コヒーレント中間子生成による核内デルタ相関の研究

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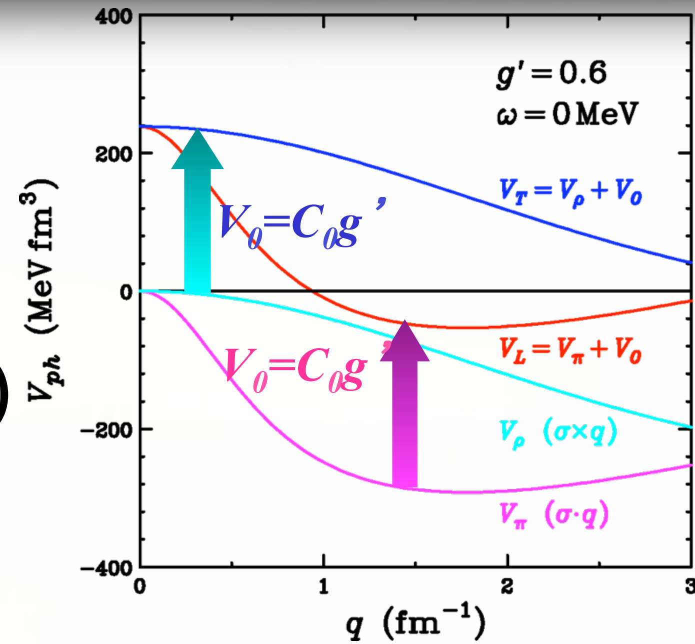
Nuclear Correlations and Δ Effects

- π+ρ+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'

$$V_{LM} = C_0\Big[g'_{NN}(\sigma_1\cdot\sigma_2)(\tau_1\cdot\tau_2) + \left\{\frac{f_{\pi N\Delta}}{f_{\pi NN}} g'_{N\Delta}\left((\sigma_1\cdot S_2)(\tau_1\cdot T_2) + (\sigma_1\cdot S_2^+)(\tau_1\cdot T_2^+)\right) + \frac{f^2_{\pi N\Delta}}{f^2_{\pi NN}} g'_{\Delta\Delta}(S_1\cdot S_2^+)(T_1\cdot T_2^+)\right\} + (1\leftrightarrow 2)\Big]$$



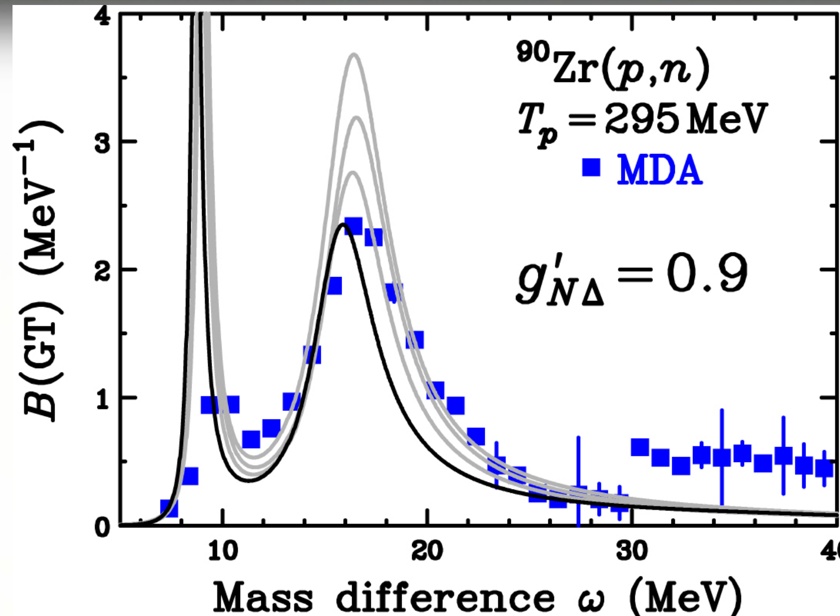
- g'_{NN}: Repulsion at $q=0$ — *Exp.*
  - Energy of GTGR
- $g'_{N\Delta}$: Coupling between N and Δ at $q=0$ — *Exp.*
  - GT quenching

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

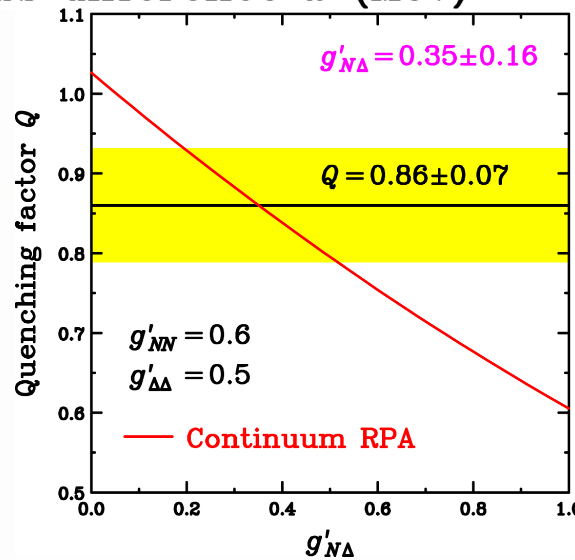
- $g'_{\Delta\Delta}$:Few experimental information
  - Coherent pion production is sensitive to $g'_{\Delta\Delta}$

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 $g'_{N\Delta} > 0$



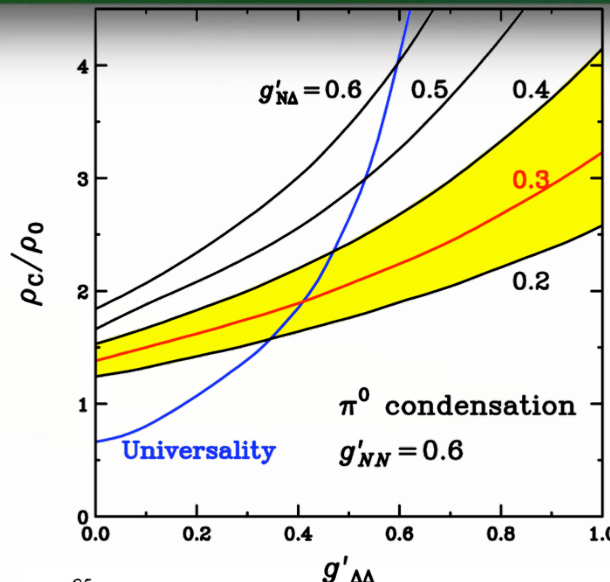
- **$g'_{N\Delta}$ Dependence of Q**
  - $Q=0.86\pm0.07$(quadratic sum of uncertainties)
  - Q evaluated in RPA
    - Strongly depends on $g'_{N\Delta}$
      - $g'_{N\Delta}=0.35\pm0.16$

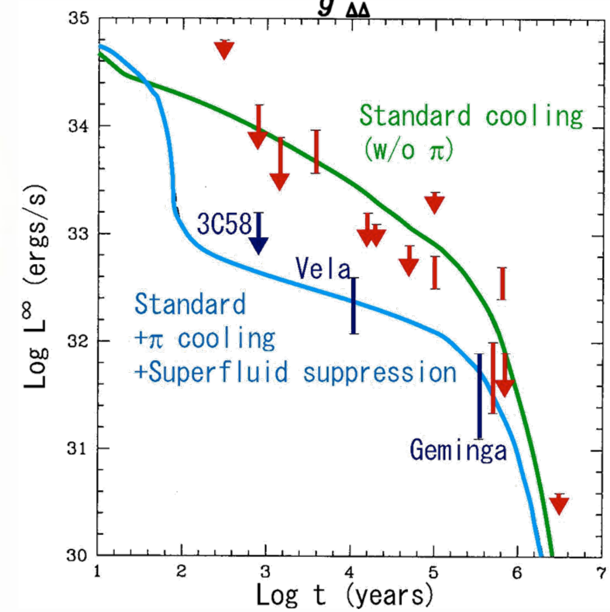


Pion Condensation in Neutron Star
-EOS and Pion Cooling-

- **Under universality ansatz**
  - $g'_{NN}=g'_{N\Delta}=g'_{\Delta\Delta}=0.6\sim0.7$
  - 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





Precursor of Pion Condensation in Nuclei

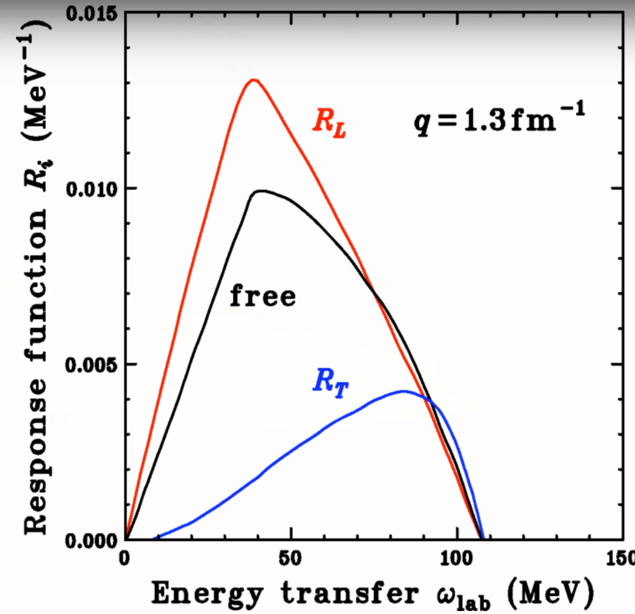
- **Precursor of π-condensation in nuclei**
  - Spin-longitudinal (pionic) $R_L \leftarrow \sigma \cdot \hat{q}$
    - Enhance and Soften
      - *W. M. Alberico, M. Ericson, and A. Molinari Nucl. Phys. A379, 429 (1982)*
- **Spin-Longitudinal Polarized Cross Section ID_q**
  - Complete set of D_{ij}

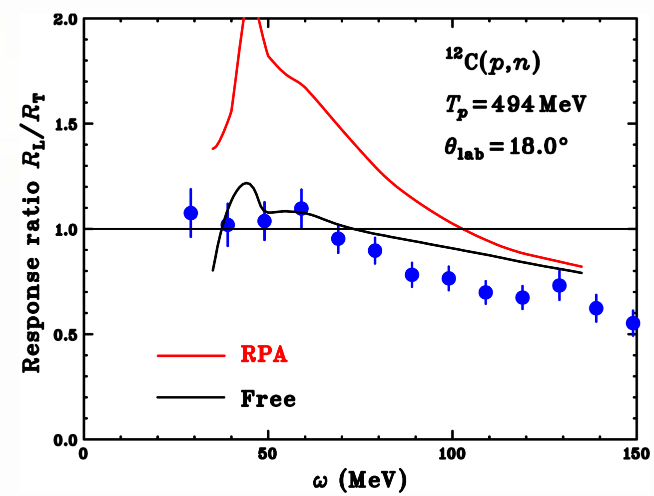
$$ID_q = \frac{I}{4}\left(1 - D_{nn} + D_{qq} - D_{pp}\right)$$

