g'_{NN}**
      - $g'_{NN}=0.6\pm0.1$
    - Weak $g'_{N\Delta}$ dependence
  - GTGR strength
    - **Quenched with $g'_{N\Delta} > 0$**

- $g'_{N\Delta}$ Dependence of Q
  - *Q=0.86±0.07(quadratic sum of errors)*
  - Q evaluated in RPA
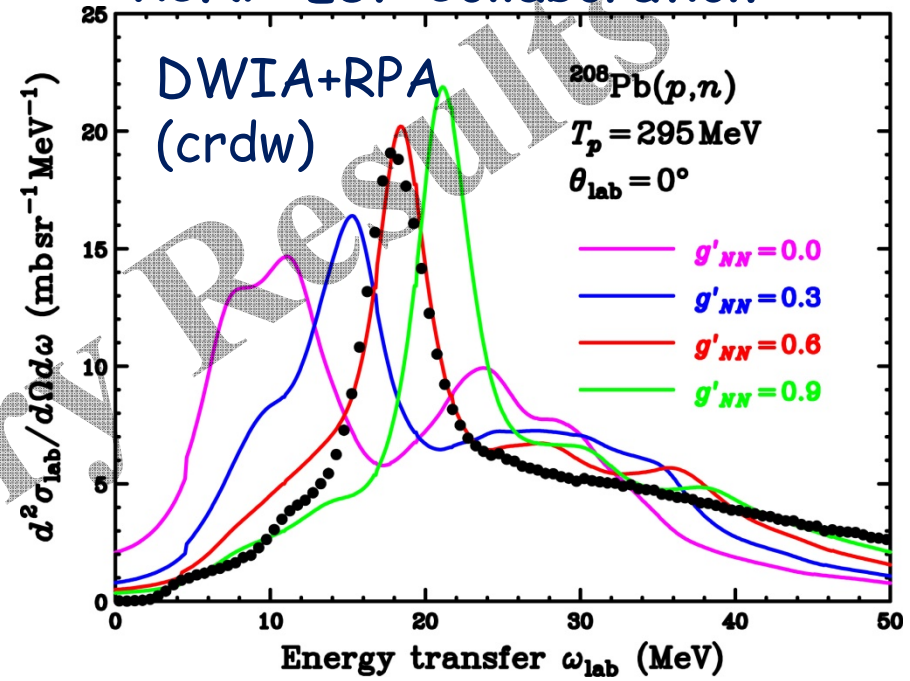   - Strongly depends on $g'_{N\Delta}$
      - $g'_{N\Delta}=0.35\pm0.16$

$^{90}Zr(p,n)$
$T_p = 295\,MeV$
■ MDA
$g'_{N\Delta} = 0.9$

$g'_{N\Delta} = 0.35\pm0.16$
$Q = 0.86\pm0.07$
$g'_{NN} = 0.6$
$g'_{\Delta\Delta} = 0.5$
— Continuum RPA

GT Strength and g'$_{NN}$ for ^{48}Ca and ^{208}Pb

M. Sasano et al.
RCNP-E272 Collaboration
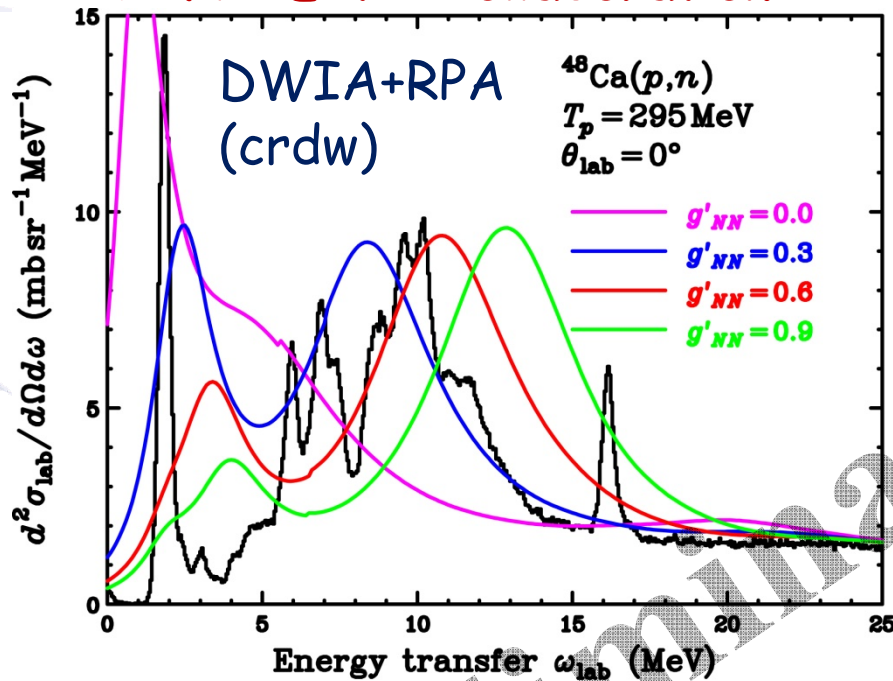
T.W. et al.
RCNP-E57 Collaboration

g'$_{NN}$=0.5 for ^{48}Ca

g'$_{NN}$=0.6 for ^{208}Pb

g'$_{NN}$=0.5-0.7 at q=0 (Common for A=48-208)

Pion Condensation in Neutron Star
-EOS and Pion Cooling-

- Under universality ansatz

  – $g'_{NN}=g'_{N\Delta}=g'_{\Delta\Delta}=0.6 \sim 0.7$

  – Critical density: $\rho_c \sim 4\rho_0$

  – Pion condensation "does not" occur

- With new information on g′

  – Universality ansatz "does not" hold

    • $g'_{NN}=0.6\pm0.1$, $g'_{N\Delta}=0.35\pm0.16$

  – $\rho_c \sim 2\rho_0$ (for $g'_{\Delta\Delta}=0.5$)

    • Pion condensation would be realized in N.S. (3C58 etc.)

    • π-cond. accelerates NS cooling

Critical density ρ_0 is sensitive to $g'_{\Delta\Delta}$ → Experimental determination $g'_{\Delta\Delta}$ is important
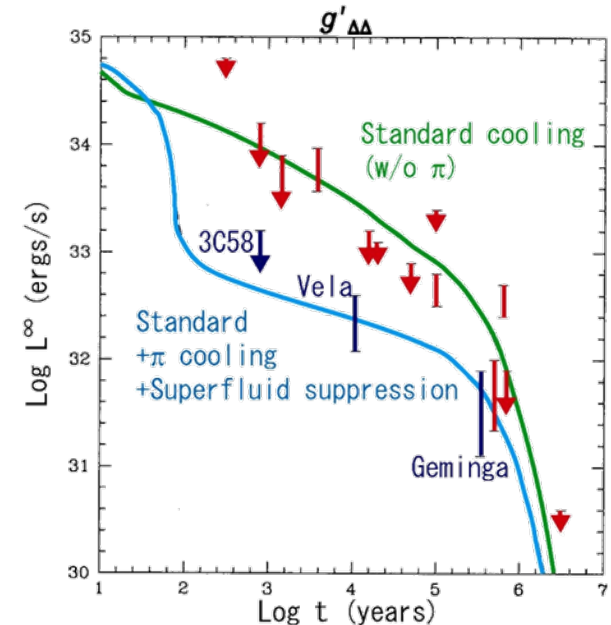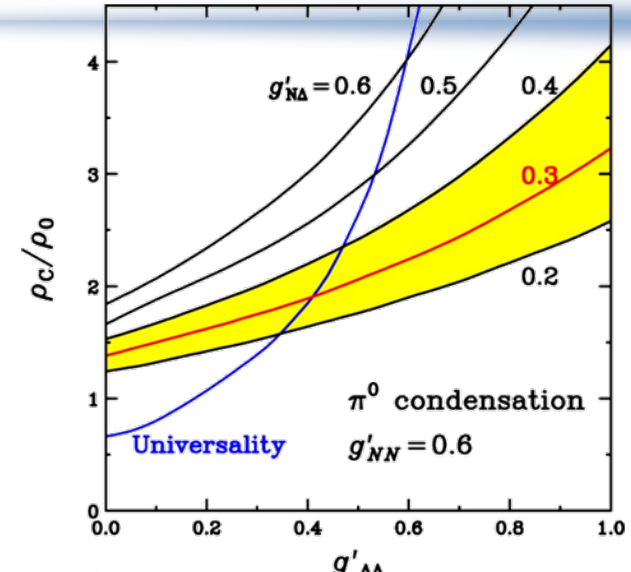
Pionic Enhancement in QES

