サイクロトロンでの物理

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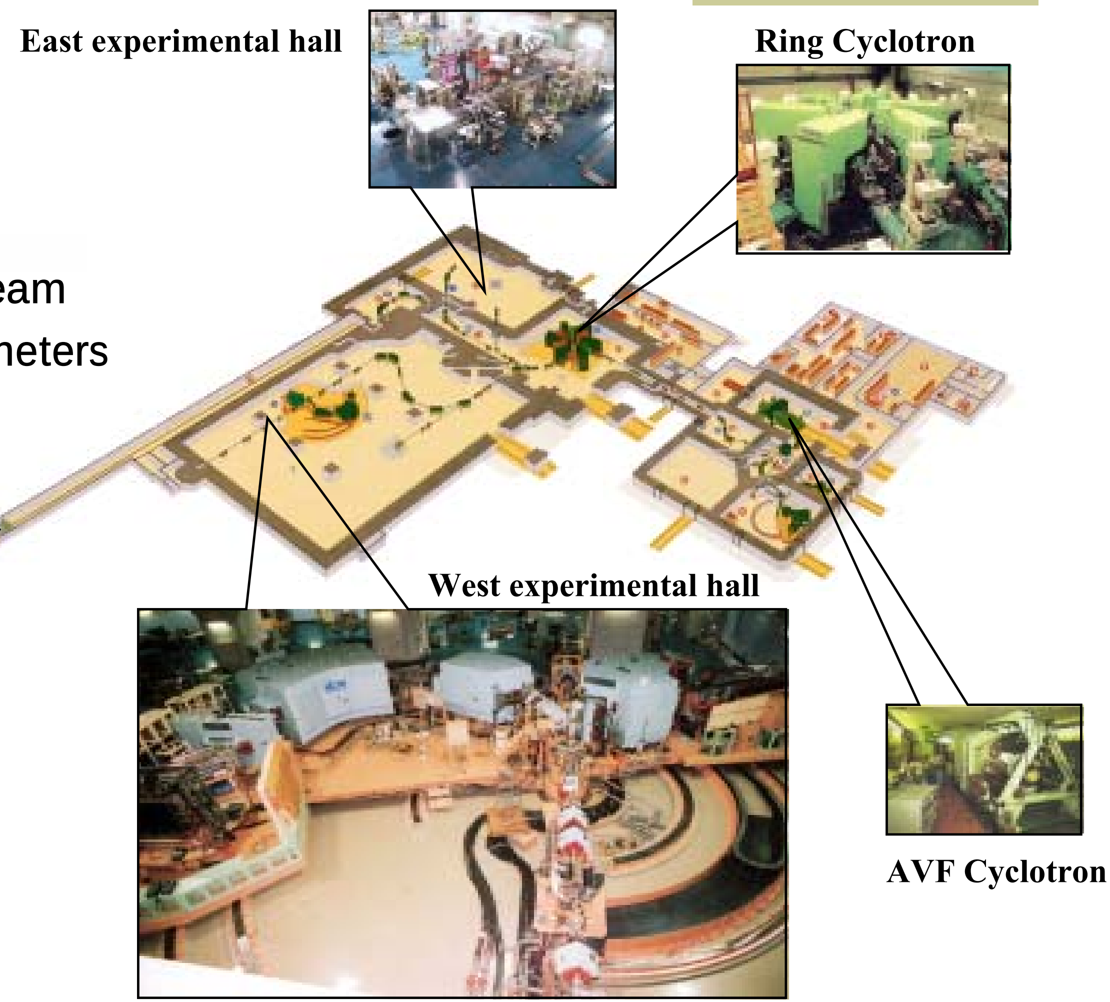
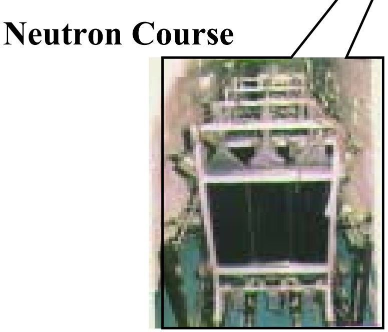
Overview

- **Overview of the Experimental Facility**
- **Overview of the Physics Programs**
- **Physics Topics at RCNP**
  - Nuclear medium effects
  - Quark (Δ) degrees of freedom in low energy phenomena
  - Precursor phenomena of pion condensation
  - Three nucleon force effects
  - High resolution WS beam line
  - Spectroscopy with high resolution beams
  - Astrophysics
- **Summary**

RCNP Ring Cyclotron Facility

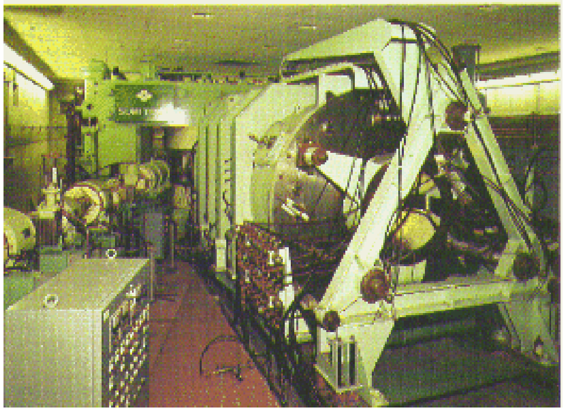
- **Unique Points**
  - Polarized beams
    - ***Protons***
    - ***Deuterons***
  - High resolution beam
  - Two-arm spectrometers
  - Polarimeters
    - ***FPP***
    - ***2^{nd} FPP***
    - ***NPOL2***





AVF and Ring Cyclotrons

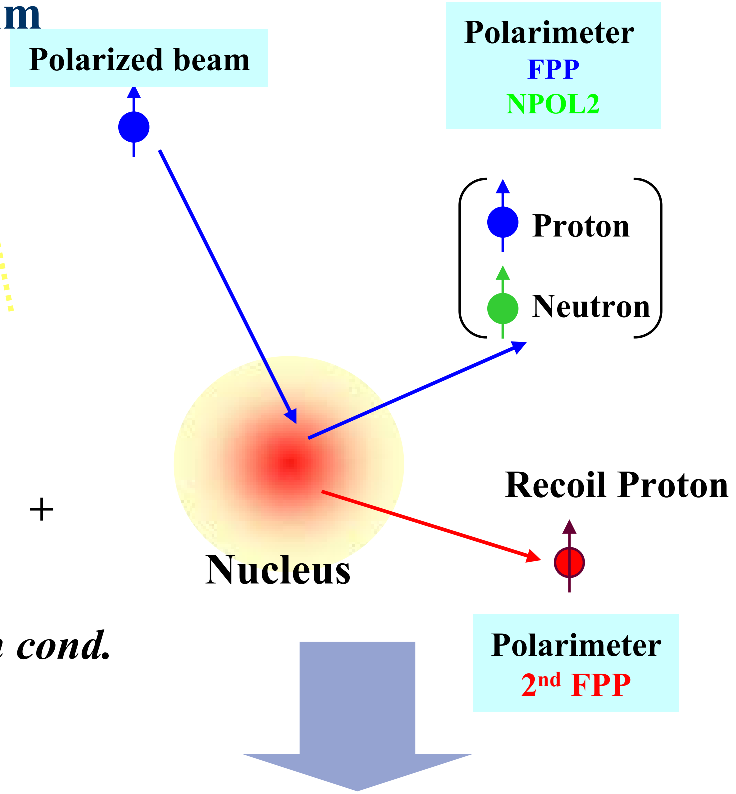
- **AVF Cyclotron**
  - K = 140
  - Max. B = 1.6 T
  - Max. acceleration V = 500 kV
  - RF Frequency = 6 – 19 MHz
  - Weight = 400 t
- **Ring Cyclotron**
  - K = 400
  - Max. B = 1.75 T
  - Max. acceleration V = 500 kV
  - RF Frequency = 30 – 52 MHz
  - Weight = 2200 t
- **Beams and Energies**
  - Protons: 100 – 400 MeV
  - Deuterons: 100 – 200 MeV
  - Helium-3 : 420, 450 MeV
  - Alpha: 200 – 400 MeV



RCNP Ring Cyclotron Facility

Physics Programs with Polarized Beams

- **Nuclear Forces in Nuclear Medium**
  - Proton elastic scattering
    - ***Mesons mass/Coupling const.***
    - ***Neutron density***
  - Proton inelastic scattering
    - ***Isoscalar interaction***
  - (p,2p) reactions
    - ***Nucleon mass***
- **Spin-isospin Modes in Nuclei**
  - (p,n) reactions
    - ***Δ/quark degrees of freedom***
    - ***Isovector interaction***
    - ***Precursor phenomena of pion cond.***
- **Three-Nucleon Force Effects**
  - P+d, d+p, d+d
    - ***Spin dependence of 3NF effects***