  - Eikonal approximation (for R_L/R_T)

$$ID_q = K\frac{A^{eff}}{A}|E|^2 R_L \quad \left(A_q^{eff} \neq A_p^{eff}\right)$$

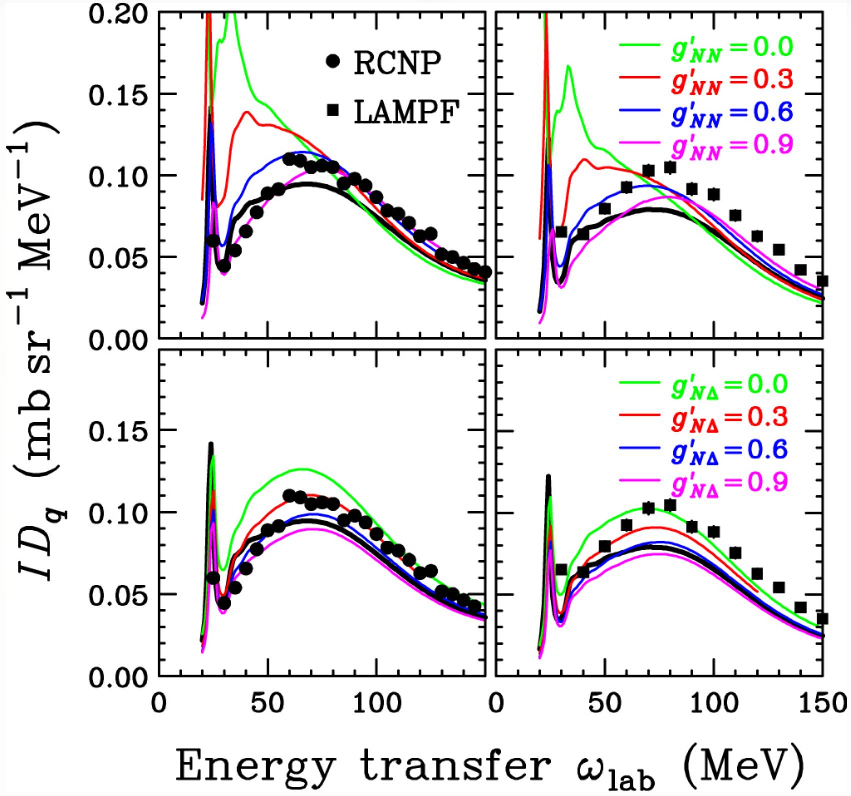
    - A^{eff} depends on spin direction
    - 2-step contributions
  - Directly compare ID_q with "DWIA+continuum RPA"+"2-step"





Pionic Enhancement in QES

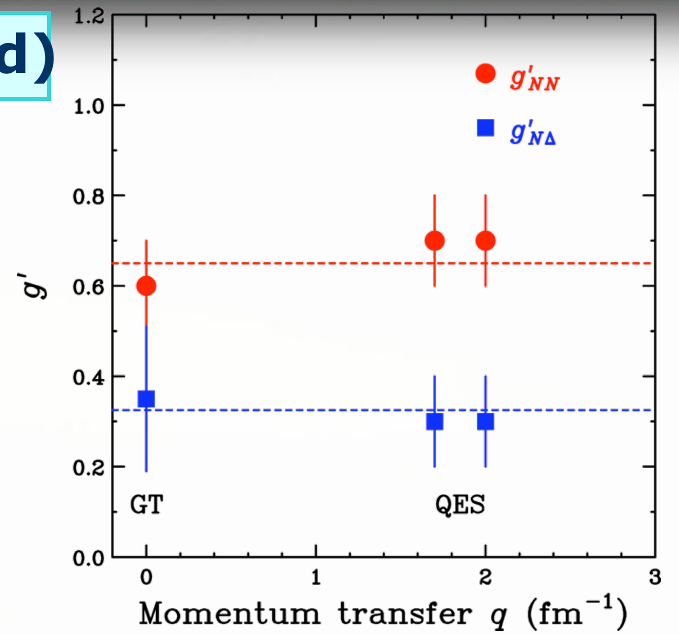
- **Pionic ID_q (^{12}C,^{40}Ca) at q=1.7 fm^{-1}**
  - RCNP data
    - *θ=22°,T_p=346 MeV*
  - LAMPF data
    - *θ=18°,T_p=494 MeV*
- **Pionic Enhancement**
  - Exp. Data > Free *(w/o Correlation)*
  - RPA is sensitive to g'_{NN} and $g'_{N\Delta}$
  - RPA is insensitive to $g'_{\Delta\Delta}$
- **Landau-Migdal Parameters**
    - g'_{NN} ~0.7
    - $g'_{N\Delta}$ = 0.2(LAMPF) — 0.4(RCNP)
  - Consistent with g's deduced from GT
    - g'_{NN}=0.6±0.1, $g'_{N\Delta}$=0.35±0.16
  - *q-dependence of g's is weak*

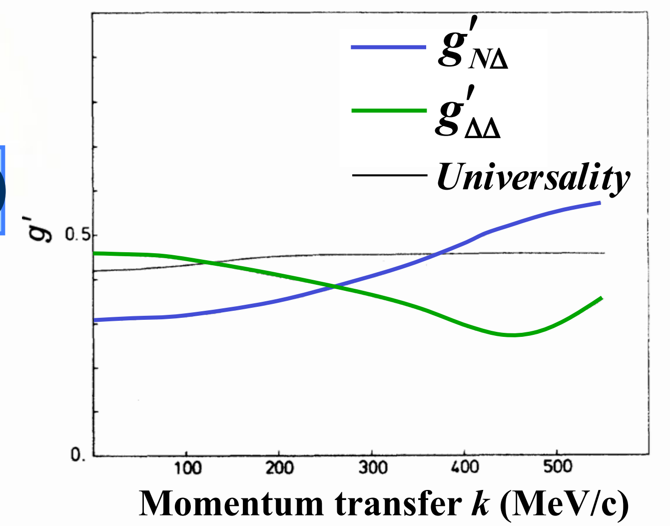


T. Wakasa et al.
Phys. Rev. C 69, 054609 (2004)
T. N. Taddeucchi et al.
Phys. Rev. Lett. 73, 3516 (1994)

Summary of our previous experiments
—Remaining subjects—

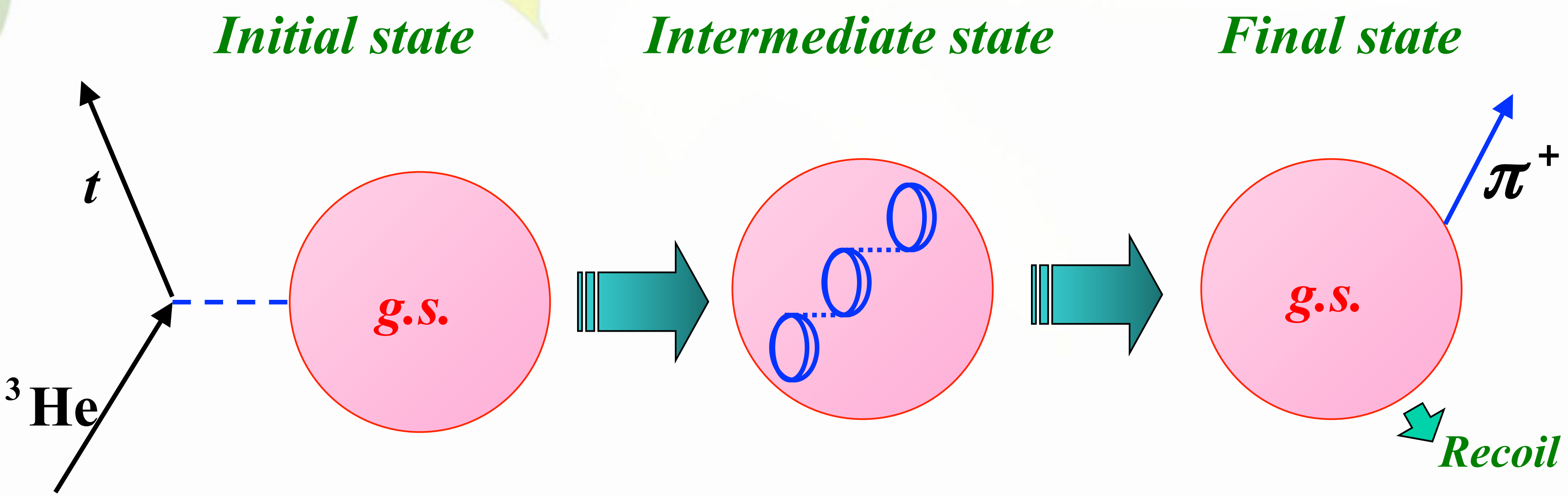
- **$g'_{NN} > g'_{N\Delta}$ (universality does NOT hold)**
- **q-dependence of g'_{NN} and $g'_{N\Delta}$**
  - q=0 from GT
  - q=1.7 and 2.0 fm^{-1} from QES
  - q-dependence of g' is weak
    - Consistent with theoretical predictions
      - W.H.Dickhoff et al. Phys. Rev. C 23, 1154 (1981)
  - Small $g'_{N\Delta}$ 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 measurement) is promising to determine $g'_{\Delta\Delta}$ experimentally*





What is "Coherent Pions (mesons)"

- **Coherent Pions in Charge-Exchange Reactions**
  - Target nucleus is left to the g.s.
    - $p + A(g.s.) \rightarrow n + \pi^+ + A(g.s.)$
    - $^3He + A(g.s.) \rightarrow t + \pi^+ + A(g.s.)$



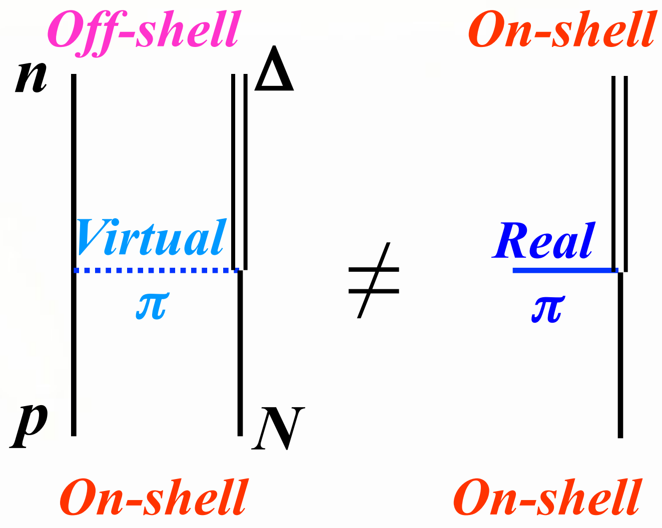
"Absorb" the virtual pion (off-shell pion)

Propagation of Δ-h states

"Emit" the real pion (on-shell pion)

What is interesting ?