Precursor of Pion Condensation

- Pionic ID_q (^{12}C, ^{40}Ca) at q=1.7 fm^{-1}
  - RCNP data
    - *$\theta=22°, T_p=346$ MeV*
  - LAMPF data
    - *$\theta=18°, T_p=494$ MeV*
- Pionic Enhancement
  - Exp. Data > Free *(w/o Correlation)*
  - RPA is sensitive to *g'_{NN}* and *$g'_{N\Delta}$*
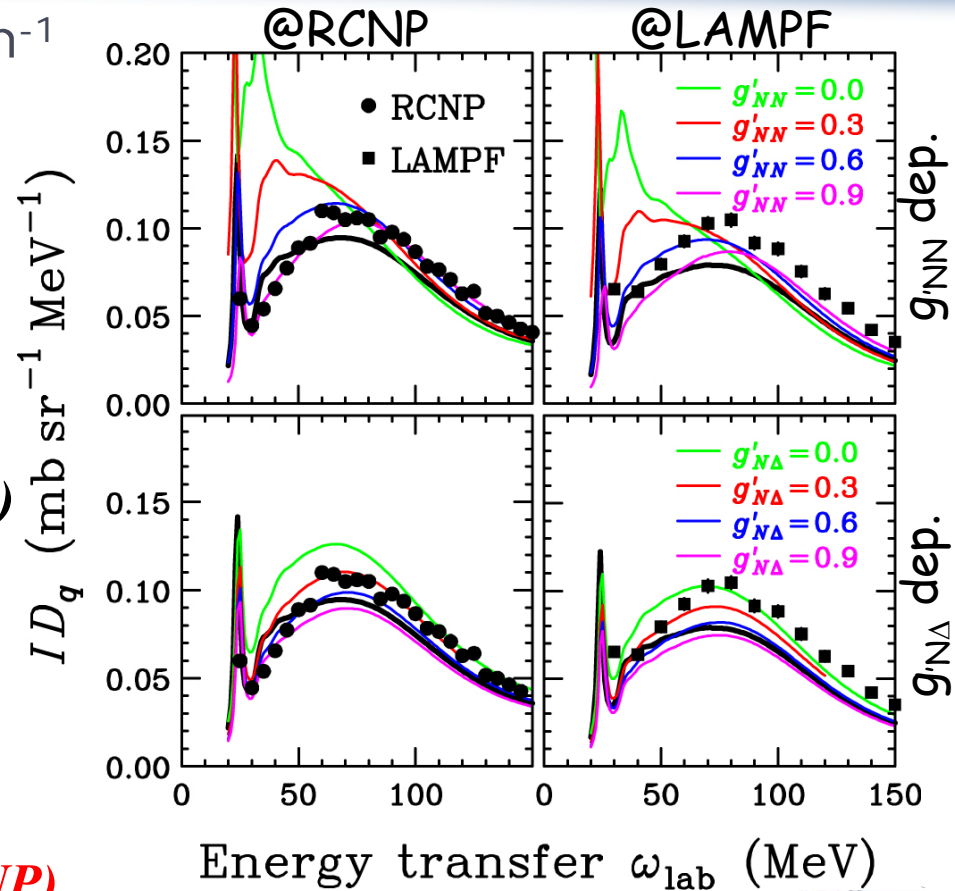 - RPA is insensitive to *$g'_{\Delta\Delta}$*
- Landau-Migdal Parameters
  - *$g'_{NN} \sim 0.7$*
  - *$g'_{N\Delta} = 0.2$(LAMPF) — 0.4(RCNP)*
  - Consistent with g's deduced from GT
    - *$g'_{NN}=0.6\pm0.1$, $g'_{N\Delta}=0.35\pm0.16$*
  - *q-dependence of g's is weak*