- ➢Nuclear Structure
- ➢Nuclear Interaction
- ➢Nuclear Reaction Mechanism

RCNP Ring Cyclotron Facility

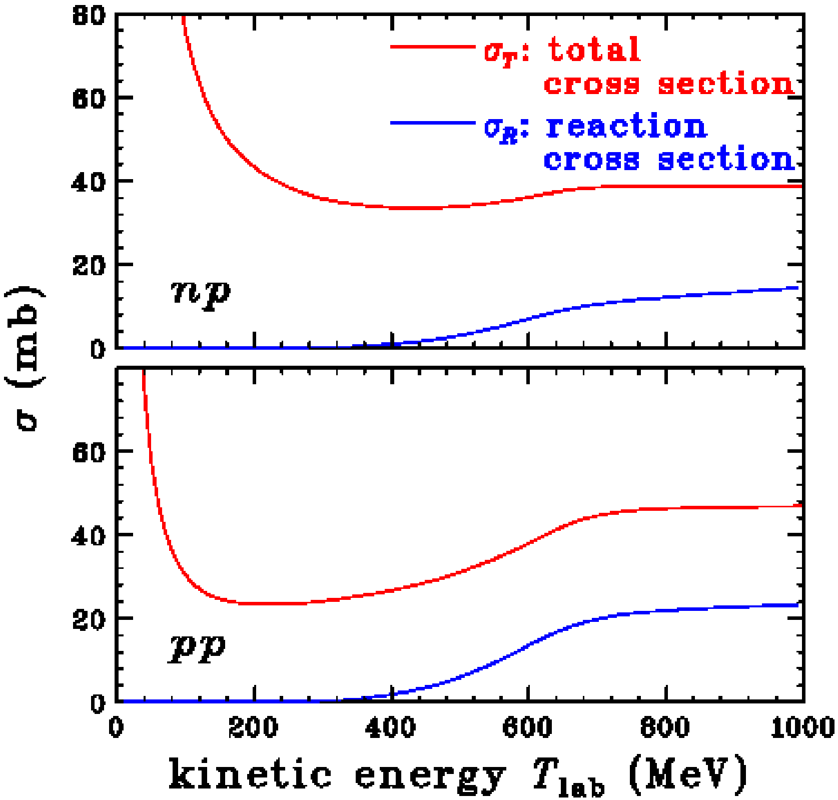
Physics Programs with Light Nuclei

- **Giant Resonances**
  - Isoscalar and Isovector Resonances
  - Monopole, Dipole, and Quadrupole Resonances
- **Pion Production Mechanism in Nucleon-Nucleus Collisions**
  - Nucleon-Nucleon Interactions with Δ in Nucei
- **Solar Neutrino Response by the ^{176}Yb(^{3}He,t) Reaction**
  - Application to the Solar Neutrino Detector
    - ***Standard Solar Model***
    - ***Neutrino Oscillation***
- **Weak Hyperon Nucleon Interaction**
- **Fragmentation of Deep Hole States in Light Nuclei**
- **Proton-Proton Bremsstrahlung (p,p'γ) Reaction**

RCNP Ring Cyclotron Facility

Distortion Effects

- **Distortions via Nuclear Mean Field**
  - NN total cross sections
- **Around E/A=300MeV/u**
  - Smallest effects of distortions
  - Total NN cross section is minimum
- **Clean Measurement**
  - Suitable for nuclear spectroscopy
- **RCNP is a Unique Facility**
  - **Energy region covered by RCNP**



Spin-Isospin Modes

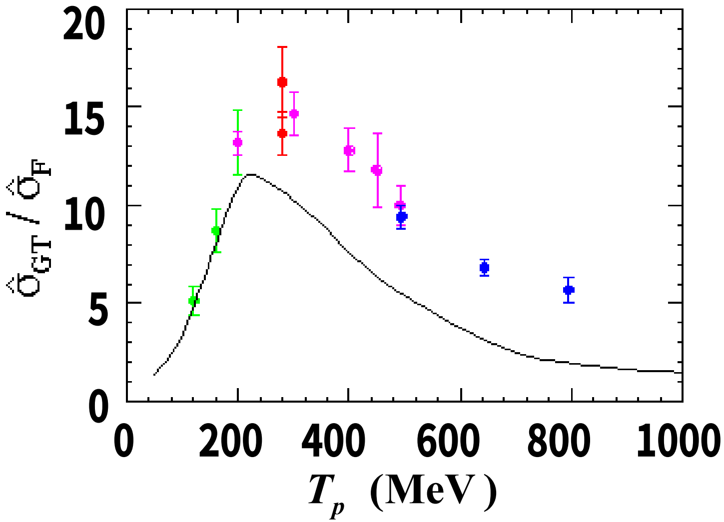
- **Filtering to Spin-Isospin Modes in Charge Exchange Reactions**
  - Momentum transfer = 0
- **For L=0 (GT vs Fermi)**

$$\sigma_{GT} = K_{GT}\, N_{GT} \left| J_{\sigma\tau} \right|^2 B(GT) = K_{GT}\, \hat{\sigma}_{GT}\, B(GT)$$

$$\sigma_{F} = K_{F}\, N_{F} \left| J_{\tau} \right|^2 B(F) = K_{F}\, \hat{\sigma}_{F}\, B(F)$$

$$R^2 = \hat{\sigma}_{GT} / \hat{\sigma}_{F} = \left| J_{\sigma\tau} / J_{\tau} \right|^2 \left(N_{GT} / N_{F} \right)$$

K Kinetic factor
N Distortion factor
J Fourier transform of t-matrices
B Nuclear structure factor
(GT and Fermi strengths)



- IUCF data, T.N. Taddeucci et al., Nucl. Phys. A469, 125 (1987).
- RCNP data, T. Wakasa et al., Phys. Rev. C51, R2871 (1995).
- TRIUMF data, W.P. Alford et al., Phys. Lett. B179, 20 (1986).
- LAMPF data, E. Sugarbaker et al., Phys. Rev. Lett. 65, 551 (1990).
- calc. using t-matrix interaction

Franey and Love, Phys. Rev. C31, 488 (1985).

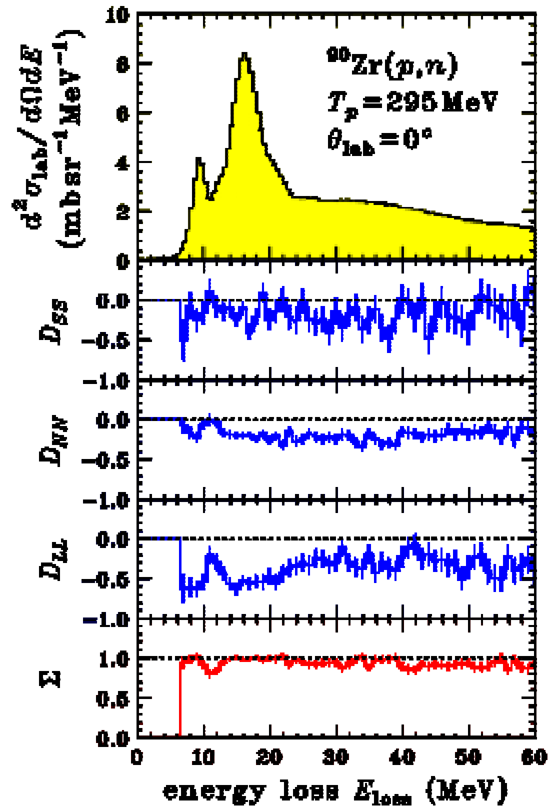
Spin-Flip (GT) Dominance in the (p,n) Reaction

- **Total Spin Transfer Σ**

$$\Sigma(0°) = \frac{3 - \left[2\, D_{NN}(0°) + D_{LL}(0°)\right]}{4}$$

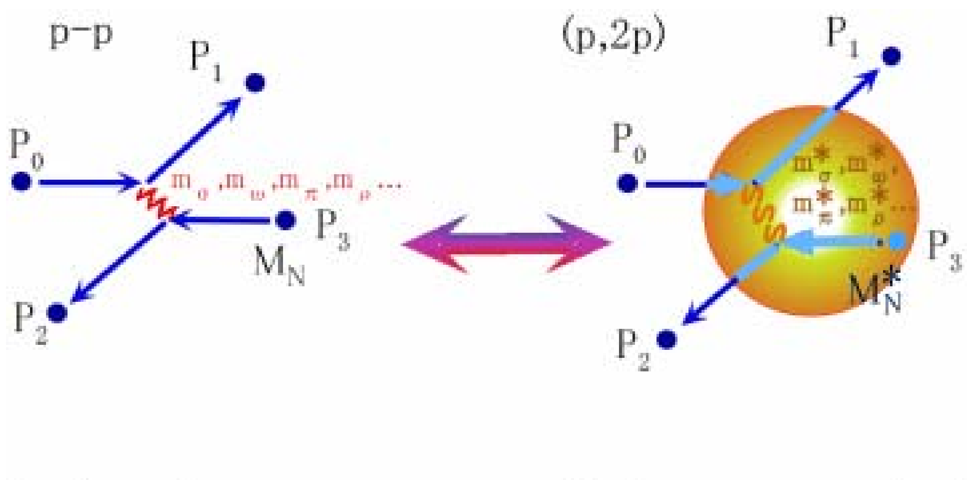
$$= 0\ (\Delta S = 0)\ \text{or}\ 1\ (\Delta S = 1)$$