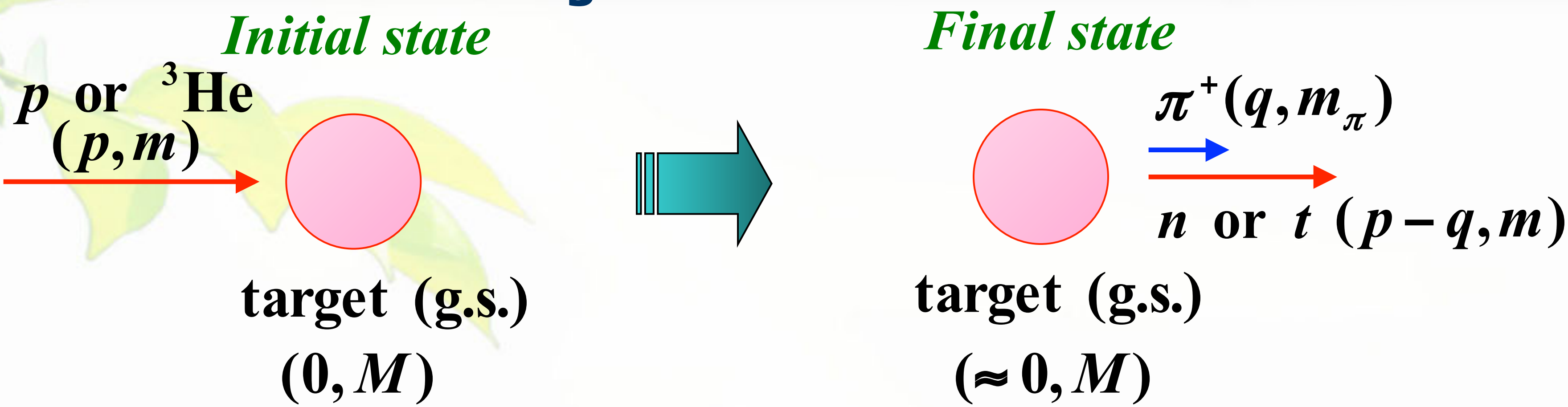
- **Virtual pion (elastic) scattering (by Ericson)**
  - Elastic means the target nucleus is left to the g.s.
  - Nuclear response can be studied in wide (q,ω) region where we cannot access with real pions
- **Information on Elementary Process**
  - Off-shell properties of t-matrix for NN→NΔ
  - Would be useful for Fujita-Miyazawa type 3NF (with Delta excitation)
- **Nuclear Structural points of view**
  - Pions in nuclear mean field are absorbed by the projectile



→ Sensitive to the nuclear correlations (many body effects)
(Difference from the simple Fermi-Gas model w/o correlations)

Kinematics of Coherent Pion Production Process

- **Kinematics at zero degrees**



- **Momentum transfer q for Coherenet Pion Production (CPP)**
  - Neglect the recoil energy (～1 MeV)
  - Non-relativistic kinematics for simplicity

$$\frac{p^2}{2m} = \frac{(p-q)^2}{2m} + \frac{q^2}{2m_\pi}$$

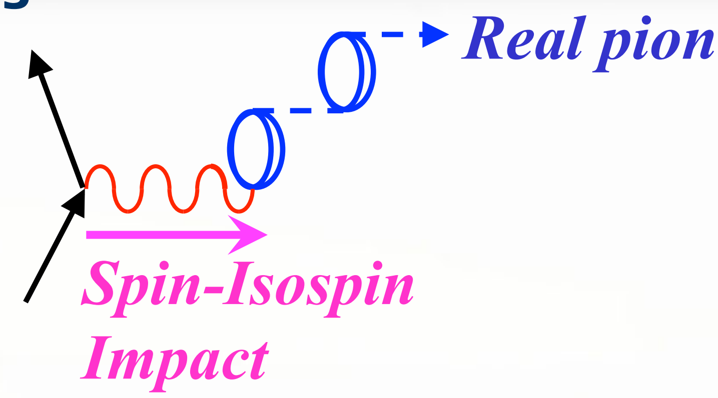
$$q = \frac{2pm_\pi}{M+m_\pi} \approx \frac{2pm_\pi}{M}$$

$$\begin{cases} q = 1.8\ \mathrm{fm}^{-1} \text{ for } (p,n) \text{ at } 800\ \mathrm{MeV} \\ q = 1.6\ \mathrm{fm}^{-1} \text{ for } (^{3}\mathrm{He},t) \text{ at } 2\ \mathrm{GeV} \end{cases}$$

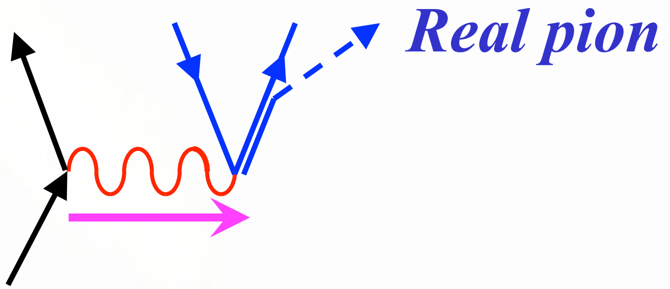
CPP is a process with large momentum transfers of q=1.5-2.0 fm^{-1}

Theoretical investigation for A(^{3}He,t) and CPP

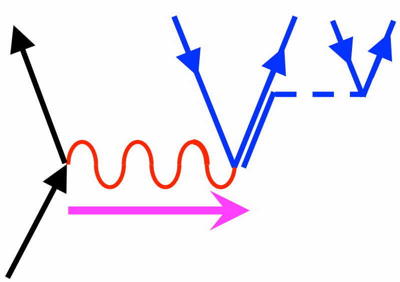
- **Physical processes important in Δ region**
  - Coherent Pion Production
    - Pions in final state



  - 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



Pionic Correlations in Δ-h States

- π and ρ-meson exchange in nuclear mean field
  - π+ρ+g' model interaction between Δ-h states

$$V_{\mathrm{eff}}^{\Delta\Delta} = V_L^{\Delta\Delta}(q,\omega) + V_T^{\Delta\Delta}(q,\omega)$$

$$V_L^{\Delta\Delta}(q,\omega) = W_L^{\Delta\Delta}\left[\left\{\underline{(T_1\cdot T_2^*)(S_1\cdot\hat{\mathrm{q}})(S_2^*\cdot\hat{\mathrm{q}})} + \underline{(T_1\cdot T_2)(S_1\cdot\hat{\mathrm{q}})(S_2\cdot\hat{\mathrm{q}})}\right\} + h.c.\right]$$

Spin-longitudinal (S·q T) channel

π-exchange + short-range repulsion (g')

$$V_T^{\Delta\Delta}(q,\omega) = W_T^{\Delta\Delta}\left[\left\{\underline{(T_1\cdot T_2^*)(S_1\times\hat{\mathrm{q}})(S_2^*\times\hat{\mathrm{q}})} + \underline{(T_1\cdot T_2)(S_1\times\hat{\mathrm{q}})(S_2\times\hat{\mathrm{q}})}\right\} + h.c.\right]$$

Spin-transverse (S×q T) channel

ρ-exchange + short-range repulsion (g')

S and T: Spin and Isospin transition operator from N to Δ

Pionic Correlations in Δ-h States

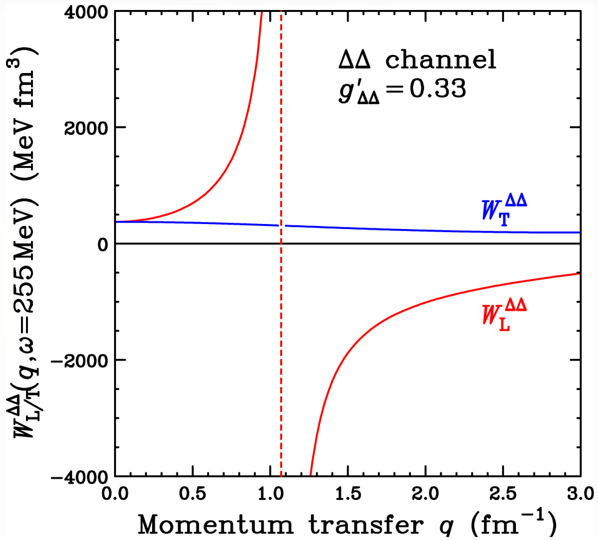
- **Residual interaction W is specified by LM parameter g' ΔΔ**

π-exchange

$$\text{LO } (S\cdot q\, T)\; W_L^{\Delta\Delta} = \frac{f_{\pi N\Delta}^2}{m_\pi^2}\left(g'_{\Delta\Delta} + \frac{q^2}{\omega^2 - q^2 - m_\pi^2}\Gamma_{\pi N\Delta}^2 \right)$$

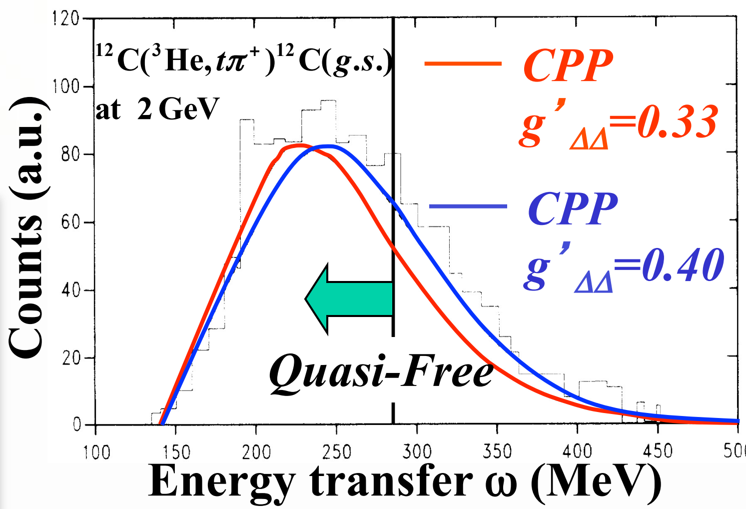
$$\text{TR } (S\times q\, T)\; W_T^{\Delta\Delta} = \frac{f_{\pi N\Delta}^2}{m_\pi^2}\left(g'_{\Delta\Delta} + C_\rho \frac{q^2}{\omega^2 - q^2 - m_\rho^2}\Gamma_{\rho N\Delta}^2 \right)$$

Short-range repulsion   ρ-exchange



- **Spin-longitudinal interaction is largely attractive at large momentum transfers**
  - This attraction leads to a collective pionic mode (CPP) at lower ω

$$\Delta E \approx \Delta g'_{\Delta\Delta}\left(\frac{\hbar c f_{\pi N\Delta}^2}{m_\pi^2}\right)\rho_0 \;\Rightarrow\; \textit{Determine } g'_{\Delta\Delta}$$