T. Wakasa et al.
Phys. Rev. C 69, 054609 (2004)
T. N. Taddeucchi et al.
Phys. Rev. Lett. 73, 3516 (1994)

Summary of our previous experiments
─*Remaining subjects*─

- **g'$_{NN}$ > g'$_{N\Delta}$ (universality does NOT hold)**
- q-dependence of g'$_{NN}$ and g'$_{N\Delta}$
  - q=0 from GT
  - q=1.7 and 2.0 fm^{-1} from QES
  - **q-dependence of g' is weak**
    - Consistent with theoretical predictions
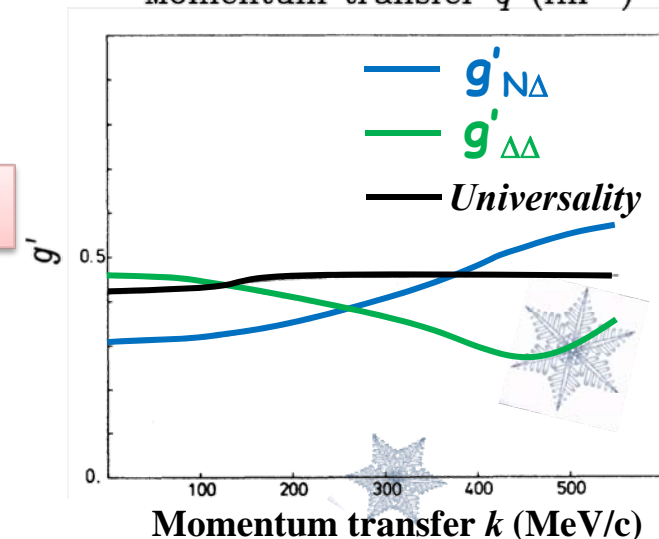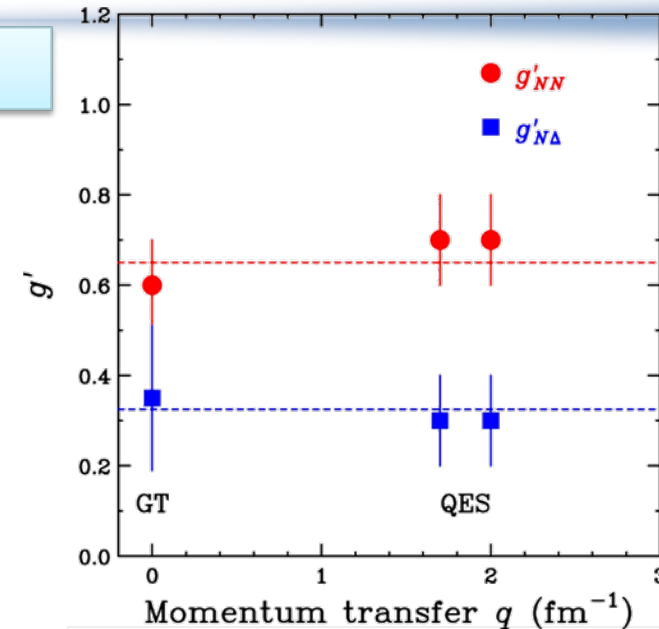   - W.H.Dickhoff et al.
        Phys. Rev. C 23, 1154 (1981)
  - Small g'$_{N\Delta}$ produces largely attractive spin-longitudinal (pionic) residual interaction
    - Pion condensation in N.S. : More likely
- **NO information on g'$_{\Delta\Delta}$ (Last unknown)**
  - g'$_{\Delta\Delta}$ is important to determine ρ_C for pion condensation
  - *CPP and PT measurements are promising to determine g'$_{\Delta\Delta}$ experimentally*
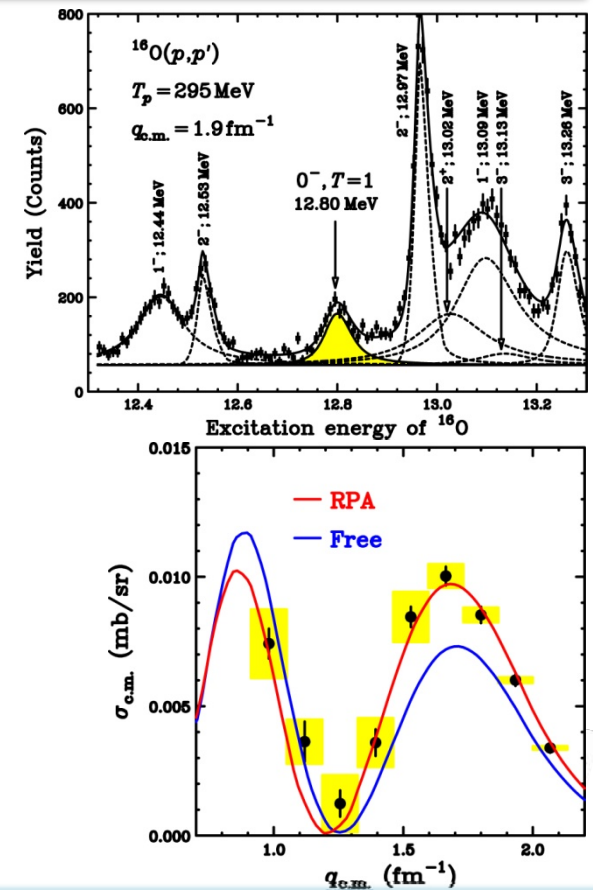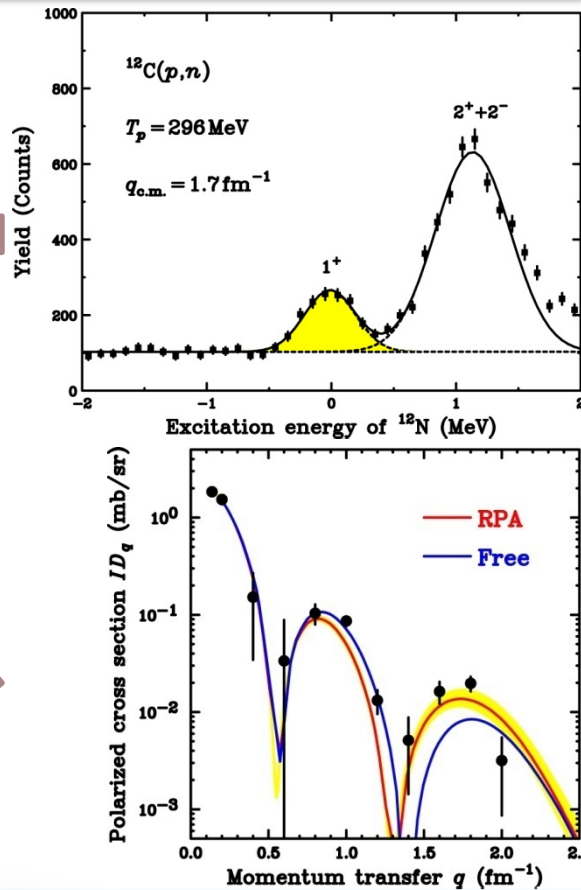
Other evidences for pionic correlations and enhancements observed at RCNP

$^{12}C(p,n)^{12}N(g.s.,1^+)$ at 296 MeV
M.Dozono, T.W. et al., PLB 656(2007)38.

$^{16}O(p,p')^{16}O(0^-,T=1)$ at 295 MeV
T.Wakasa et al., PLB 632(2007)485.

PTO
(D_{ij})

High resolution and/or PTO(D_{ij}) measurements are important and powerful

Physical Processes Important in Δ Region

- **Spin-isospin responses important in Δ region**
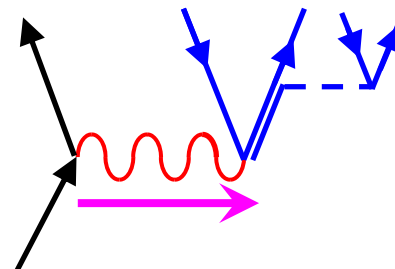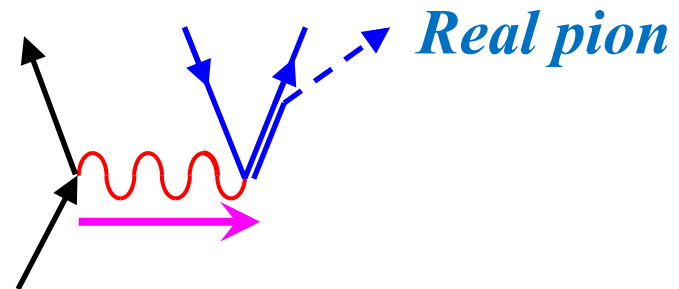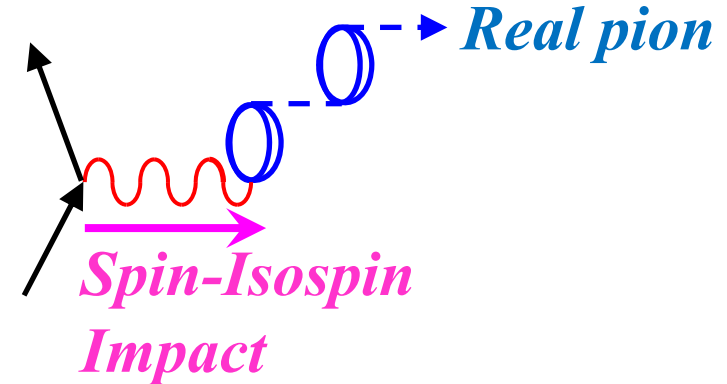 - Coherent Pion Production
    - Pions in final state

  - Quasi-free Δ decay
    - Δ (in Δ-h) decays into π + N
    - Pions in final state

  - Δ spreading
    - Δ (in Δ-h) interacts with N (Δ conversion process)
      - Δ + N → N + N
    - No pions in final state

Real pion

Spin-Isospin Impact

Real pion

Inclusive Charge-Exchange Spectra in GeV region
Signatures of CPP process in previous exp. ?

- CPP has been considered as a reason of
  the downward energy shift of the Δ resonance peak