  - Independent of NN amplitudes and transition form factors
  - Distinctive values of either 0 (Σ=0) or 1 (Σ=1)
- **Experimental Results**
  - Σ in GTGR = 0.99±0.01
    almost all strength
    = spin-flip GT strength
  - Σ in the continuum > 0.86
    Predominance of spin-flip strength



Modification of Hadron Properties in Nuclei

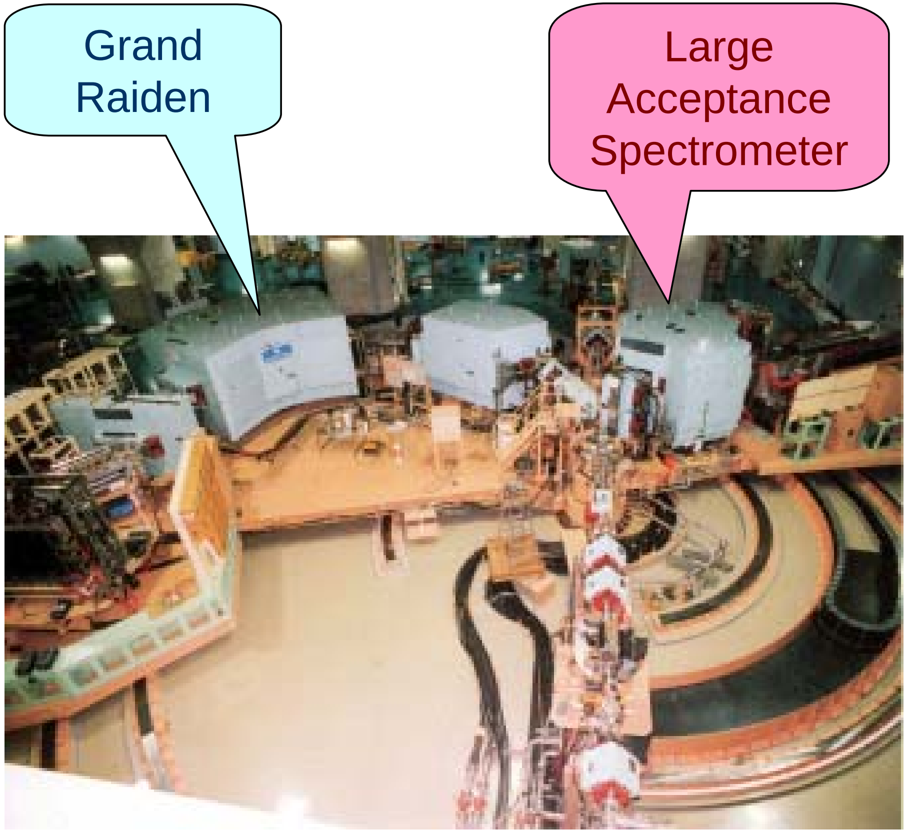
- **Partial Restoration of Chiral Symmetry in Nuclei**
  - Modification of Hadrons
    - ***Nucleon mass***
    - ***Meson mass***
  - Modification of NN Int.
- **Physics Goal**
  - Extract NN Int. in Nuclei
  - Extract Hadron Properties in Nuclei
- **Experiment**
  - Exclusive (p,2p) measurements
  - Complete measurements of polarization observables
  - Control nuclear density



RCNP Ring Cyclotron Facility

Two-Arm Spectrometers

- **Grand Raiden**
  - Resolution = 37,000
  - Momentum Byte = 1.05
  - Acceptance = 5.6 msr
  - Max. Bρ = 5.4 Tm
  - Weight = 600 t
- **Large Acceptance Spectrometer**
  - Resolution = 6,000
  - Momentum Byte = 1.35
  - Acceptance = 20 msr
  - Max. Br = 3.2 Tm
  - Weight = 150 t

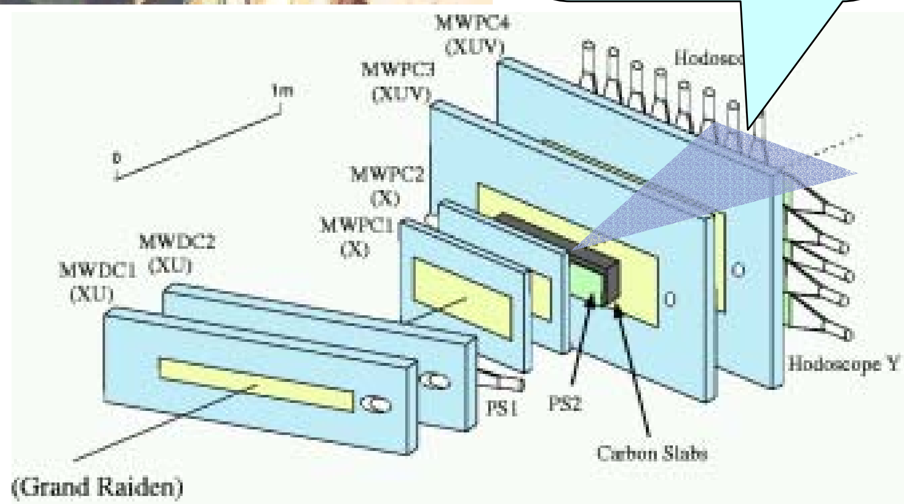


Polarization Measurement

- **Observables**
  - Cross sections
  - Analyzing powers
  - Polarization transfer observables (with FPP)

$$D_{ij} \propto \frac{1}{Ay}\frac{Y_{L(U)} - Y_{R(D)}}{Y_{L(U)} + Y_{R(D)}}$$

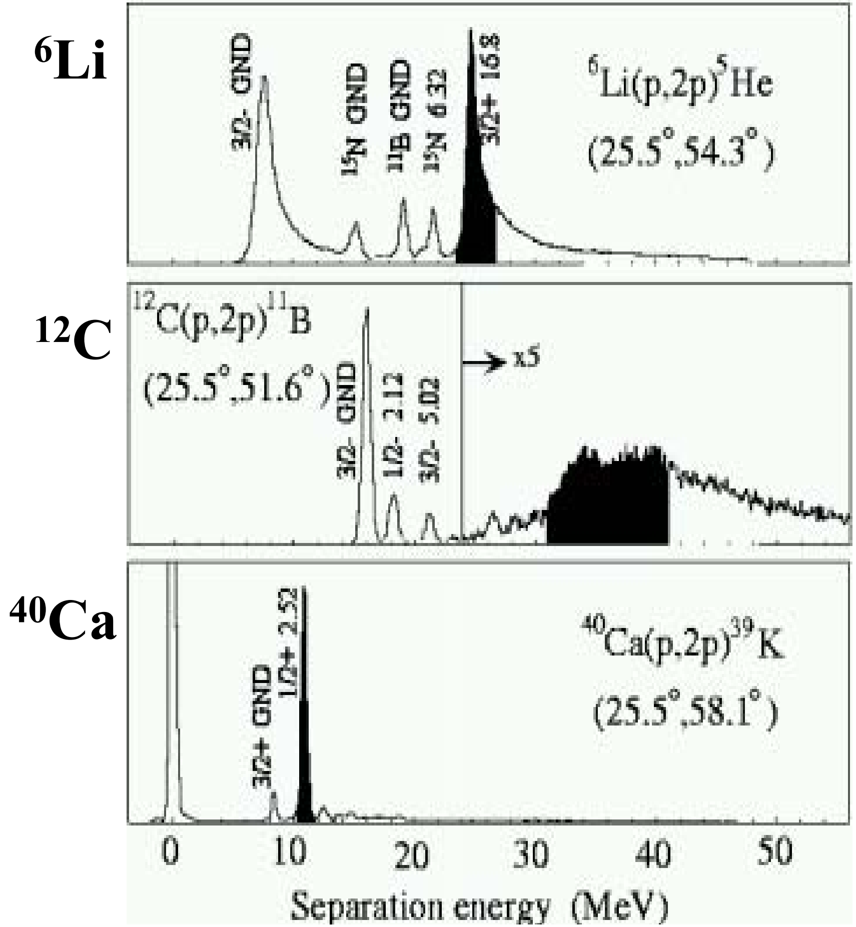
2nd level trigger :
→Use FPGA (Field Programmable Gate Array)
Reject the events scattered at forward angles which is not necessary to determine Dij



- **Experimental Conditions**
  - Beam = 392 MeV protons
  - Current = 0.1 – 100 nA
  - Targets = ^{6}Li, ^{12}C, ^{16}O, ^{40}Ca,
  - Resolution = 350 keV