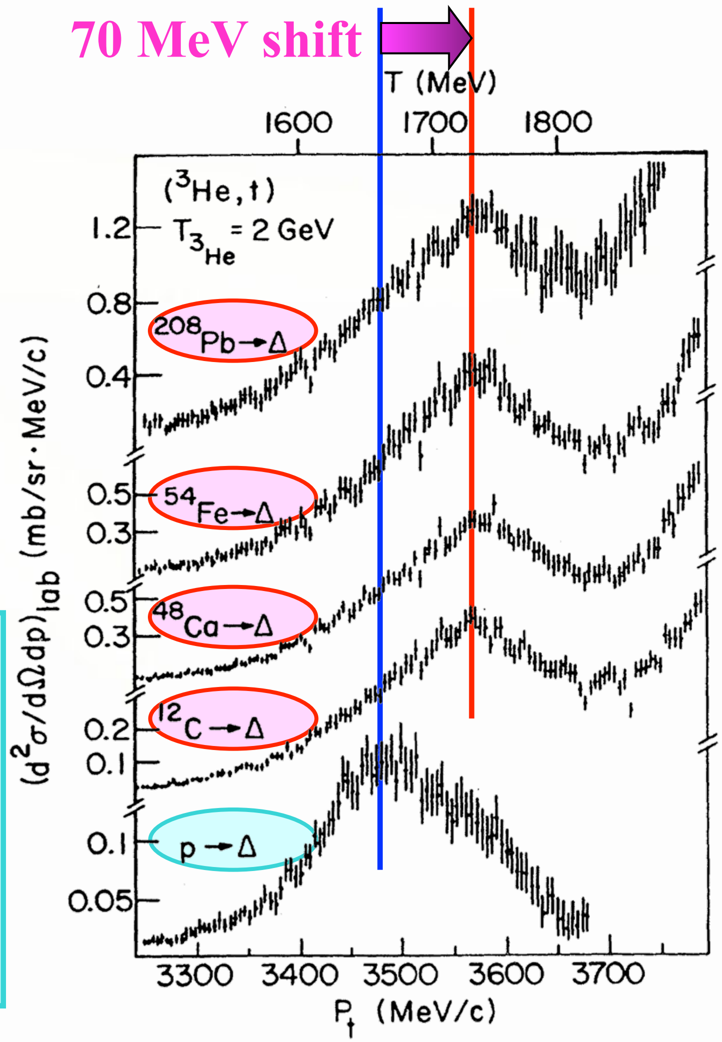
B.Korfgen et al., Phys. Rev. C 50, 1637 (1994)

Signatures of CPP process in previous experiments

- **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 $m_\Delta - m_N$=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



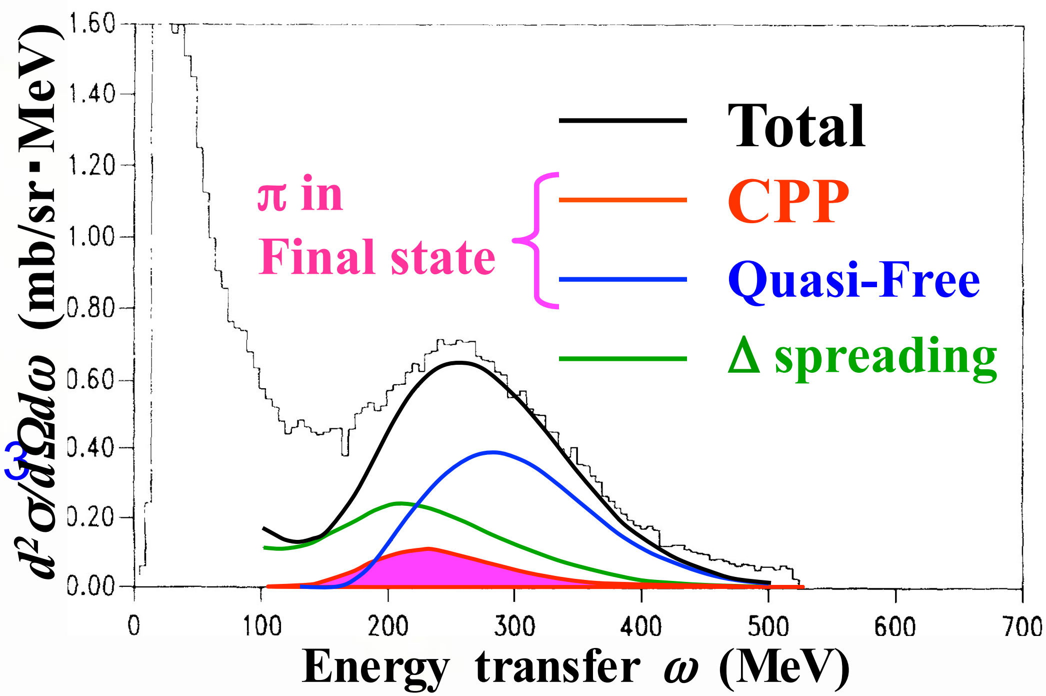
Inclusive process and pionic correlations

- **Is *the downward energy shift of the Δ resonance peak* <u>a "direct" signature of pionic correlations</u> (attractive $W_L^{\Delta\Delta}$)?**
  - Answer is "No". Because inclusive cross sections includes both
    - Spin-longitudinal (pionic) modes
    - Spin-transverse (non-pionic, ρ-mesonic) modes

- **How to separate these two modes "experimentally"**
  - Measure a complete set of polarization transfer observables
    - Measure spin transfer $\boldsymbol{S}$ with its direction
    - Separate σ into $\boldsymbol{S}\cdot\boldsymbol{q}$ and $\boldsymbol{S}\times\boldsymbol{q}$ components
  - Measure π decay of Δ in coincidence with the ejectile
    - Exclusive measurement
    - Extract pionic $\boldsymbol{S}\cdot\boldsymbol{q}$ component

Fraction of CPP and other processes in Δ region

- **Experimental Data**
  - $^{12}C(^{3}He,t)$ at 2 GeV and 0°
    - D.Contardo et al. Phys. Lett. B 168, 331 (1986)
  - Clear Δ-resonance peak at ω=260 MeV
- **Theoretical calculations**
  - Residual interaction with g'_{NN}=0.6 and $g'_{N\Delta}$=$g'_{\Delta\Delta}$=0.33
    - T.Udagawa et al. Phys. Rev. C 49, 3162 (1994)
  - CPP peaks at lower w compared with QF
    - *Pionic correlation effect*
  - CPP is 10-20% of the total strength

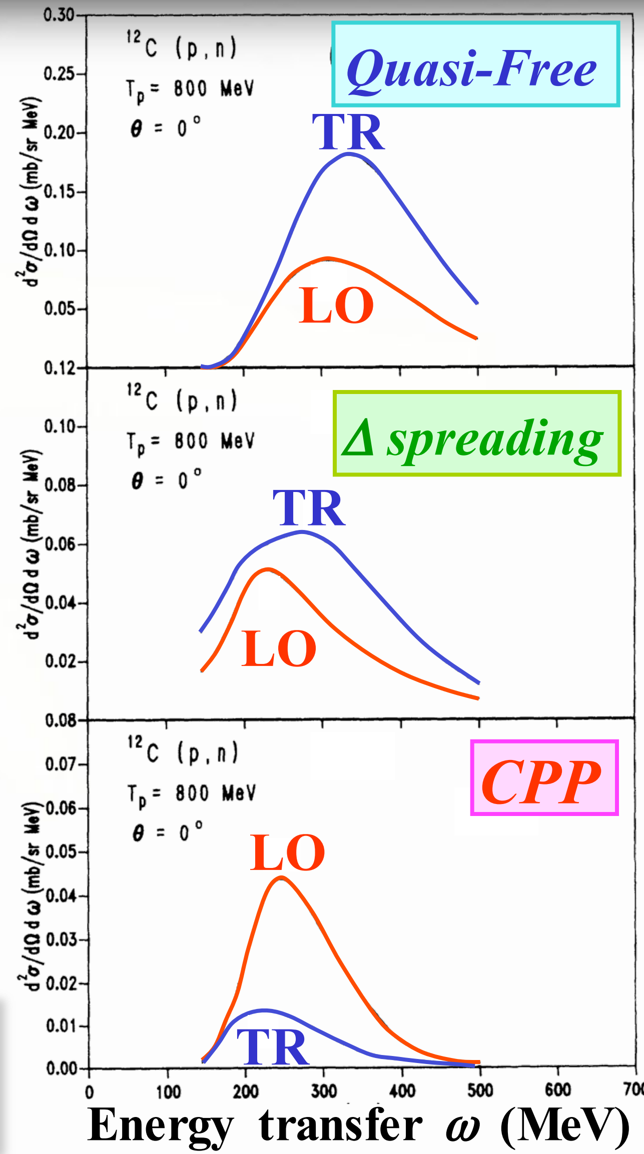


Inclusive is NOT sensitive to CPP (Pionic correlations)
→Exclusive measurement is important!

Sensitivity to pionic correlations

—Ratio of spin-longitudinal and spin-transverse modes—

- **Real (Experimental) impact is spin-isospin interaction via (^{3}He,t)**
  - **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 interaction with g'_{NN}=0.6 and $g'_{N\Delta}$=$g'_{\Delta\Delta}$=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***

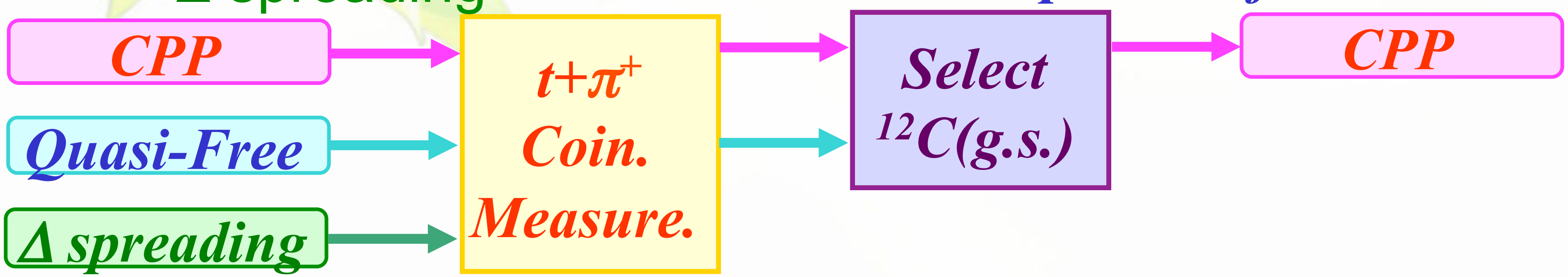


How to distinguish CPP from other processes

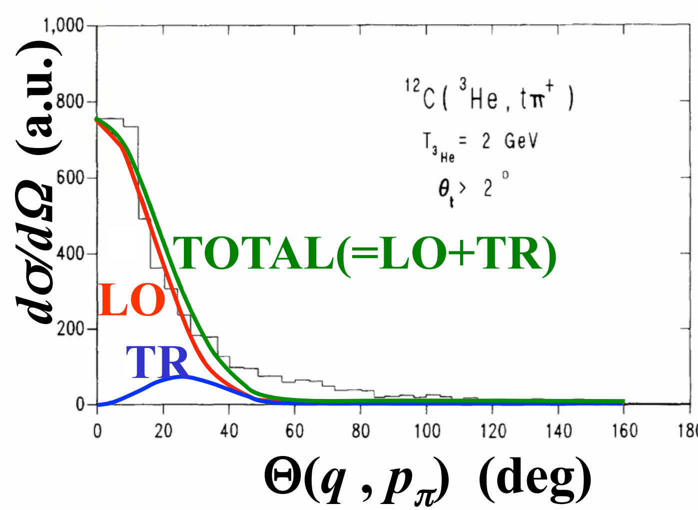
- **Main processes in Δ region are**
  - Coherenet Pion Production
  - Quasi-Free Δ decay