  - (^{3}He,t) at 2 GeV
    - *D. Contardo et al. PLB168,331 (1986)*
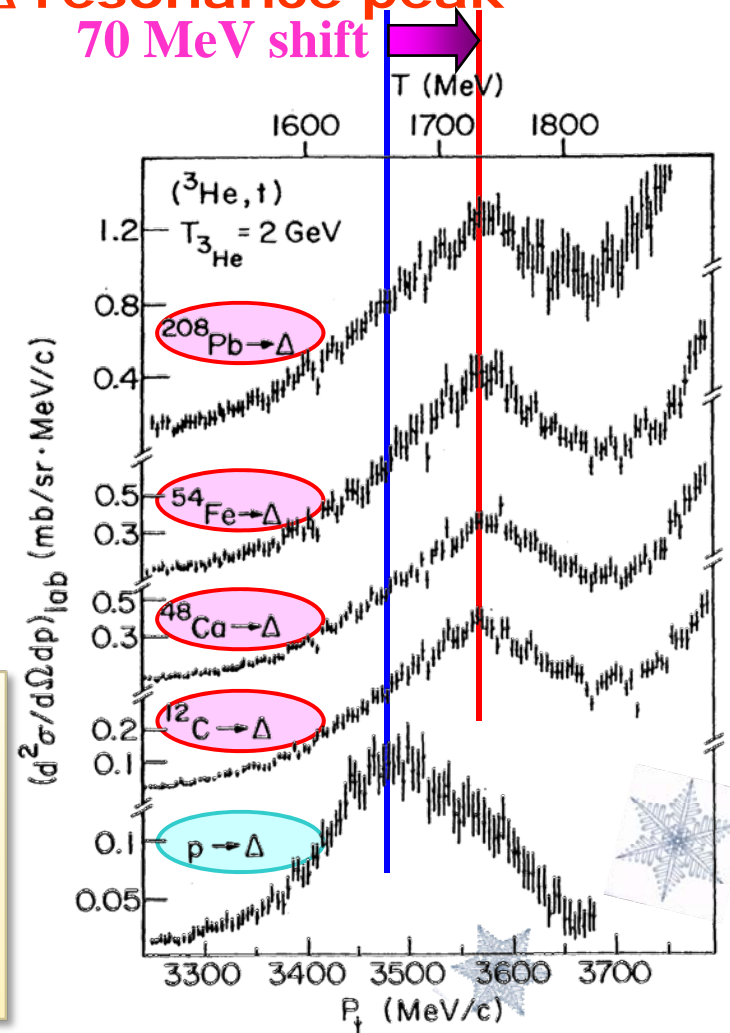 - $p(^3\mathrm{He},t)$ peaks at T_t=1675 MeV
    (ω=325 MeV)
    - Shift from m_Δ-m_N=294 MeV is due to the q-dependence of form factors.
  - $A(^3\mathrm{He},t)$ peaks at T_t=1745 MeV
    (ω=255 MeV)
    - 70 MeV shift from $p(^3\mathrm{He},t)$
      - 40 MeV shift is due to change in the Δ self-energy (mass) in nuclear mean field
      - Leaving 30 MeV shift would be due to nuclear correlation effects including CPP

Sensitivity to pionic correlations
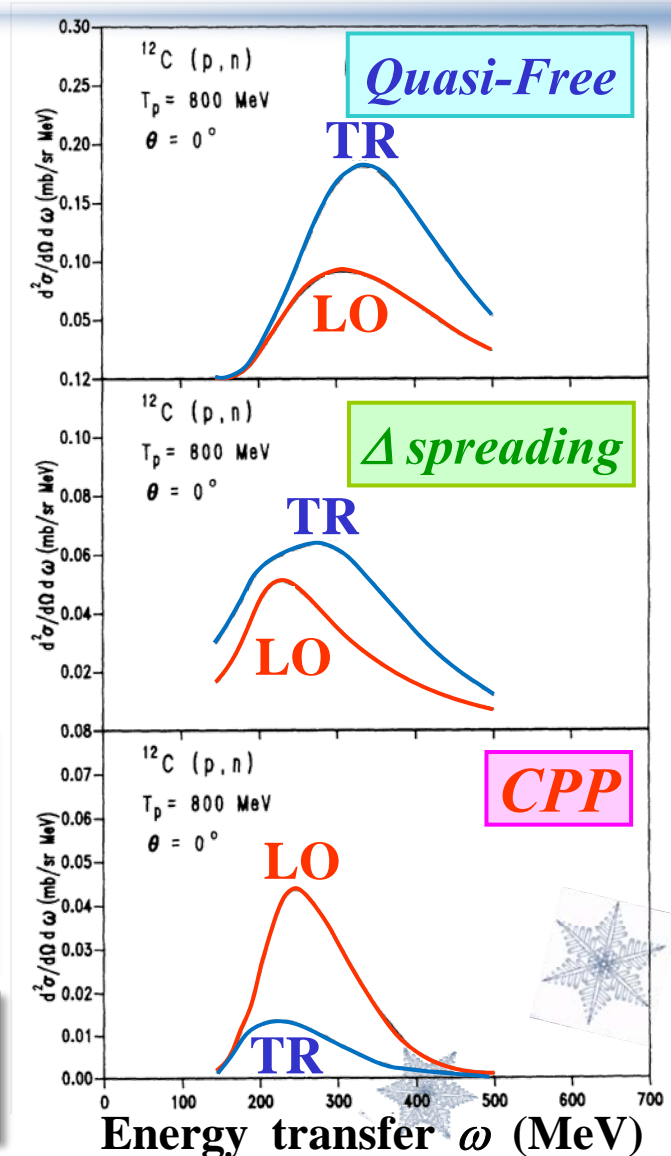## ─ *Ratio of spin-longitudinal and spin-transverse modes* ─

- **Real (Experimental) impact is spin-isospin interaction via (p,n)**
  - NOT a pure (virtual) pion
  - Excite several J^π modes
    - Spin-longitudinal (LO:pionic)
    - Spin-transverse (TR:non-pionic)
- **Theoretical calculations**
  - ^{12}C(p,n) at 800 MeV and 0°
  - Residual int. with g'$_{NN}$=0.6, g'$_{N\Delta}$=g'$_{\Delta\Delta}$=0.33
    - T.Udagawa et al. Phys. Rev. C 49, 3162 (1994)
  - TR (non-pionic) modes are dominant in Quasi-free and Δ-spreading
    - PT measurements are needed to study LO (pionic) modes
  - LO (pionic) is dominant in CPP
    - *Sensitive to pionic correlations in nuclei*

^{12}C (p,n) T_p = 800 MeV θ = 0° — *Quasi-Free* (TR, LO)

^{12}C (p,n) T_p = 800 MeV θ = 0° — *Δ spreading* (TR, LO)

^{12}C (p,n) T_p = 800 MeV θ = 0° — *CPP* (LO, TR)

Energy transfer ω (MeV)

PT Observables in Δ region
$^{12}C(p,n)$ at 795 MeV (LAMPF)

- **Unpolarized cross section**
  - Peak shift to lower ω
    $\Rightarrow$ Nuclear correlation ?
  - Significant enhance from DWIA+RPA
    - Same as QES (@q=1.7fm-1)
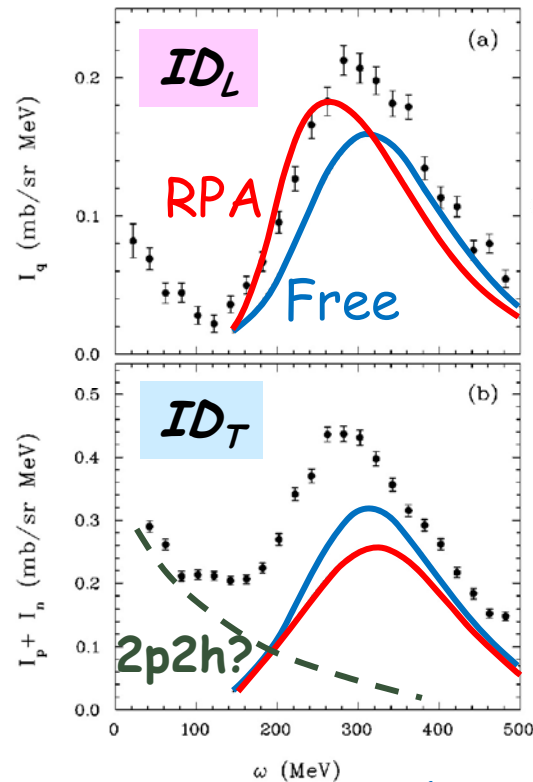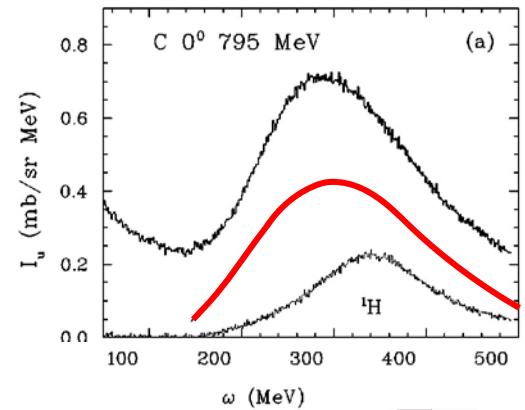   - Same reason ?
- **Polarized cross section**
  - Spin-longitudinal ID_L
    - Consistent with DWIA+RPA
      g'$_{NN}$=0.6, g'$_{N\Delta}$=g'$_{\Delta\Delta}$=0.4
  - Spin-transverse ID_T
    - Significant enhancement
    - Contribution from 2p2h etc. ?