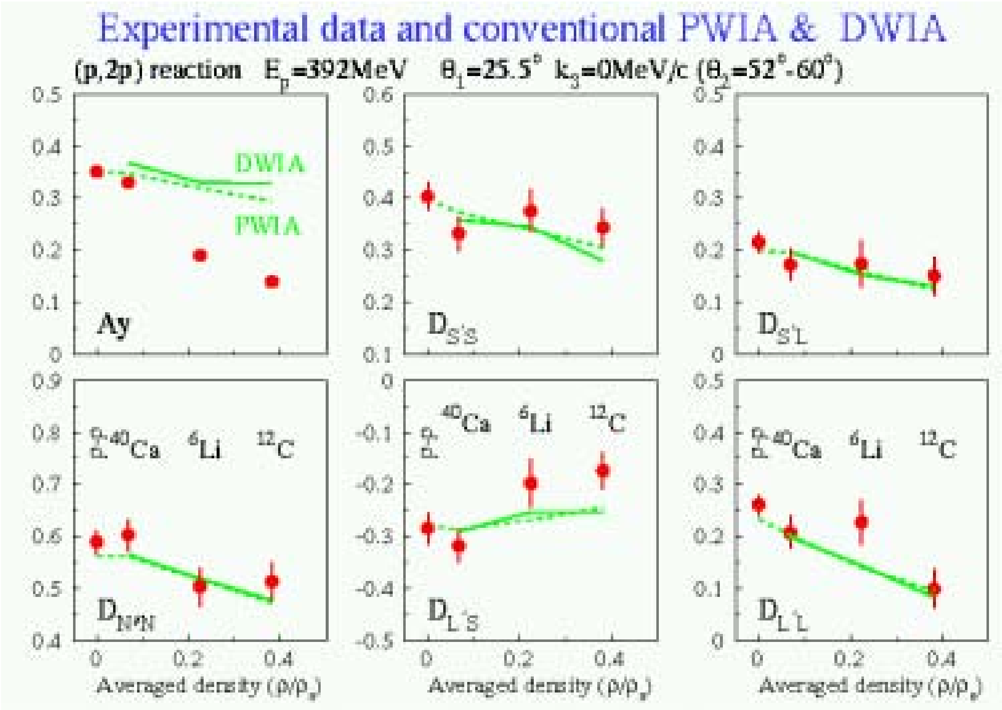
Energy Spectra

- **Measurements**
  - Knockout of $s_{1/2}$ at rest
    (Zero Recoil Condition)
- **Advantage**
  - Unpol. Target nucleons in $s_{1/2}$
  - Simple relation between (p,2p) measurements and NN interactions in nuclei
- **Observed Spectra**
  - Resolution = 350 keV
  - Clear observation of $s_{1/2}$
  - Filled $s_{1/2}$ events were used



Results

- **Features**
  - A_y and D_{ij}: Clear Density Dependence
  - A_y: not reproduced by DWIA
  - D_{ij}: well reproduced by DWIA
  - Small distortion effects (DWIA = PWIA)
- **Medium Effects**
  - Multi-step: Not likely (D_{ij} are well reproduced by DWIA)
  - Small distortion effects
  - Modification of NN interactions



RCNP Ring Cyclotron Facility

Medium Effects in A_y

- **Pauli Blocking effects**
  - G-matrix (NN int. in nuclei)
    - ***Amos Group***
      Fully microscopic
    - ***Kelly Group***
      Empirical
  - Not reproduce Ay
- **Hadron Mass Reduction**
  - Reduction of nucleon mass
    (In strong scalar potential)

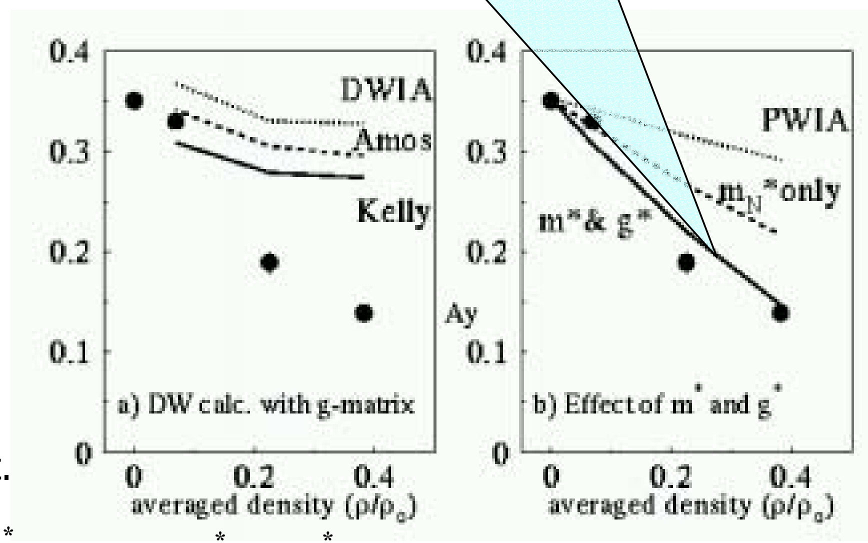
$$\mathbf{m_N}^* = \mathbf{m_N} + S(r)$$

  - Reduction of meson mass
  - Reduction of coupling const.

$$\frac{\mathbf{m_N}^*}{\mathbf{m_N}} = \frac{\mathbf{m_\sigma}^*}{\mathbf{m_\sigma}} = \frac{\mathbf{m_\omega}^*}{\mathbf{m_\omega}} = \frac{\mathbf{m_\rho}^*}{\mathbf{m_\rho}} = 0.7\,, \quad \frac{\mathbf{g_\sigma}^*}{\mathbf{g_\sigma}} = \frac{\mathbf{g_\omega}^*}{\mathbf{g_\omega}} = 0.75$$

  - Well reproduce Ay

Reproduce the density dependence of Ay well by the hadron mass reduction



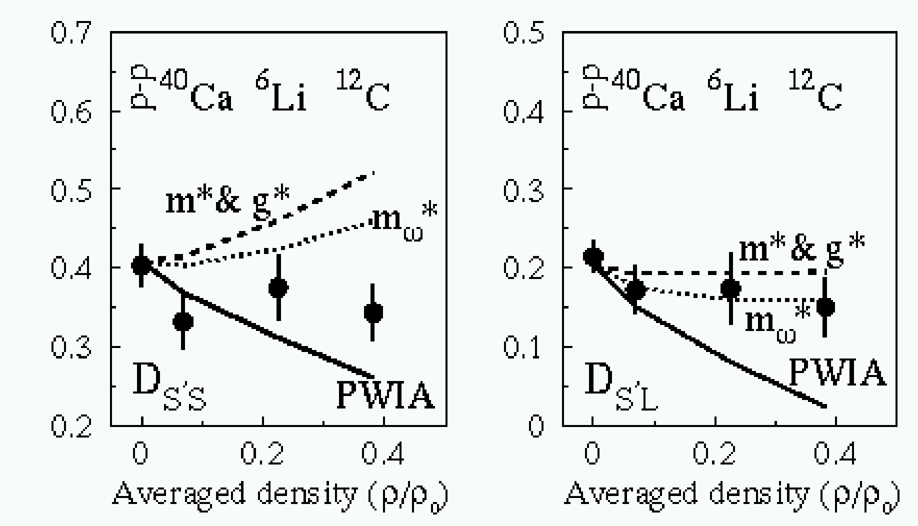
Medium Effects in D_{ij}

- **Universal Scaling**

$$\frac{m_N^*}{m_N} = \frac{m_\sigma^*}{m_\sigma} = \frac{m_\omega^*}{m_\omega} = \frac{m_\rho^*}{m_\rho} = 0.7$$

$$\frac{g_\sigma^*}{g_\sigma} = \frac{g_\omega^*}{g_\omega} = 0.75$$

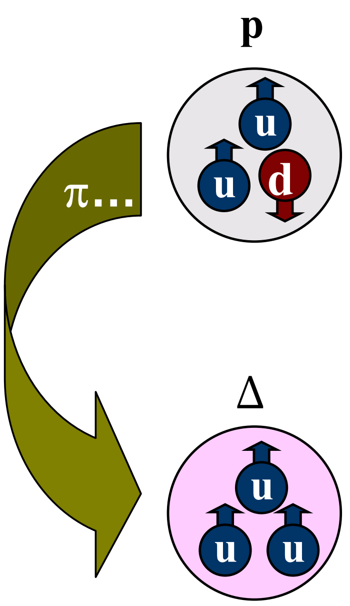
  - Not reproduce all D_{ij} (universal scaling → ×)
  - D_{ij} is sensitive to one meson mass scaling (not all masses)



- **D_{ij} are important to extract the information on hadron properties (mass and coupling constant) w/o universal scaling ansatz**

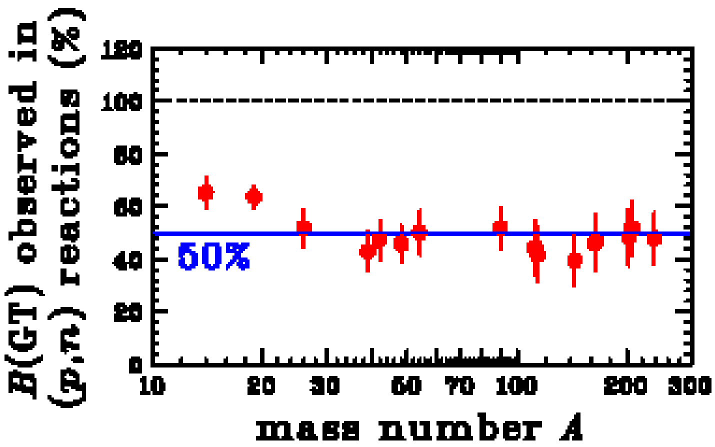
Pions in Nuclei

- **Pions in Nuclei**
  - Strong attractive force
  - **Induce pionic nuclear collectivity**
- **Framework**
  - Nucleon, pion (meson), and Δ (quark spin-flip)
  - Interactions
    - ***Long-range OPE***
    - ***Middle-range heavy-meson exchange (ρ,ω,σ,…)***
    - ***Short-range tensor***
    - ***Zero-range Landau-Migdal***
- **Physics**
  - Quenching of Gamow-Teller strength at q = 0
    - ***Quark (Δ) degrees of freedom in low-energy phenomena***
  - Enhancement of Spin-longitudinal Response at large q
    - ***Precursor phenomena of pion condensation***
  - **Explorer pions in nuclei (pionic collectivity) in wide q region**