  } *Pions in final state*

  - Δ spreading ---------- *No pions in final state*

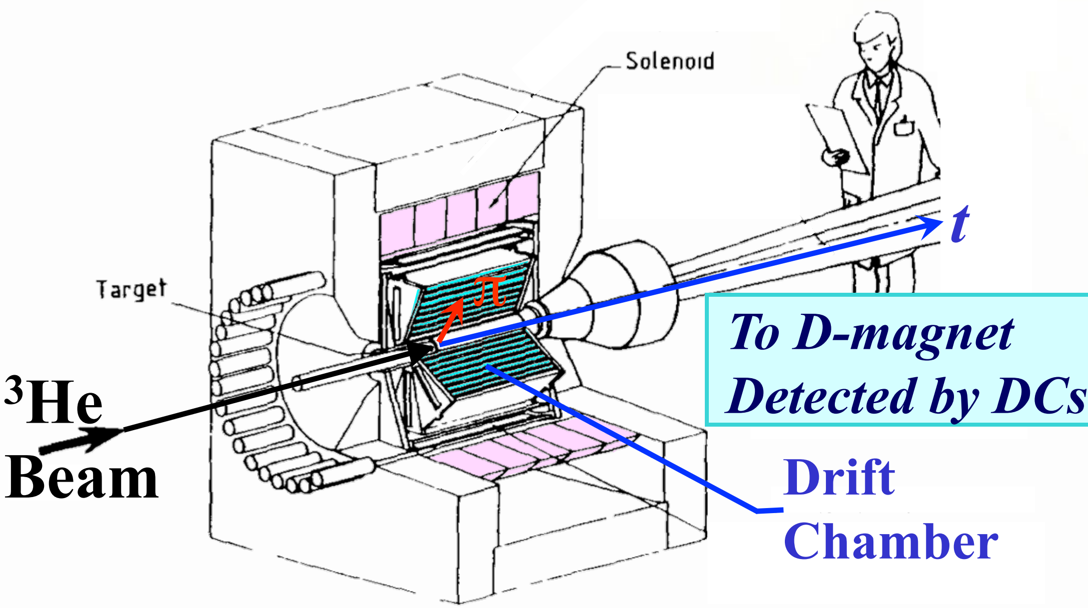


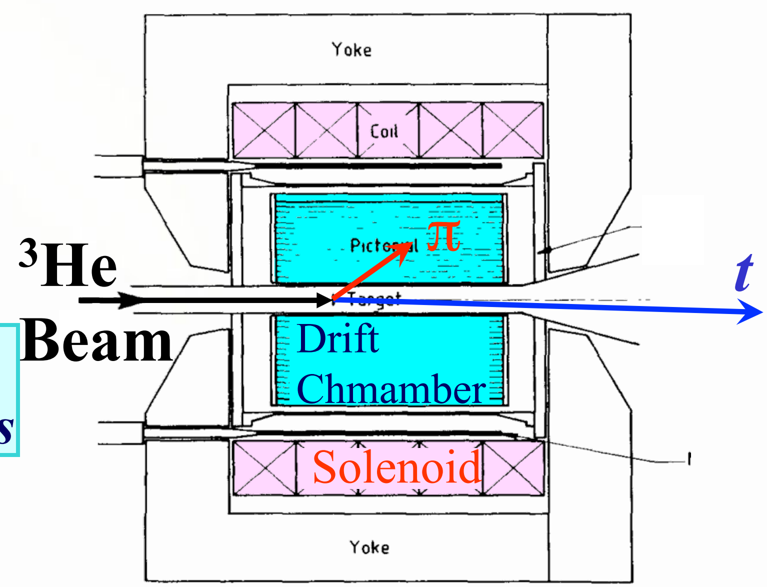
- **Measure correlation between momentum-transfer q and momentum $p_{\pi+}$ of pion**
  - Strong (parallel) correlation has been expected
    - T.Udagawa et al.
      Phys. Rev. C 49, 3162 (1995)



CPP Experiment at Saturne

- **$^{12}C(^{3}He,t\pi^{+})^{12}C(g.s.)$ 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%**

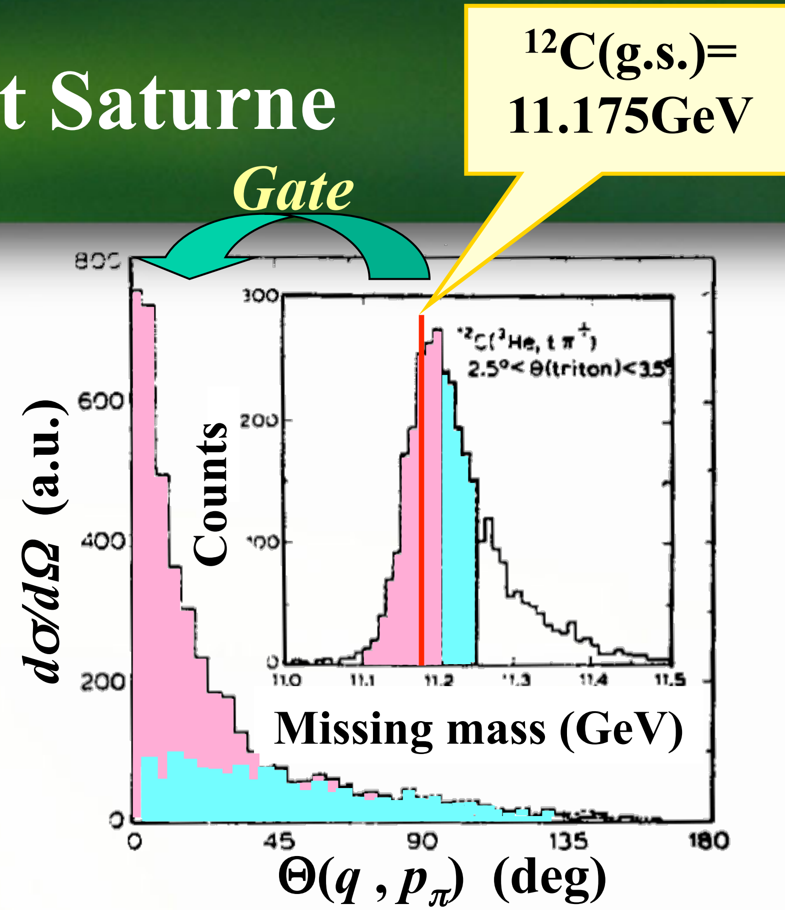


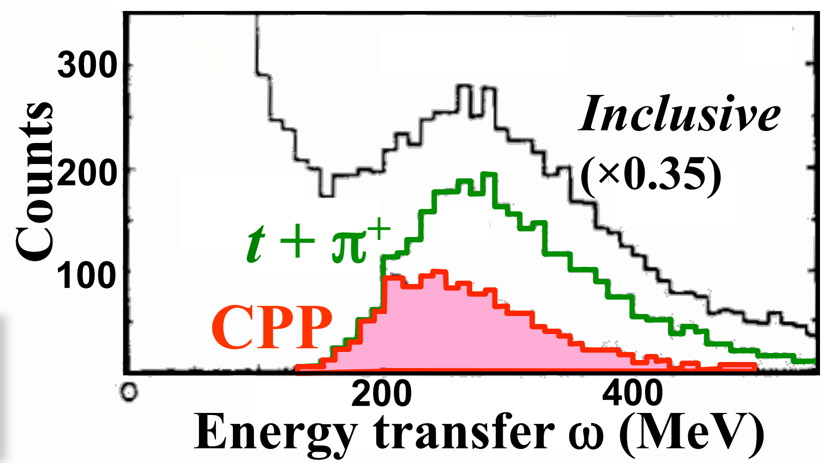


Results of CPP Experiment at Saturne

- **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 pp**
  - ***Signature of CPP***
    - Consistent with theoretical prediction
- **Downward energy shift of the Δ resonance peak for CPP**
  - ***Signature of (attractive) pionic correlations in nuclei***

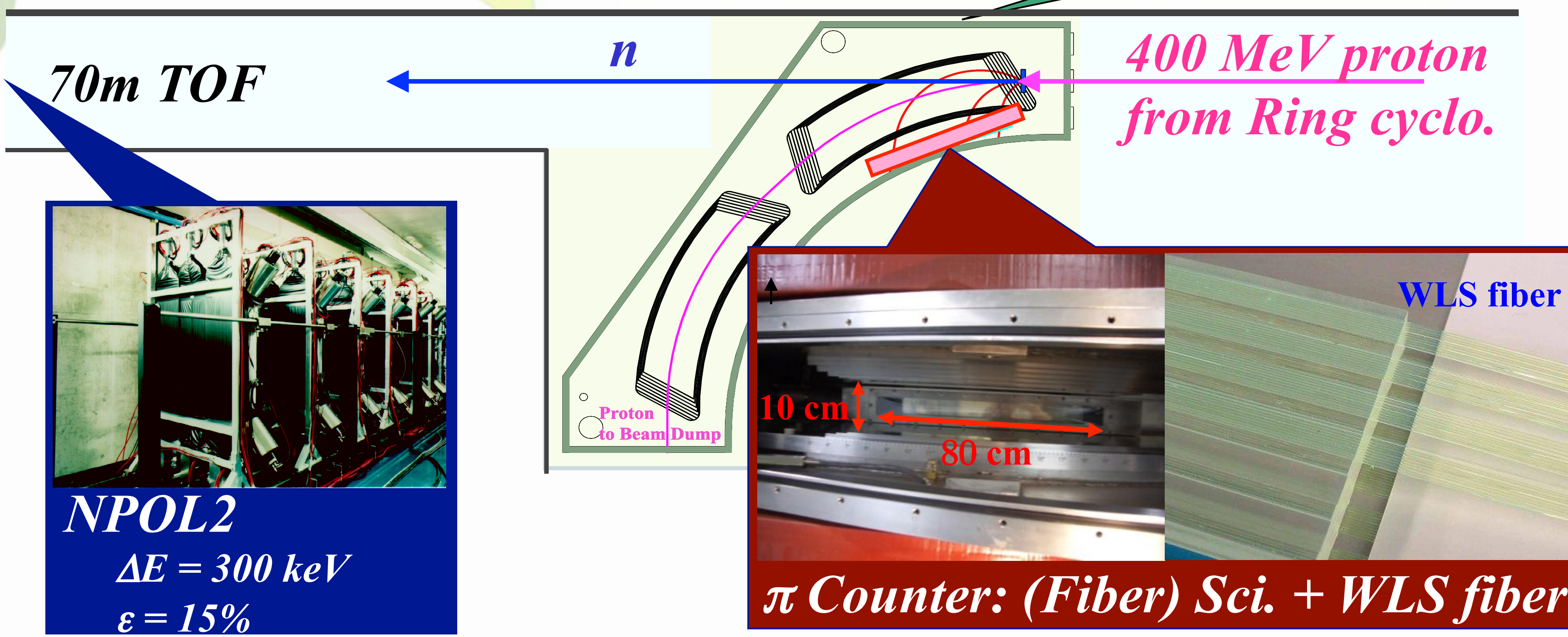
High resolution (g.s. separated) measurement are highly desired