D.L.Prout et al., PRL 76(1996)4488.

Simultaneous measurement/interpretation(DWIA+RPA) for GT and Δ region on ^{90}Zr/^{208}Pb(p,n) is very interesting
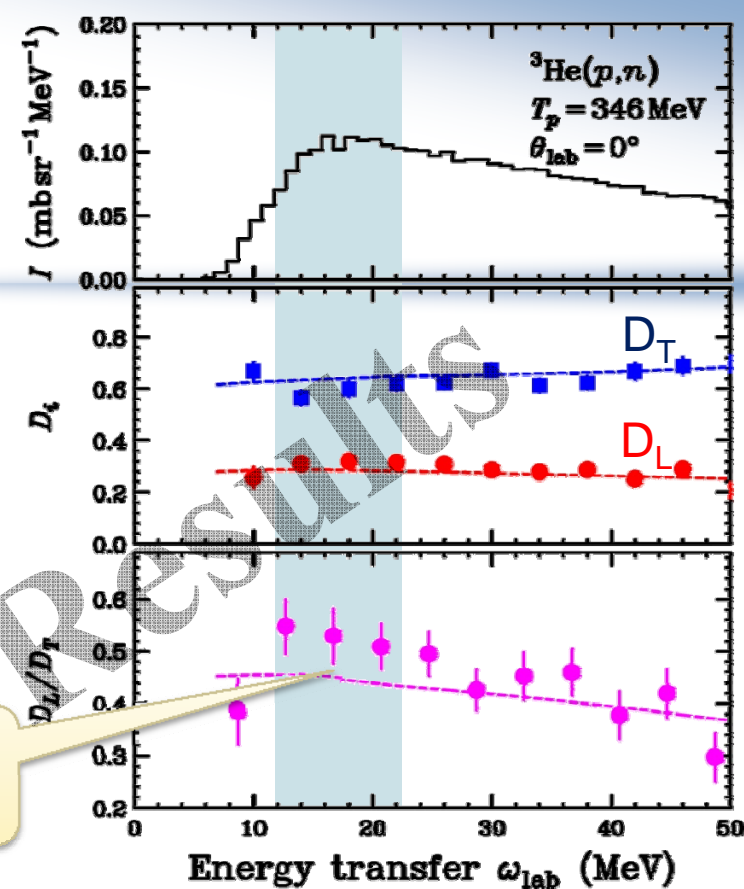
Power of PTO
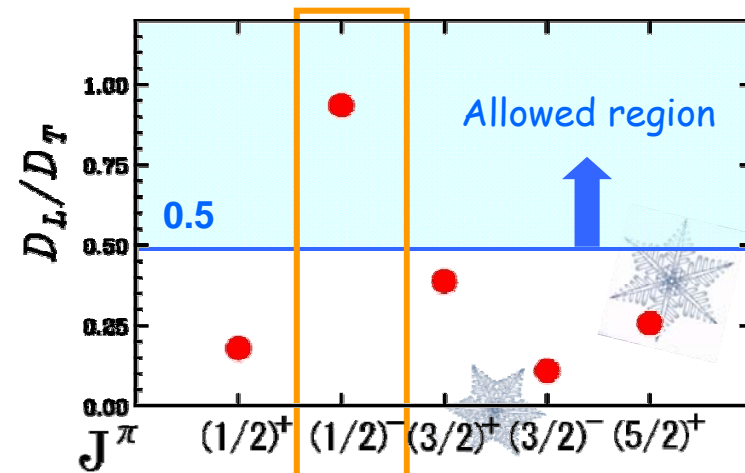## *Three Nucleon Force for T=3/2*

E.Ihara at Kyushu (RCNP-E300)

- **3N system with T=3/2**
  - NO bound/resonance state
    - Faddeev calc. with 2NF
  - **If a resonance exists ⇒ Evidence for 3NF with T=3/2**
- **³He(p,n) at 0 degrees**
  - Large B.G. from QES
  - Shape (c.s.) of QES is complicated
    - Pauli blocking, q-distribution, etc.
    - B.G. subtraction is difficult
  - PT observables are sensitive to Jp

If strength with J^π is concentrated as resonance ⇒ Evidence will be clearly observed in PTO

Resonance $D_L/D_T > 0.5$

$^3\mathrm{He}(p,n)$
$T_p = 346\,\mathrm{MeV}$
$\theta_{lab} = 0°$

D_T

D_L

$I\ (\mathrm{mbsr}^{-1}\mathrm{MeV}^{-1})$

D_t

D_L/D_T

Energy transfer ω_{lab} (MeV)

DWIA prediction

Allowed region

0.5

D_L/D_T

J^π $(1/2)^+$ $(1/2)^-$ $(3/2)^+$ $(3/2)^-$ $(5/2)^+$

Physics with GeV Polarized Beams

Isovector (Spin) Monopole Resonance

- **Isovector (spin) monopole**

$$O_{IVSM} = \sum_i r_i^2 \sigma_i \tau_i \qquad O_{IVM} = \sum_i r_i^2 \tau_i$$
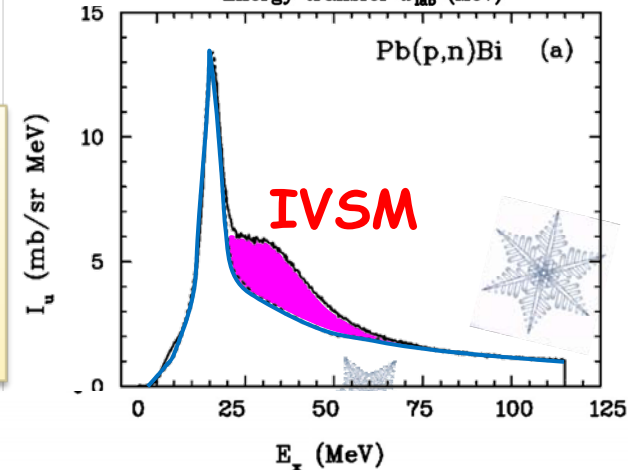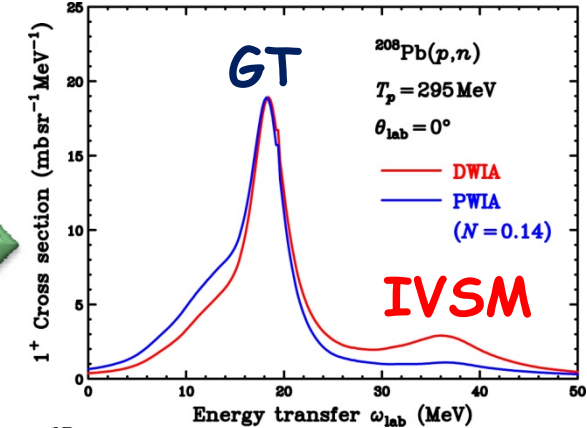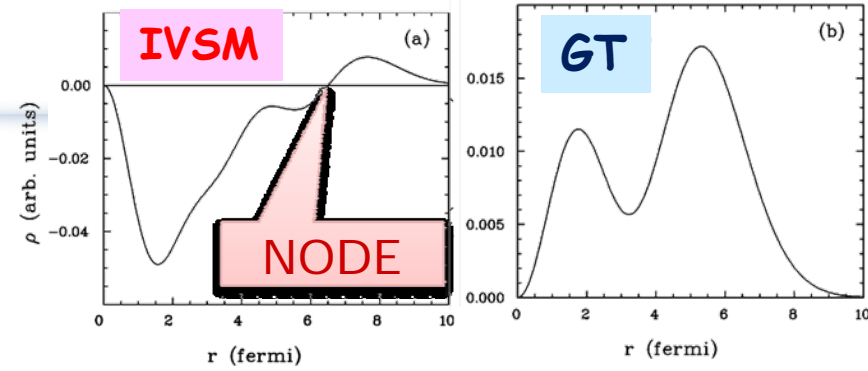