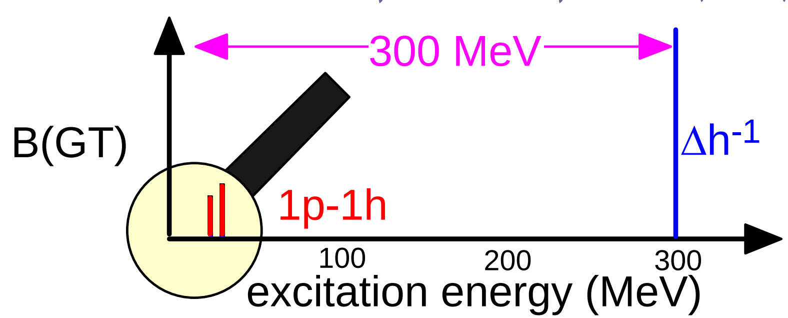


Quenching Problem for Gamow-Teller Strength

- **B(GT) Observed from (p,n) Reactions**
  - 50% of Ikeda sum rule value of 3(N-Z)
- **Mechanisms Proposed for Quenched B(GT)**
  - ΔN^{-1} admixture into 1p1h GT states
  - Nuclear configuration mixing
- **GT strength might be located in the continuum beyond GTGR**
  - MDA should be performed to extract L=0 GT strength



C. Gaarde, NP A396, 127c (1983)



Bohr and Mottelson, PL 100B, 10 (1981)

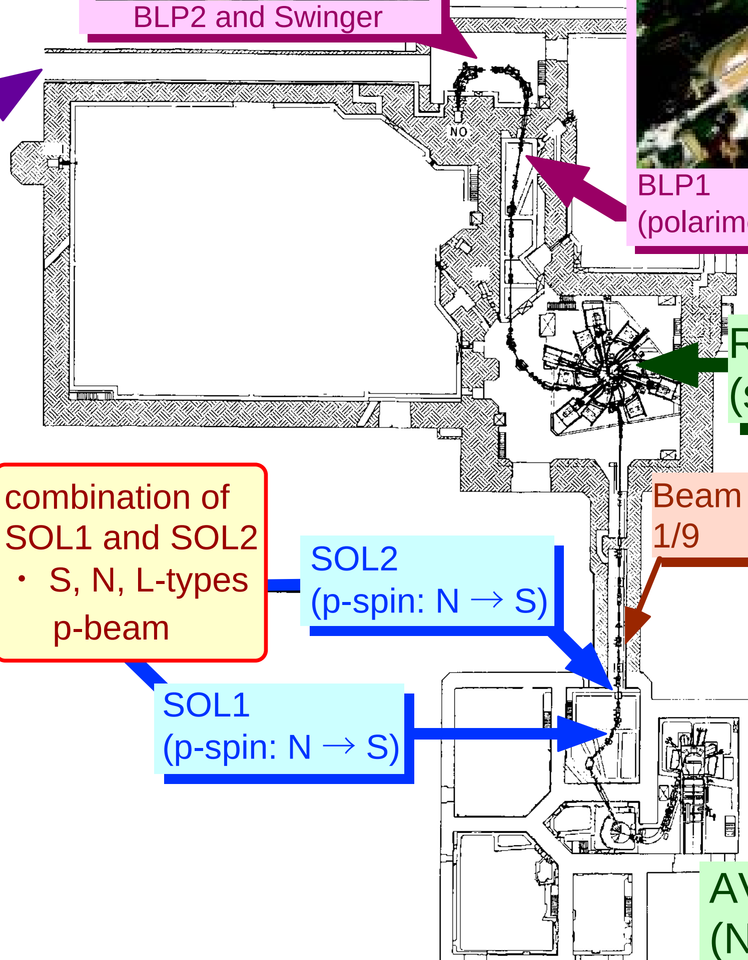
NTOF Facility and NPOL2

BLP2 and Swinger

combination of BLP1 & BLP2
- determine (p_S, p_N, p_L)

BLP1
(polarimetry: $^1H(p,p)^1H$)

n-Polarimeter NPOL II



RING cyclotron
(single-turn ext.)

Beam Pulsing Device
1/9

combination of SOL1 and SOL2
- S, N, L-types p-beam

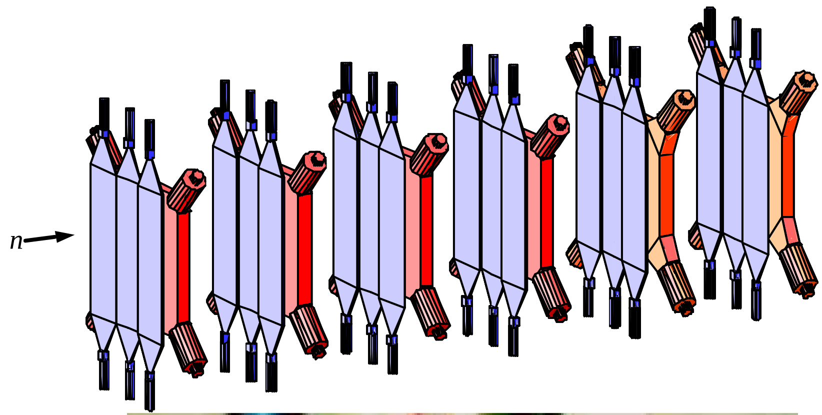
SOL2
(p-spin: N → S)

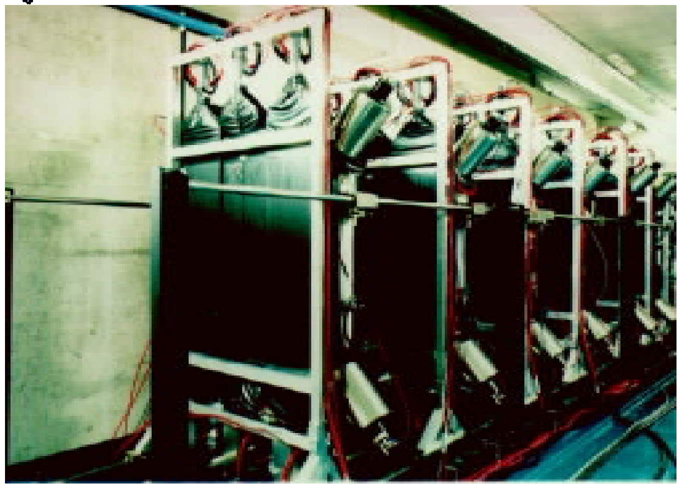
SOL1
(p-spin: N → S)

AVF cyclotron
(N-type p-beam)