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

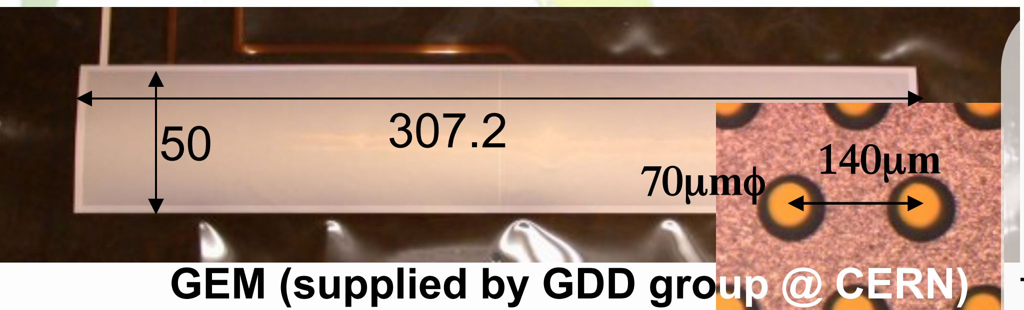
- **Advantage (Compared with Saturne exp.)**
  - High resolution ***p***-beam: 500 keV
  - High energy resolution for ***n***: 300 keV
  - Resolution for π^+: a several MeV with (Fiber)Sci.
    - ***1 MeV by replacing to GEM***



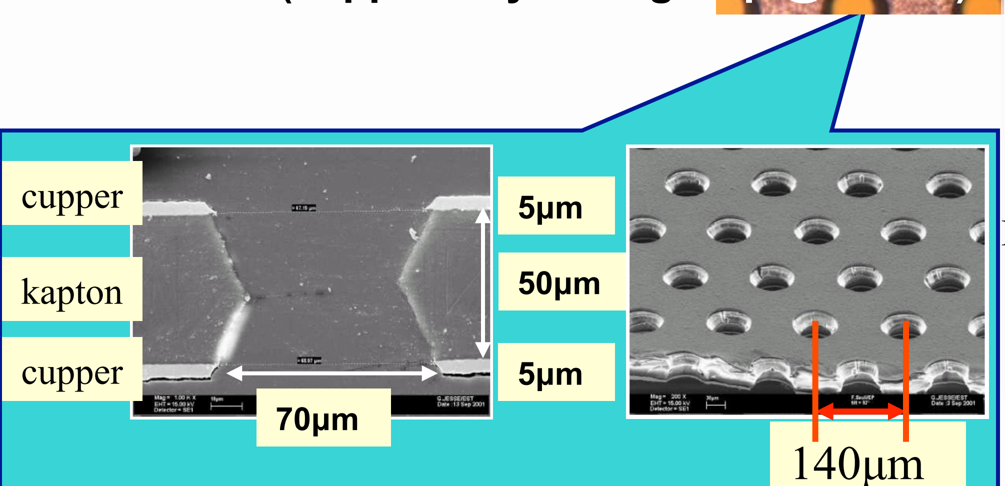
Gas Electron Multiplier (GEM) detector

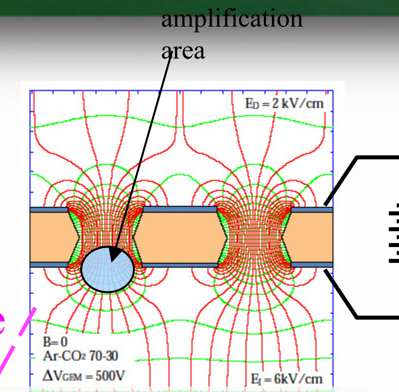
—For charged particle (π^+…) detection in magnet—

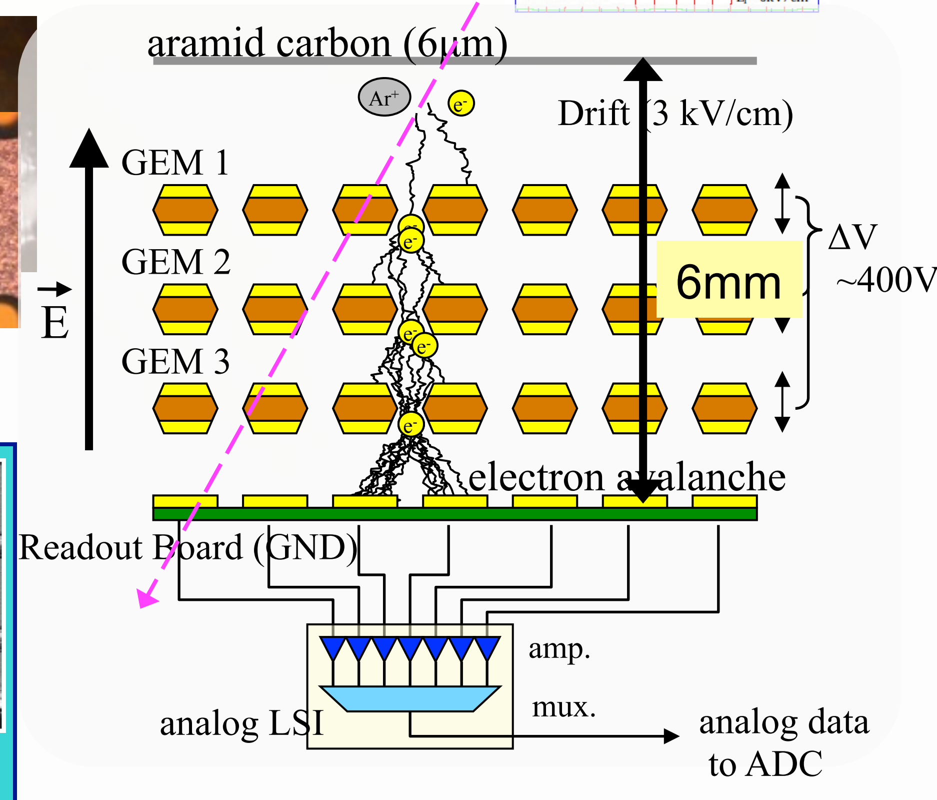
- **Detector components**
  - Three layers of GEM foil: High gain
  - 2-dim. Readout board: High resolution
- **Specification**
  - High position resolution: 100 μm
  - Effective area: 300 × 50 mm



GEM (supplied by GDD group @ CERN)