  – A node at nuclear surface
  - Excited by surface probe
  - NOT excited by volume probe
    (Insensitive at RCNP energies)

- **Evidence for IVSM is observed at LAMPF**
  – 795 MeV at LAMPF (Surface-like)
  – 200 MeV at IUCF (Volume-like)

- **IVSM is clearly excited by (p,n) at ~ GeV**
- **PT observables are useful to assign J^π=1$^+$**
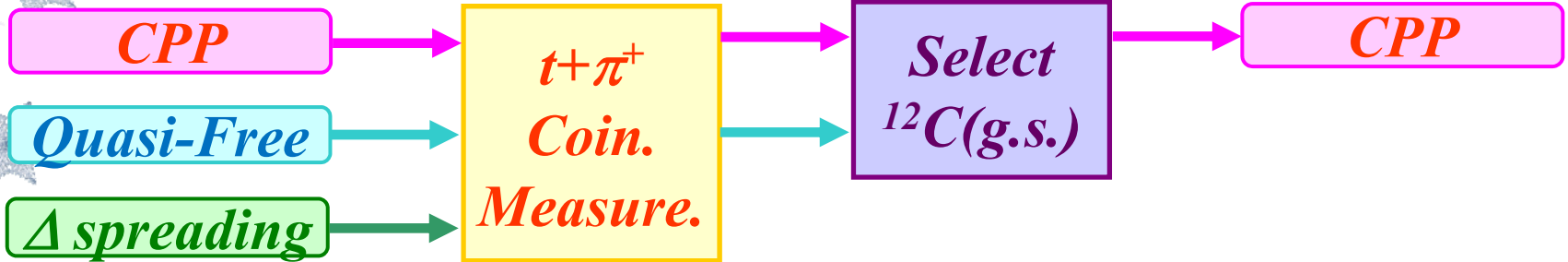 *(PT observables are sensitive to J^π)*

D.L.Prout et al., PRC 63(2000)014603

How to distinguish CPP from other processes

- **Main processes in Δ region are**
  - Coherenet Pion Production
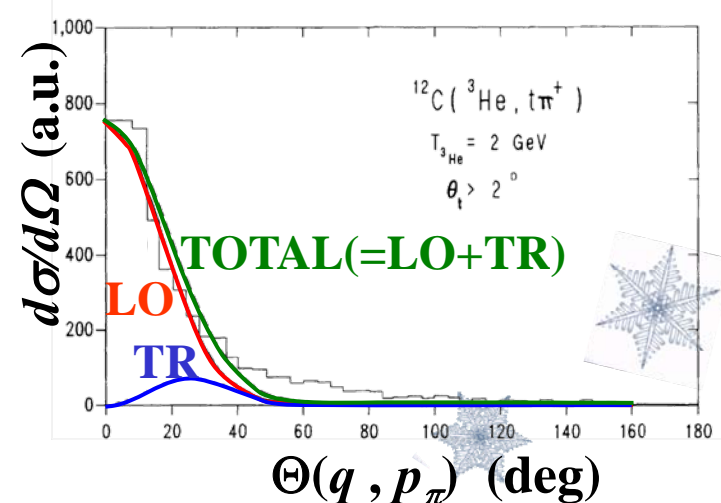 - Quasi-Free Δ decay

  } *Pions in final state*

  - Δ spreading

  ------------------------- *No pions in final state*

CPP	→	$t+\pi^+$ Coin. Measure.	→	Select ^{12}C(g.s.)	→	CPP
Quasi-Free	→					
Δ spreading	→					

- **Measure correlation between momentum-transfer q and momentum $p_{\pi+}$ of pion**
  - Strong (parallel) correlation has been expected
    - T.Udagawa et al. Phys. Rev. C 49, 3162 (1995)

$^{12}C(^{3}He, t\pi^+)$
$T_{^3He} = 2$ GeV
$\theta_t > 2^\circ$

TOTAL(=LO+TR)
LO
TR

$d\sigma/d\Omega$ (a.u.)

$\Theta(q, p_\pi)$ (deg)

CPP Experiment at Saturne

- $^{12}C(^3He, t\pi^+)^{12}C$(g.s.) at 2 GeV and $\theta_t \sim 0°$
  - T_t=2GeV: Dispersion matching was tried
    - poor energy resolution?
  - θ_{3He} = -1° ~ 4°
    - Analyzed by D-magnet and detected by DCs
    - Poor energy resolution of 15 MeV
  - θ_π=20° ~ 132°
    - Analyzed and detected by CDC
    - Poor momentum resolution of 10%