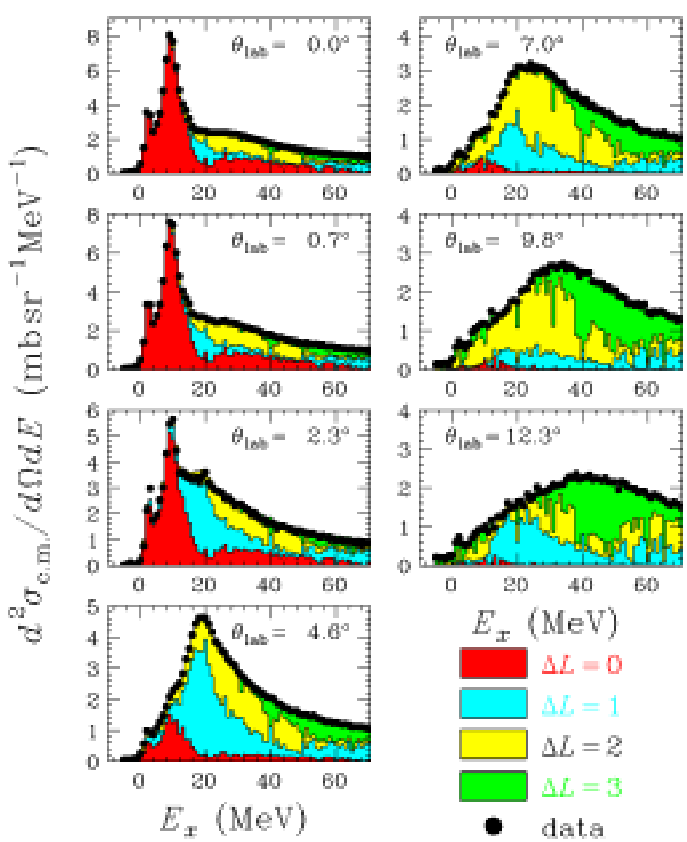
Neutron Polarimenter NPOL2

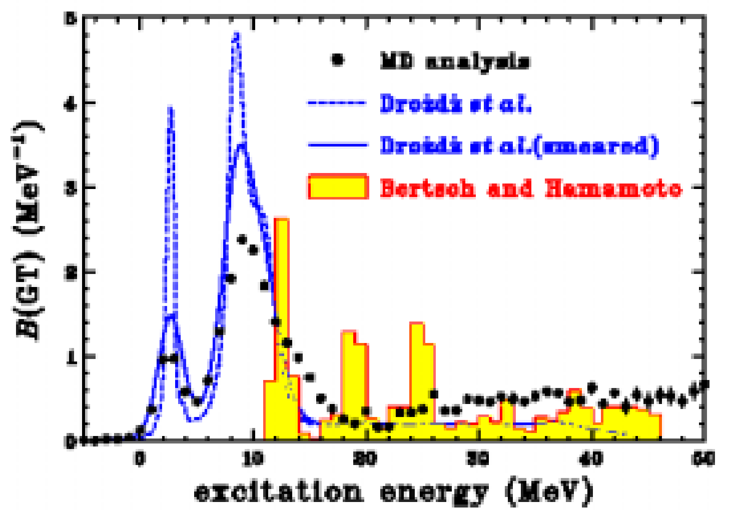
- **Position Sensitive 2D Neutron Detectors**
  - 6 layers
  - 1 m x 1 m x 0.1 m
  - 4 layers: Liquid sci. BC519
  - 2 layers: Plastic sci. BC408
- **High Performance of Neutron Polarimetry (FOM)**
  - IUCF 4.6×10^{-5} @ 160 MeV
  - LAMPF 2.3×10^{-4} @ 500 MeV
  - RCNP 4.9×10^{-4} @ 300 MeV
- **High Efficiency of Neutron Detection**
  - RCNP 0.15 @ 150- 400 MeV





Result of MDA and B(GT) Strength in the Continuum



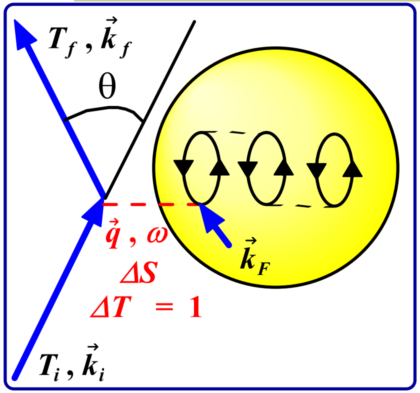


G.F. Bertsch and I. Hamamoto, PRC 26, 1323 (1982)
S. Drożdż et al., PL B166, 18 (1986)

$$\sum B(\mathrm{GT})\left[E_x \le 50\ \mathrm{MeV}\right]$$
$$= 28.0 \pm 1.6(\mathrm{MDA}) \pm 5.4(\hat{\sigma}_{\mathrm{GT}})$$
$$= 93\%\ \text{of minimum sum–rule} : 3(N - Z) = 30$$

Quasi-elastic Scattering

- **QES Process**
  - Momentum Transfer: q
  - Energy Transfer: ω
  - Spin Transfer: ΔS
    - *Longitudinal (π) vs. Transverse (ρ)*
  - Isospin Transfer: ΔT



- **Simple Reaction Mechanism**

Factorized impulse-approximation model

$$\sigma_{\text{QES}}(q,\omega) = N_{\text{eff}} \cdot \sigma_{NN}(q,\omega) \cdot R(q,\omega)$$

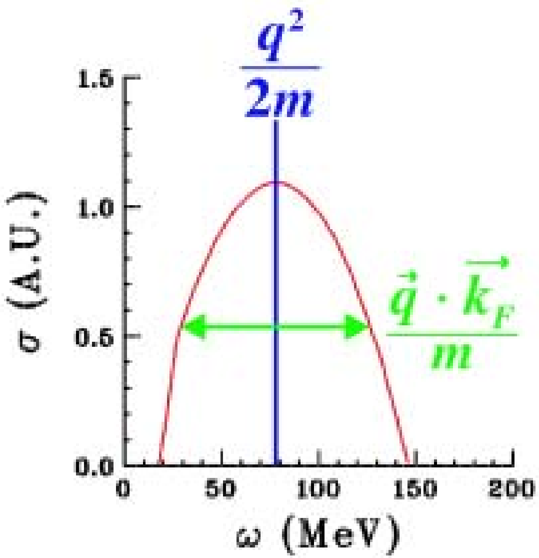
$D_{ij} \rightarrow$ (distortion) ⊗ (NN interaction) ⊗ (response)

- **Kinematics**

$$\omega = \frac{(\vec{q}+\vec{k}_F)^2}{2m} - \frac{(\vec{k}_F)^2}{2m}$$

$$= \frac{q^2}{2m} + \frac{\vec{q}\cdot\vec{k}_F}{m}$$

peak ($\frac{q^2}{2m}$) width ($\frac{\vec{q}\cdot\vec{k}_F}{m}$)



Pionic Correlations in Nuclei

- **π+ρ+g' Model Interaction**
  - Spin-longitudinal (π) interaction
    - ***Attractive at $q > 0.8\ fm^{-1}$***
  - Spin-transverse (ρ) interaction
    - ***Repulsive***
- **Nuclear Spin Response**
  - Longitudinal Response

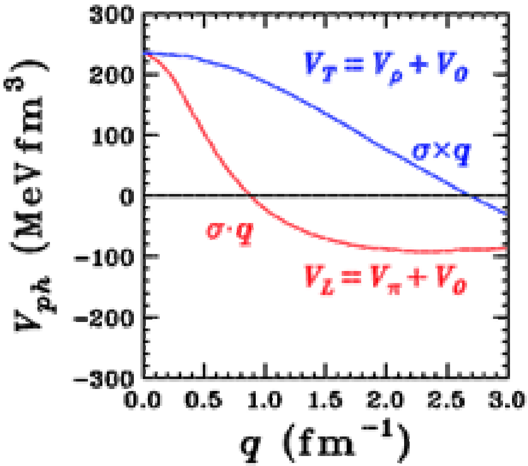
$$R_L \propto \left| \langle n | \sigma \cdot \mathbf{q} | 0 \rangle \right|^2$$

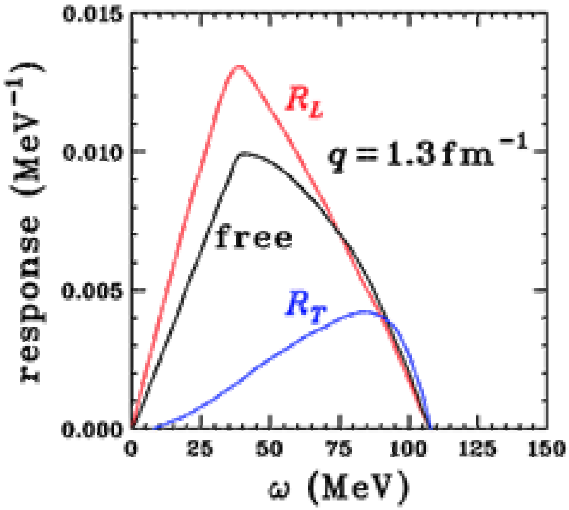
    - ***Enhancement and Softening***
  - Transverse Response

$$R_T \propto \left| \langle n | \sigma \times \mathbf{q} | 0 \rangle \right|^2$$

    - ***Quenching and Hardening***

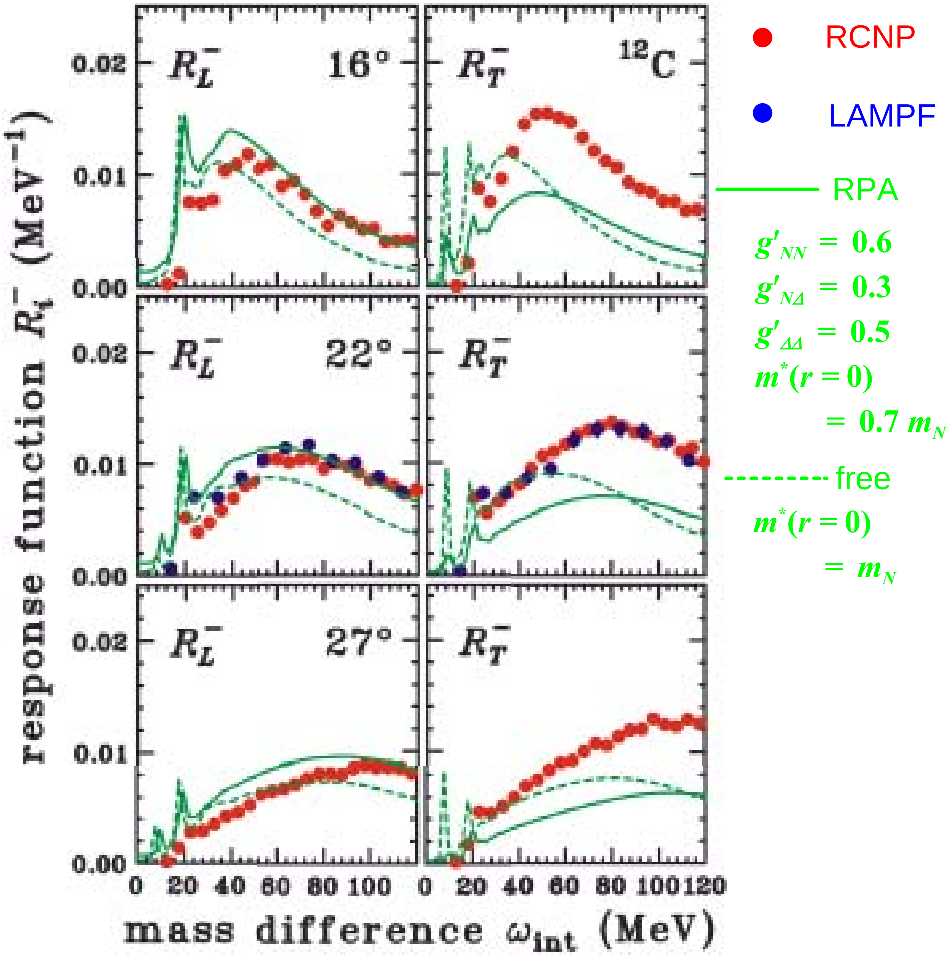
$$\Rightarrow \textbf{enhancement of } \frac{R_L}{R_T}$$