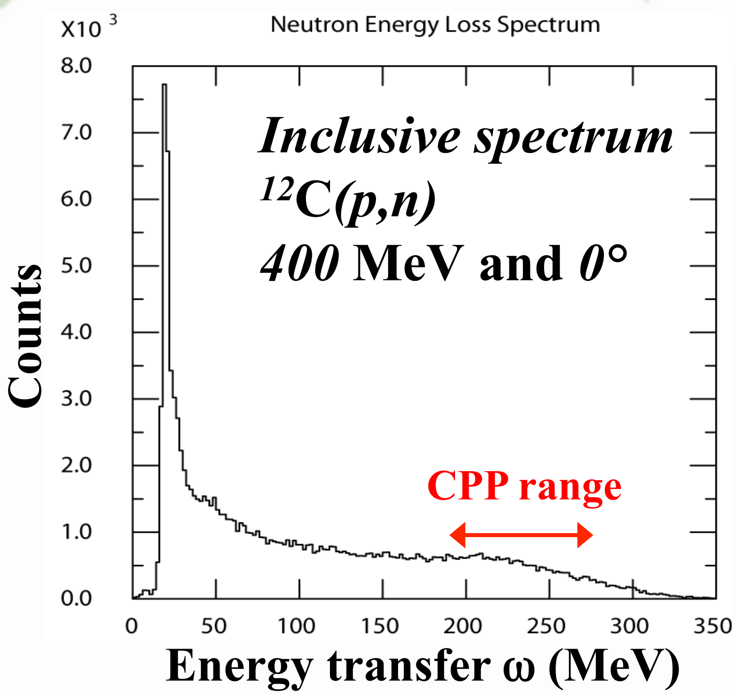


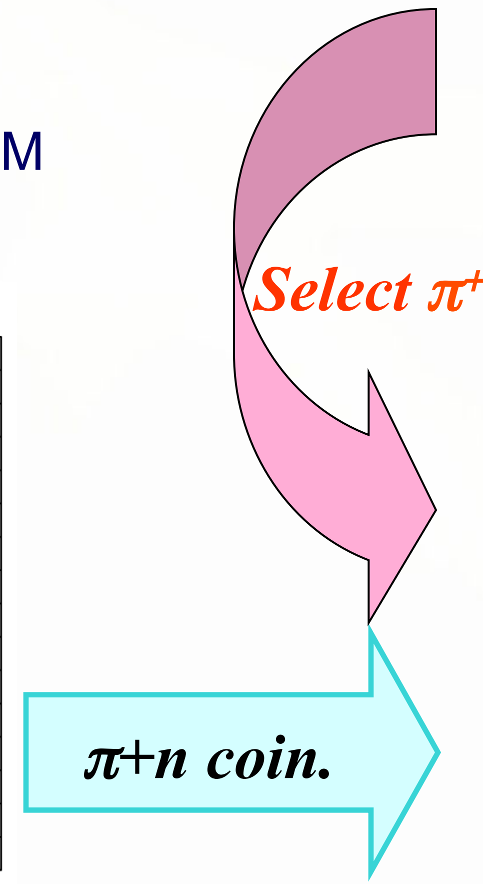


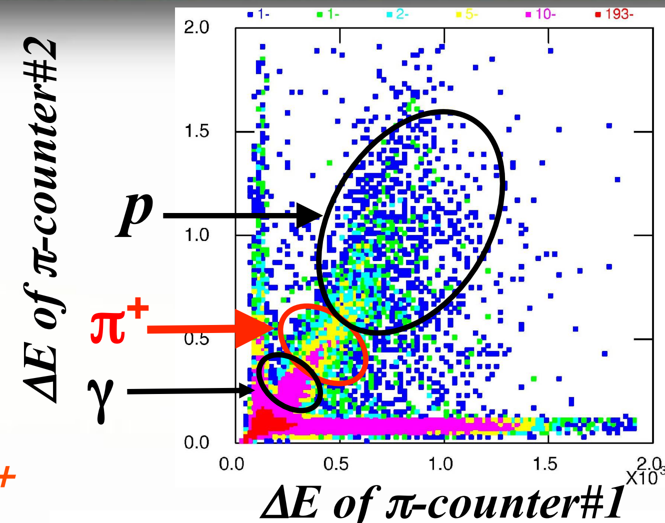


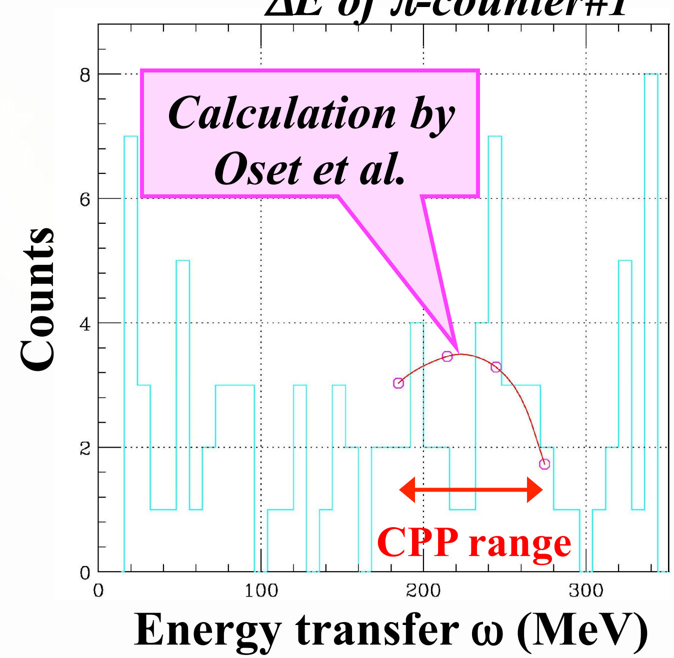
Preliminary Result of CPP Test Experiment

- **Poorer resolution for π**
  - Could not separate CPP from other excited states
- **Future measurement**
  - High resolution with GEM
  - High statistics data



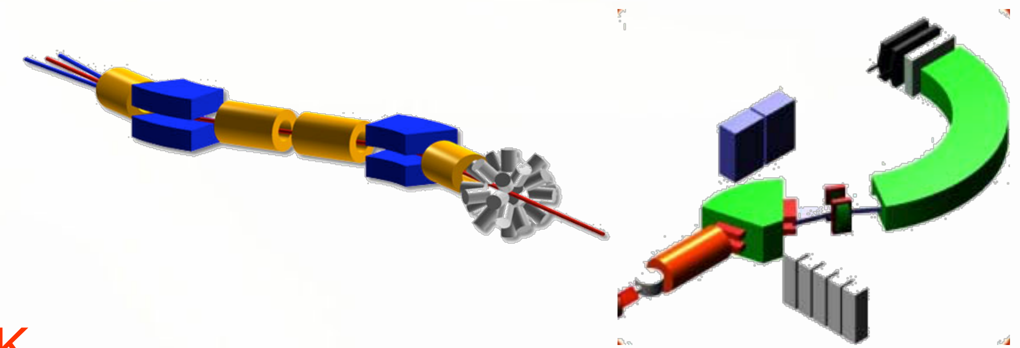






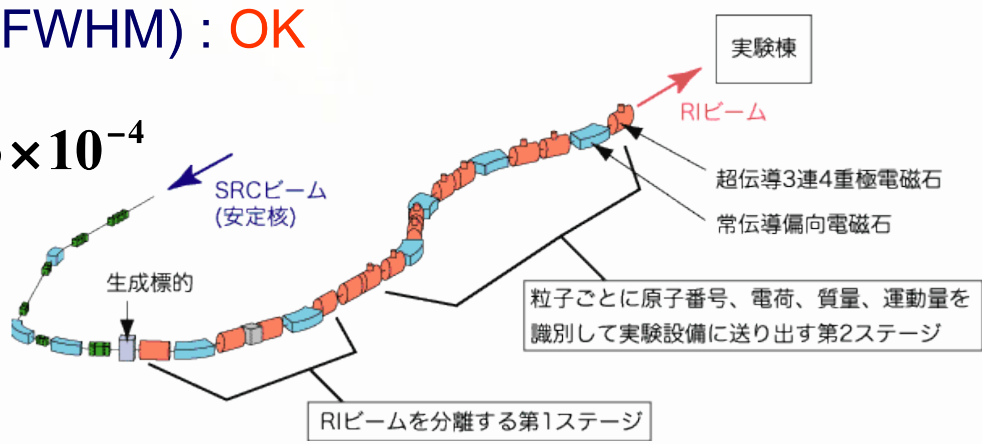
CPP Experiment at RIBF with $^{3}He^{++}$ Primary Beam

- **High resolution beam (Special thanks to Fukunishi-san)**
  - 400 MeV/n $^{3}He^{++}$: Δp=0.03% (σ) → ΔE=1.4 MeV (FWHM) : OK
- **High resolution triton measurement**
  - Requirement: $\Delta E \sim$ 2 MeV and θ < 2.5°including 0°
  - Facility (not studied)
    - Zero-degree Spectrometer
    - SHARAQ
  - Big-RIPS
    - $\Delta\theta$ = ±40 mrad = ±2.3° : OK
    - D = 2.3 m → ΔE = 1.7 MeV (FWHM) : OK



$$\frac{\Delta p}{p} = \frac{1}{R} = \left|\frac{M_x}{D}\right| \Delta x_0 = 4.3\times 10^{-4}$$

$$(M_x = 1,\ \Delta x_0 = 1\,\mathrm{mm})$$



CPP Experiment at RIBF with $^3He^{++}$ Primary Beam

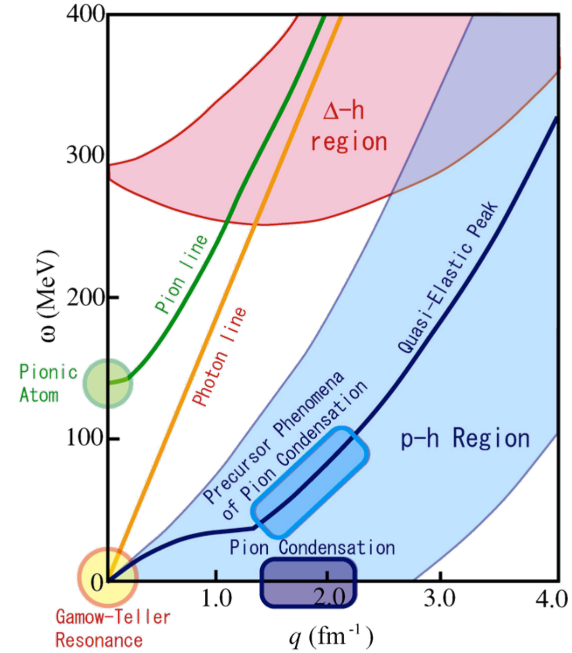
- **Typical π energy for CPP: 100 MeV**
  - ∼1% energy resolution is required
- **How to measure p in coincidence with tritons**
  - Large acceptance detector (4π like CDC) with low intensity $^3He^{++}$ beam (10^6-10^7 cps)
    - Typical energy resolution of CDC: < 10%
    - *DC → GEM(∼100μm) : Good (enough?) energy resolution*

      (Investigation is in progress)
      - Cylindrical GEM is also available
  - Standard spectrometer (moderate resolution) with high intensity $^3He^{++}$ beam (nA-μA)
    - Enough energy resolution could be easily achieved
    - Both tritons and pions are emitted at (relatively) forward angles
      - *How to arrange two spectrometers for tritons and pions?*

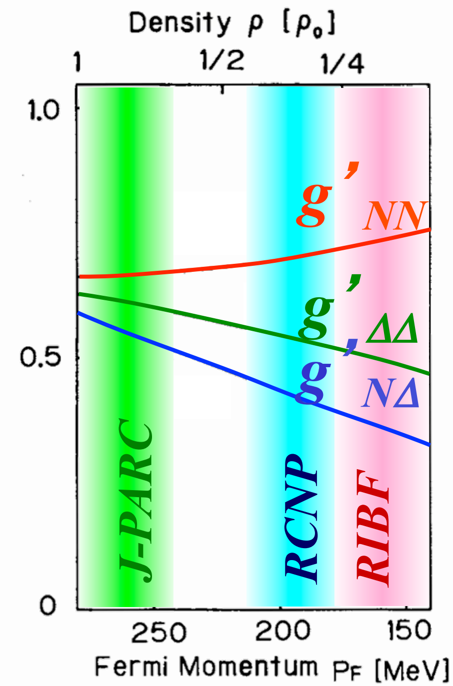
Summary

- **CPP is a promising tool to obtain the information on g'$_{\Delta\Delta}$**
- **g'$_{\Delta\Delta}$ as well as g'$_{NN}$ and g'$_{N\Delta}$ (known)**
  - Spin-isospin responses in wide (q,ω) of
    - q = 0 – 3 fm^{-1}
    - ω = 0 – 400 MeV

  can be ***understood (expressed) in a unified (ultimate) way***



- **CPP experiments are performed/proposed at other Labs**
    - ^{12}C(p,nπ$^+$)^{12}C(g.s.) at RCNP
    - ^{12}C(ν_μ,μ$^-$π$^+$)^{12}C(g.s.) at J-PARC
      - *First ν-CPP data from K2K: no-evidence for CPP*
  - ***Density dependence of g' could be investigated***

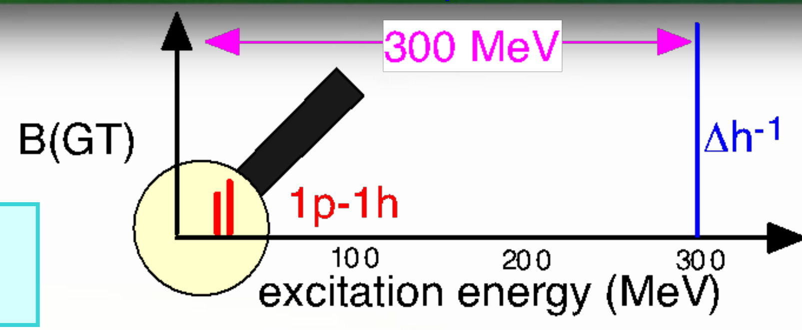


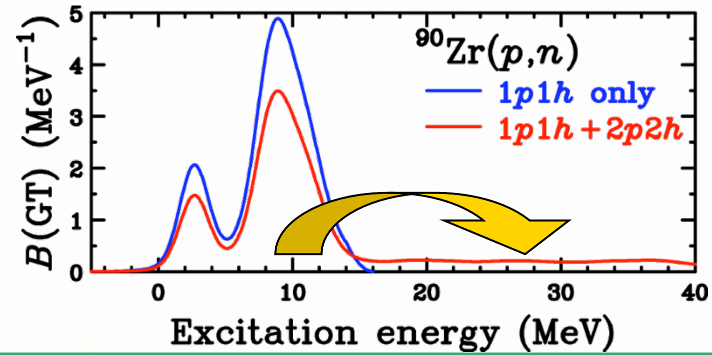
A.Hosaka and H.Toki, PTP 76, 1306 (1986)