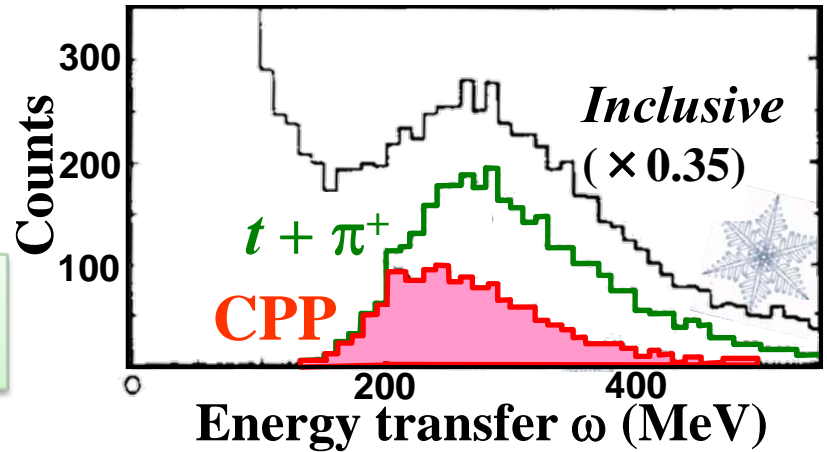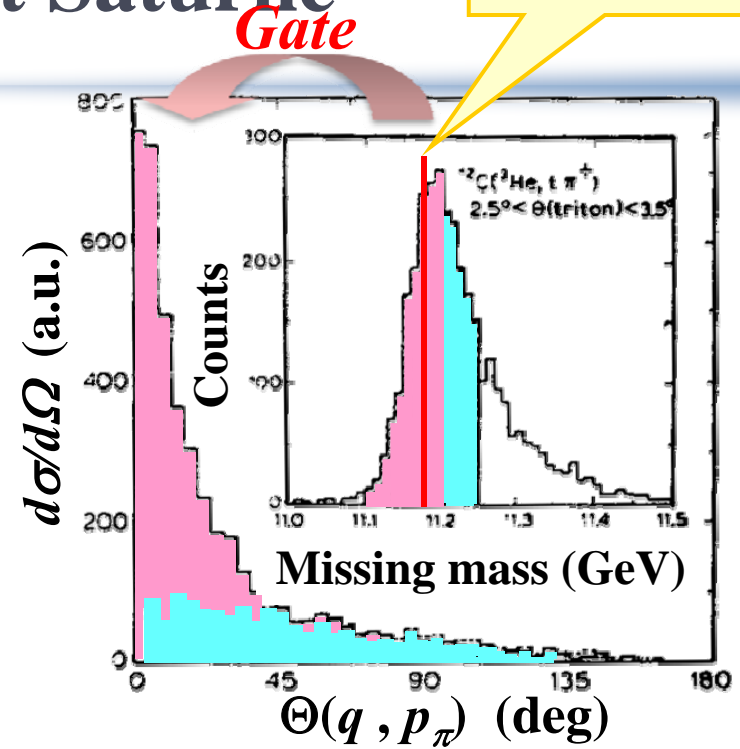

^{3}He Beam

t

π

To D-magnet Detected by DCs

Drift Chamber

^{3}He Beam

Drift Chmamber

Solenoid

t

π
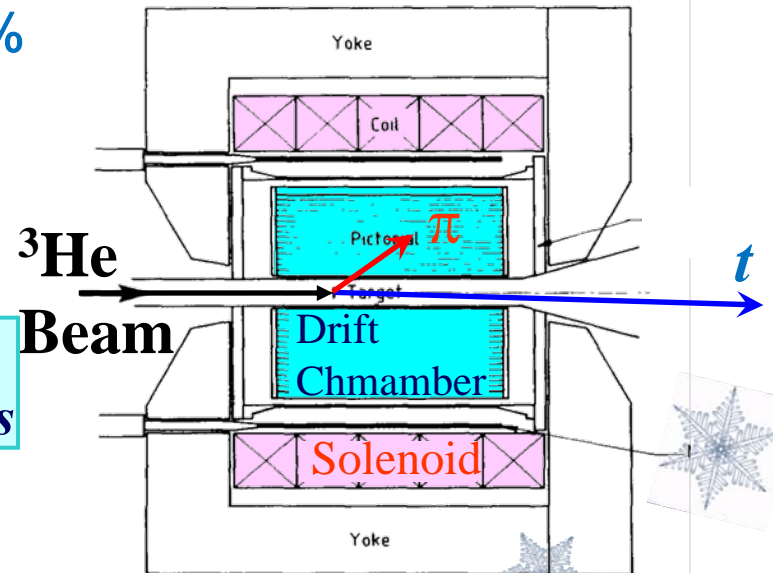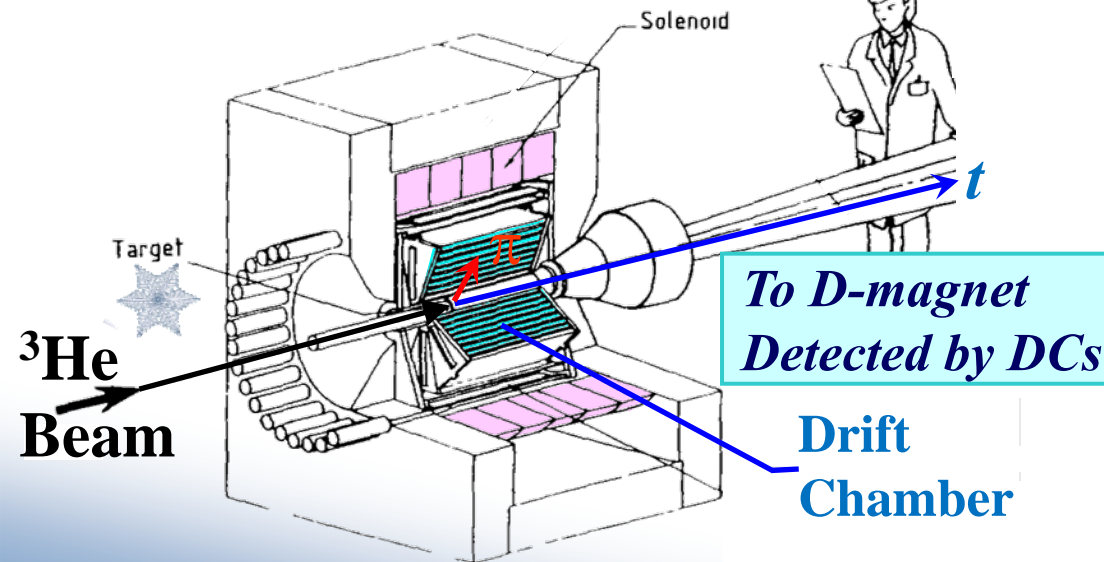
Results of CPP Experiment at Saturne

- **Poor missing mass resolution of 25 MeV (FWHM)**
  - Could not separate ^{12}C(g.s.) (CPP) from excited states
- **Strong (parallel) correlation between q and p_π**
  - *Signature of CPP*
  - Consistent with theoretical prediction
- **Downward energy shift of the Δ resonance peak for CPP**
  - *Signature of (attractive) pionic correlations in nuclei*

High resolution (g.s. separated) measurement are highly desired

^{12}**C(g.s.)= 11.175GeV**

Gate

^{12}C(^{3}He, t π^+)
2.5° < θ(triton) < 3.5°

Missing mass (GeV)

$d\sigma/d\Omega$ (a.u.)

$\Theta(q , p_\pi)$ (deg)

Inclusive (×0.35)

$t + \pi^+$

CPP

Energy transfer ω (MeV)

CPP Experiment at RCNP

$^{12}C(p,n\pi^+)^{12}C(g.s.)$ at 400 MeV

K.Fujita, Y.Sakemi et al.

NPOL2

$\Delta E = 300\ keV,\ \varepsilon = 15\%$

GEM Counter (NEW!!)
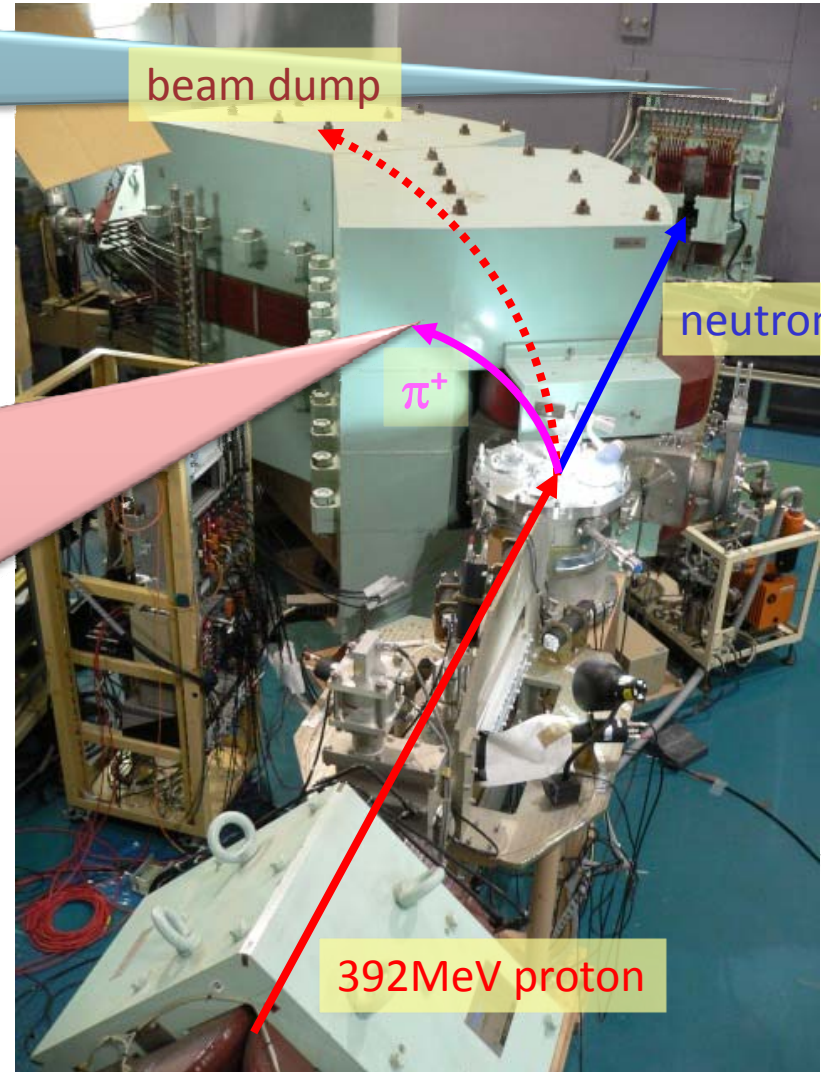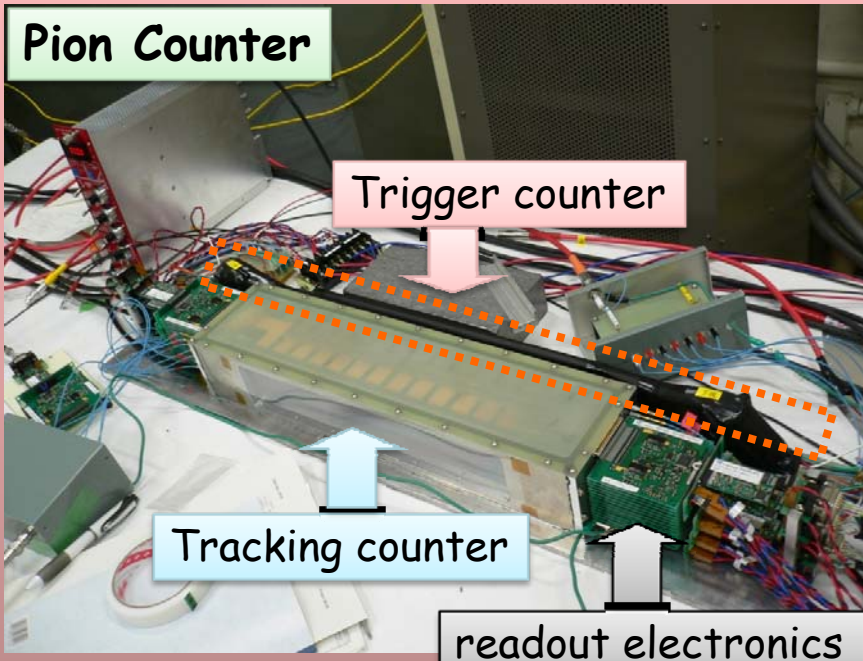
Pion Counter