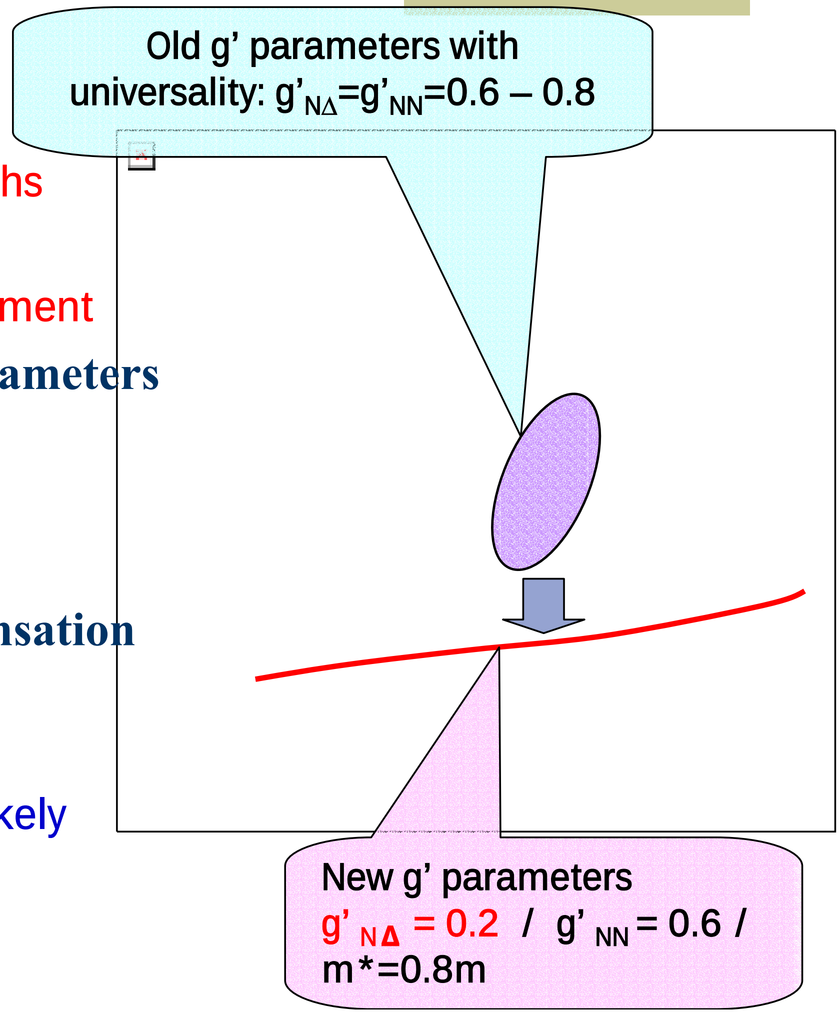
Response Functions

- **Enhancement of R_L**
  - Signature of pionic correlations at low q
  - Pionic correlations is not strong at large q (2.0 fm^{-1})
- **Hardening of R_T**
  - Standard ρ-exchange model is OK
- **"No" Quenching of R_T**
  - Reaction Mechanisms
    - ***Spin-dependent distortion effects***
    - ***Two-step processes***
  - Relativistic Effects



Pion Condensation in Neutron Star

- **Experimental data**
  - Excitation energy of GT states
  - Quenching factor of GT strengths
    - $Q = 0.8 - 0.9$
  - Observation of pionic enhancement
- **Determine Landau-Migdal Parameters**
  - $g'_{NN} = 0.6$
  - $g'_{N\Delta} = 0.2 - 0.3$
  - $g'_{\Delta\Delta} < 1$ (not sensitive)
- **Critical Density of Pion Condensation in Neutron Star**
  - Density: $1.4 - 2.2\ \rho_0$
  - Pion condensation becomes likely
  - Accelerate the cooling of neutron star



2N Forces and Triton Binding Energy

- **Hamiltonian of Many Body System**

$$H = \sum_i \frac{p_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \cdots$$

2N force 3N force

- **NN Interaction**
  - Reproduce NN data with $\chi^2/N=1$
  - Reproduce Deuteron Properties
    - E_B, A_S, D/S, Q…
- **3N Systems**
  - Faddeev solution of 3N bound (triton) system
  - Consistent results within 10 keV with different NN interactions
  - Underbind the triton by 800 keV

	B of ^3H	χ^2/N	Type
Nijm II	7.6 MeV	1.0	local
Reid 93	7.6 MeV	1.0	local
Argonne AV18	7.6 MeV	1.1	local
Nijm I	7.7 MeV	1.0	non-local
CD Bonn	8.0 MeV	1.0	non-local
CD Bonn	8.2 MeV	1.0	relativistic & non-local
Exp.	8.5 MeV		

- Clear signature of 3NF (V_{123}) effects

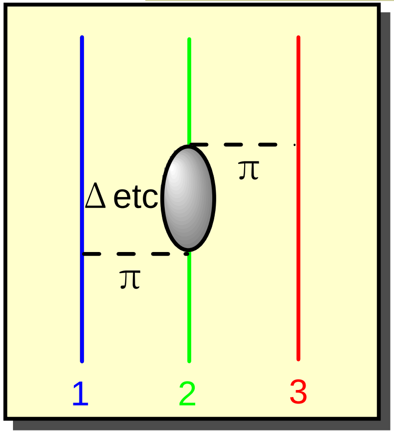
3N Forces

- **2π-Exchange 3NF**
  - A virtual Δ resonance induces 3NF (Fujita-Miyazawa type)
  - Extended to
    - ***Urbana-Argonne 3NF***
    - ***Tucson-Melbourne 3NF***
- **Urbana-Argonne 3NF**

$$A_{2\pi}\ [2\pi - \text{exchange (Fujita} - \text{Miyazawa type)}]$$

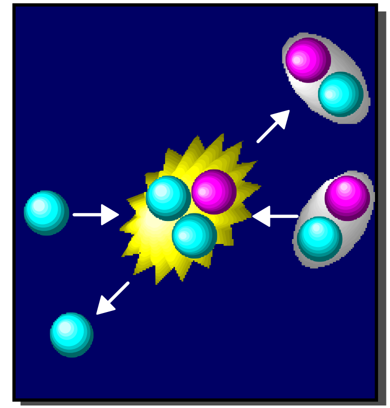
$$+\ U_0\ [\text{Short Range (Tensor type)}]$$

  - $A_{2\pi}$,U_0: Adjustable parameters
- **Tucson-Melbourne 3NF**
  - Generated with πN scattering amplitudes
  - One free (adjustable) cutoff parameter of πNN vertex
- **Adjusted 3NFs reproduce triton binding energy very well**

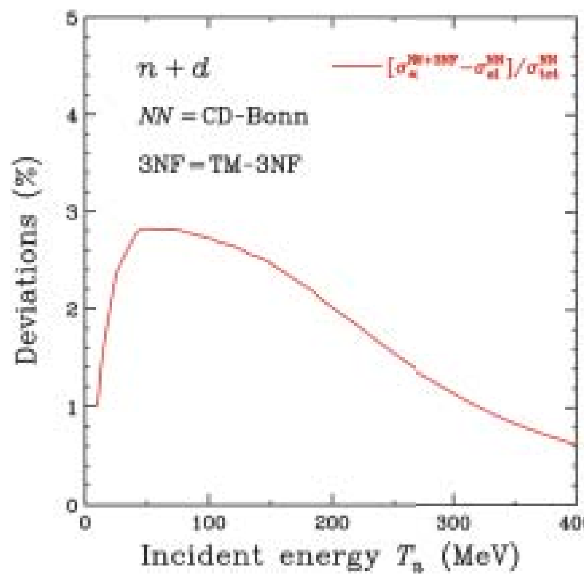


	B of ^3H
CD Bonn + TM-3NF	8.5 MeV
Nijm II + TM-3NF	8.5 MeV
AV18 + TM-3NF	8.5 MeV
AV18 + UA-3NF	8.5 MeV
Exp.	8.5 MeV