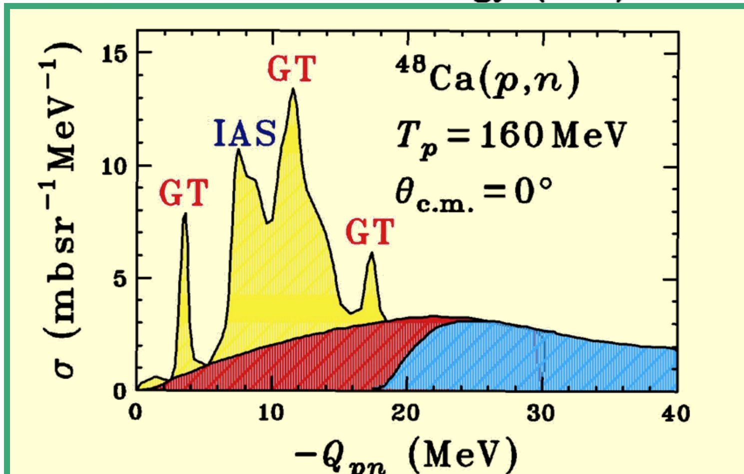
Backup Slides

GT Quenching Mechanisms

- **Δh admixture into ph GT state**
  - Shift B(GT) from ph region to Δh region at ω~300 MeV
  - Coupling strength between p-h and Δ-h is specified by $g'_{N\Delta}$
- **Nuclear configuration mixing**
  - Shift B(GT) from ph region to 2p2h region in the continuum
- **B(GT) in the continuum**
  - B.G. in the GTGR region
    - Dipole (L=1) resonance, etc.
  - GT strength in high excitation
    - Contribution from L≧1 strength
- **Multipole Decomposition (MD)**
  - Determine L=0 (GT) strength in the continuum







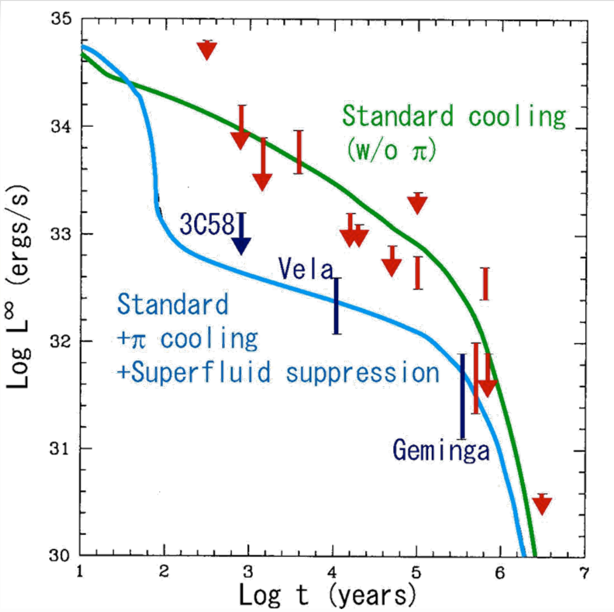
Drozdz et al. PL 166B, 18(1986)

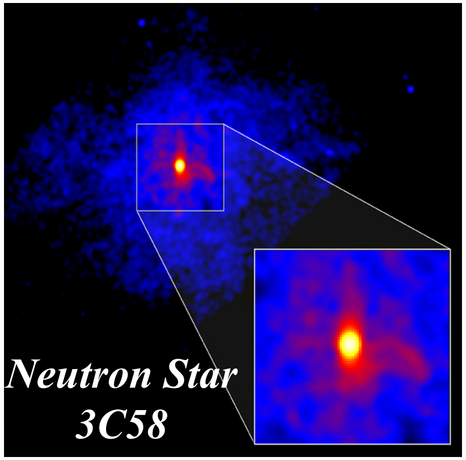
Bohr and Mottelson PL 100B, 10(1981)

Pion Cooling

- **Cooling mechanism for N.S.**
  - $M < 1.3 M_{SUN}$
    - Standard cooling (modified URCA)
  - $M > 1.4 M_{SUN}$ (3C58 etc.)
    - Standard + pion cooling

Pion condensation accelerates the neutron star cooling





Pionic Correlations in Δ-h States

- **Residual interaction W is specified by LM parameter g'ΔΔ**

π-exchange

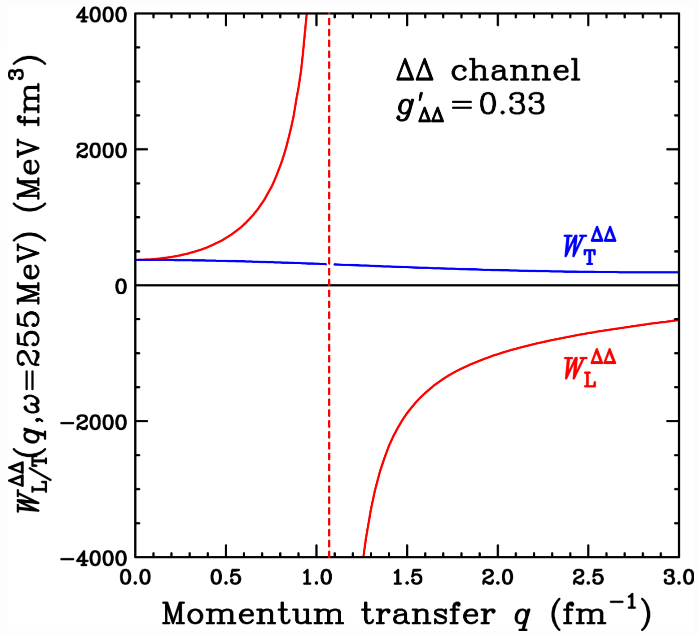
$$\begin{cases} W_L^{\Delta\Delta} = \dfrac{f_{\pi N\Delta}^2}{m_\pi^2}\left(g'_{\Delta\Delta} + \dfrac{q^2}{\omega^2 - q^2 - m_\pi^2}\Gamma_{\pi N\Delta}^2 \right) \\ W_T^{\Delta\Delta} = \dfrac{f_{\pi N\Delta}^2}{m_\pi^2}\left(g'_{\Delta\Delta} + C_\rho \dfrac{q^2}{\omega^2 - q^2 - m_\rho^2}\Gamma_{\rho N\Delta}^2 \right) \end{cases}$$

Spin-longitudinal $(\mathbf{S}\cdot\mathbf{q}\,\mathbf{T})$

Spin-transverse $(\mathbf{S}\times\mathbf{q}\,\mathbf{T})$

Short-range repulsion

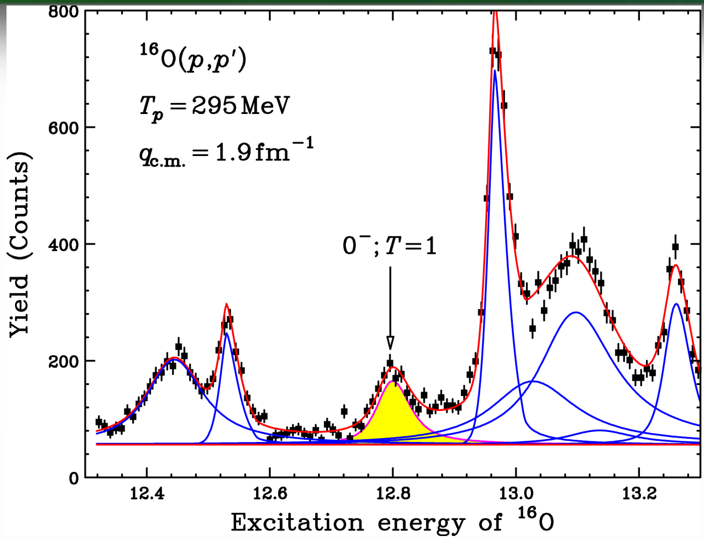
ρ-exchange

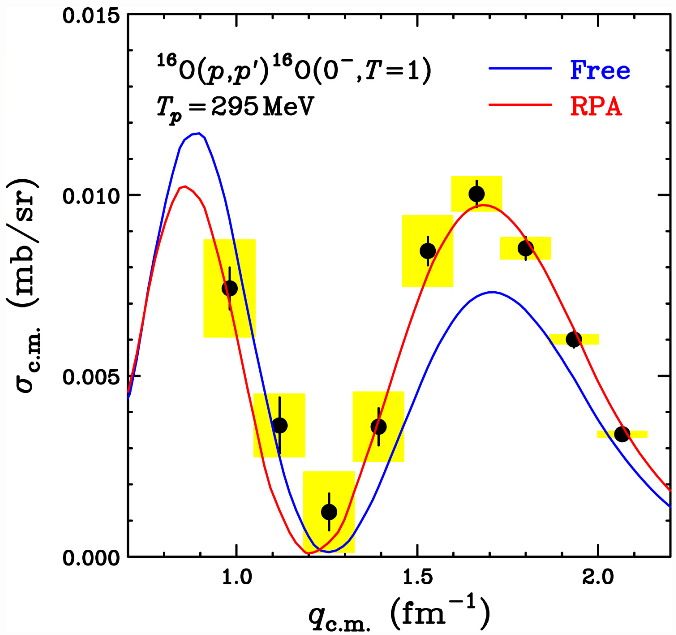


- **Spin-longitudinal interaction is largely attractive at large momentum transfers**
  - This attraction leads to a collective pionic mode (CPP) at lower excitation energies

Pionic Enhancement in $^{16}O(p,p')^{16}O(0^-,T=1)$
—*Exclusive measurement for spin-parity state*—

- **Isovector $J^\pi=0^-$ excitations**
  - Carry π-like quantum number
  - Pure information on pionic mode
- **Experiment: $^{16}O(p,p')^{16}O(0^-,T=1)$**
  - *ΔE=30 keV* with WS+GR
  - $q_{c.m.} = 0.9 – 2.1\ fm^{-1}$
- **Comparison with Theory**
  - — Without correlation (Free)
    - Significant enhancement
  - — With RPA correlation
    - $g'_{NN}=0.7, g'_{N\Delta}=0.4$ (RCNP-QES)
    - Predict the enhancement of the 3rd peak ($q=1.7fm^{-1}$)
    - π-exchange interaction is attractive
  - Our data support pionic enhancement
    - ***Signature of precursor for pion condensation in normal nuclei***





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

- **Advantage (Compared with Saturne exp.)**
  - High resolution *p*-beam: 500 keV
  - High energy resolution for *n*: 300 keV
  - Resolution for π^+: a several MeV with (Fiber)Sci.
    - ***1 MeV by replacing to GEM***

Beam swinger (Proton beam is bent by 90°)