Trigger counter

Tracking counter

readout electronics

beam dump

neutron

π^+

392MeV proton

Neutron+Pion "True" Coincidence
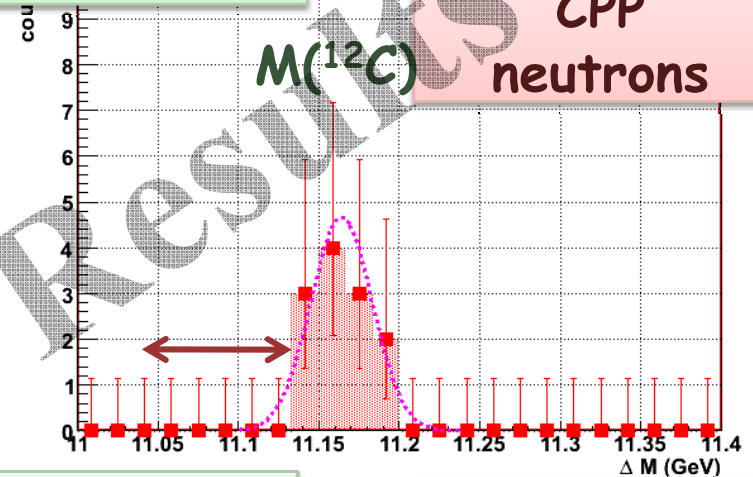
K.Fujita, Y.Sakemi et al.

- ## Missing mass spectrum
  - From neutron/pion momenta
  - Peak at $\Delta M = M(^{12}C)$
    - $M(^{12}C) = 11.175 \text{GeV}$
  - Signagure for CPP events

- ## Energy resolution
  - 9 MeV (before correction)
    - << 25 MeV at Saturne
      - Magnetic field of swinger
      - Pulse-height correction for neutron counter

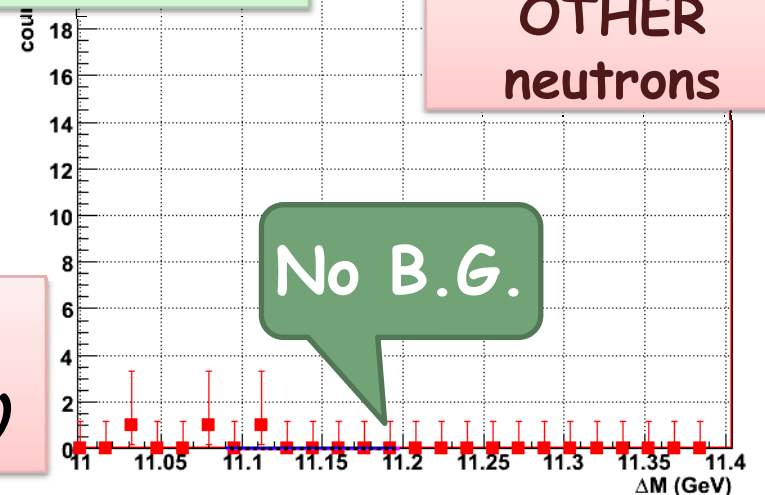⇒ **3-4 MeV after full correction**
(Not sufficient to resolve 2⁺(4.4MeV))

Missing Mass — Gate for CPP neutrons

$M(^{12}C)$

Missing Mass — Gate for OTHER neutrons

No B.G.

Preliminary Results for CPP at RCNP

K.Fujita, Y.Sakemi et al.

- **Selection of CPP**
  - 11.14 GeV < ΔM < 11.19 MeV
  - Including both
    - ^{12}C(g.s.) (CPP)
    - ^{12}C(4.4MeV,2^+)
- **Pion energy**
  - Exp. (GEM pion counter)
    - Less acceptance at $T_\pi < 120$ MeV
  - Theory (Universality of g'=0.6)
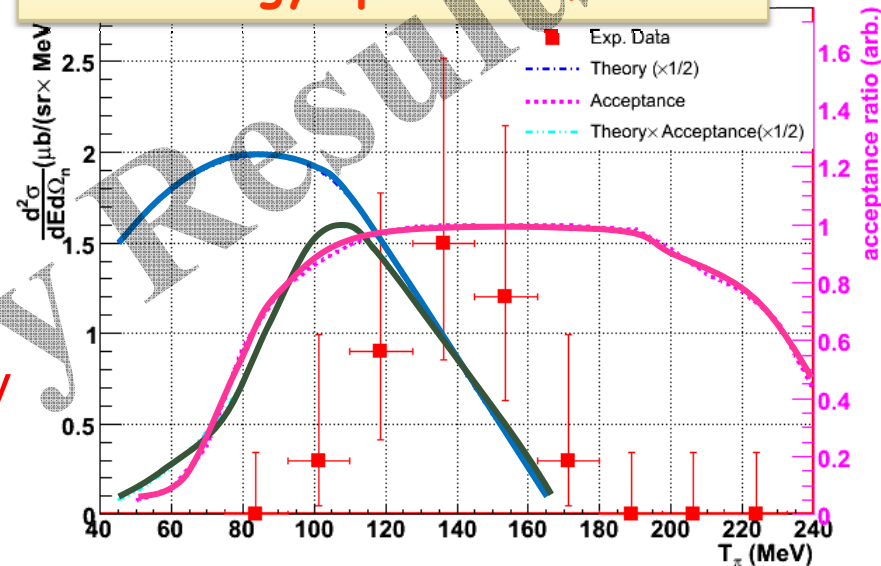   - Peak at $T_\pi = 90$ MeV

Acceptance effects are large (significant)

- **Preliminary results for CPP peak**
  - Exp. (140 MeV) > Theory (110 MeV) after acceptance correction

$g'_{\Delta\Delta}$ would be larger than $g'_{\Delta\Delta}$=0.6 (universality)
(More experimental and theoretical works are needed!!)

Pion energy spectrum for CPP

Summary

- "Unified" understanding of spin-isospin responses of nuclei is very interesting and challenging
- N-D coupling affects the phenomena in both
  N-region and Δ-region (ω = 300 MeV)

  $g'_{N\Delta}$ determined in N-region is adequate in Δ-region ?

- Experiments
  - Polarization transfer measurements
    - Transferred spin and J^π determination
  - CPP measurements
    - Sensitive to spin-longitudinal (pionic) mode

  Polarized GeV beams as well as excellent equipments

- Other facilities
  - ICHO/SHARAQ at RIBF
  - $^{12}C(\nu_\mu,\mu^-\pi^+)^{12}C$(g.s.) at J-PARC
  - First ν-CPP data from K2K: no-evidence for CPP

  Density dependence of g' could be investigated (?)

A.Hosaka and H.Toki, PTP 76, 1306 (1986)