3N Forces in 3N Systems



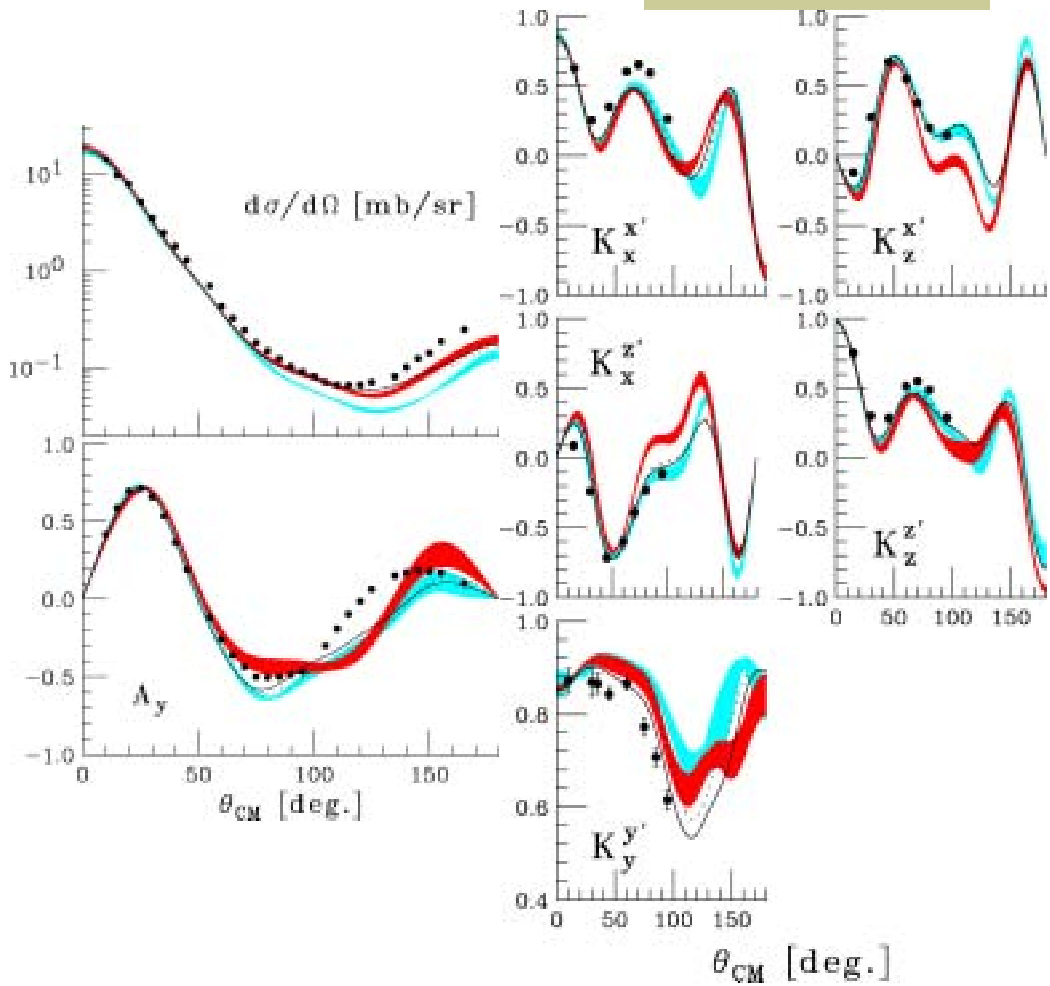
- **Test of 3NF**
  - Free parameters in 3NF:
    Adjusted to reproduce ^{3}H binding energy
  - Can explain other properties of 3N systems ?
- **Unbound 3N Systems**
  - p+d elastic scattering: A simplest case
  - ω-/q-transfers can be controlled
  - Various observables including PTO are measurelable
- **3NF Effects**
  - Effects in elastic channel are fairly large arount 100 MeV
  - RCNP is a unique facility to explorer 3NF effects



RCNP Ring Cyclotron Facility

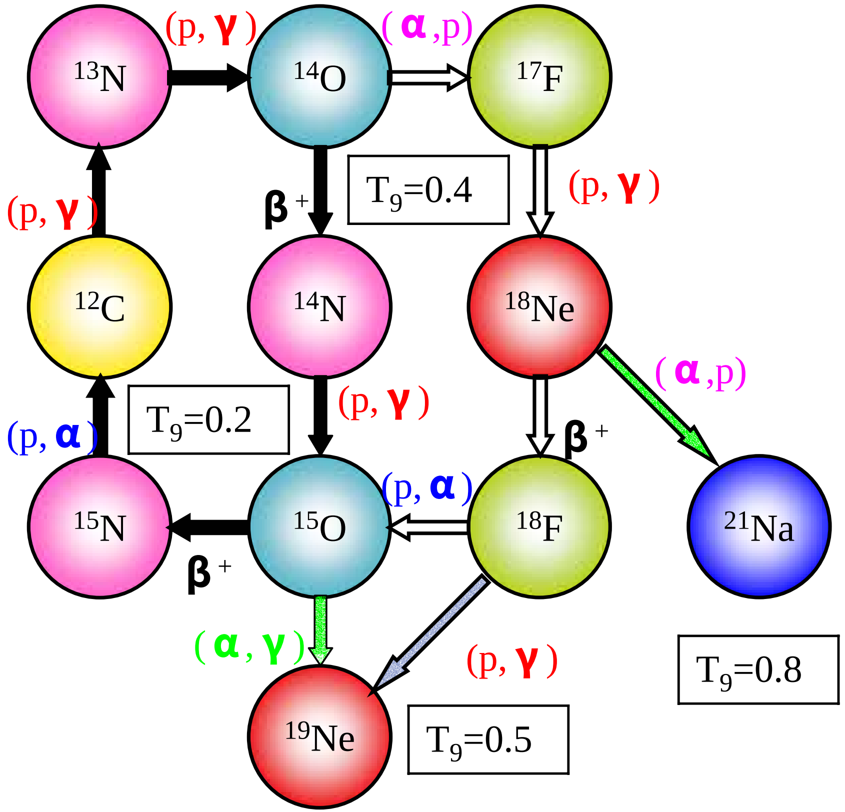
3NF Effects in p+d Elastic Scattering

- **2N Force only**
  - Not reproduce σ
  - Not reproduce A_y
  - Reproduce D_{ij} fairly well
- **2N+3N Forces**
  - Reproduce σ fairly well
  - Not reproduce A_y
  - Not reproduce D_{ij}
- **Difference between Experimental Data and Faddeev Calc.**
  - Spin-dependent 3NF
  - Relativistic Effects



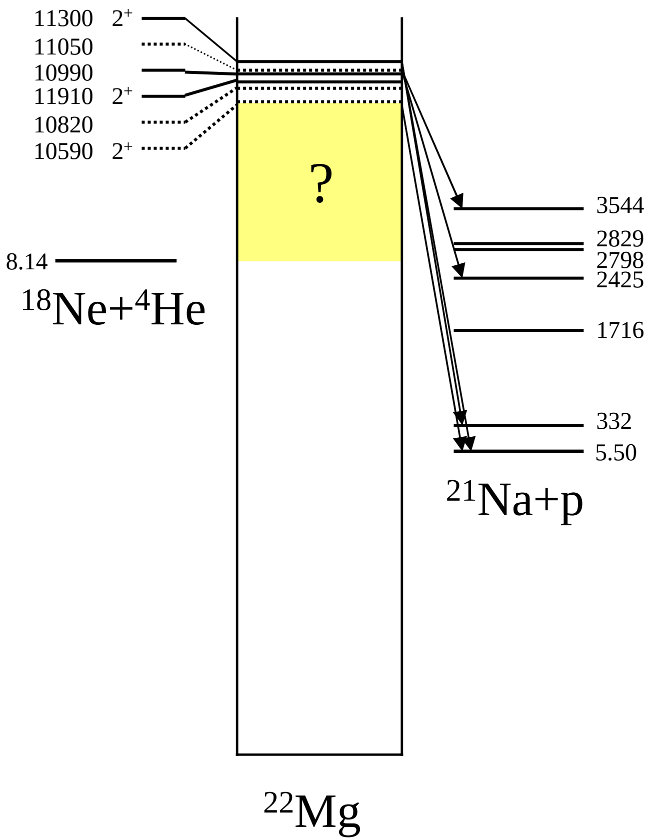
H-CNO Cycle

- **At T_9=0.2**
  - CNO cycle only
- **At T_9=0.4**
  - Start bypass cycle through $^{14}O(\alpha,p)^{17}F$
- **At T_9=0.5**
  - Breakout from CNO cycle through $^{15}O(\alpha,p)^{19}N$
- **At T_9=0.8**
  - Breakout from CNO cycle through $^{18}Ne(\alpha,p)^{21}Na$



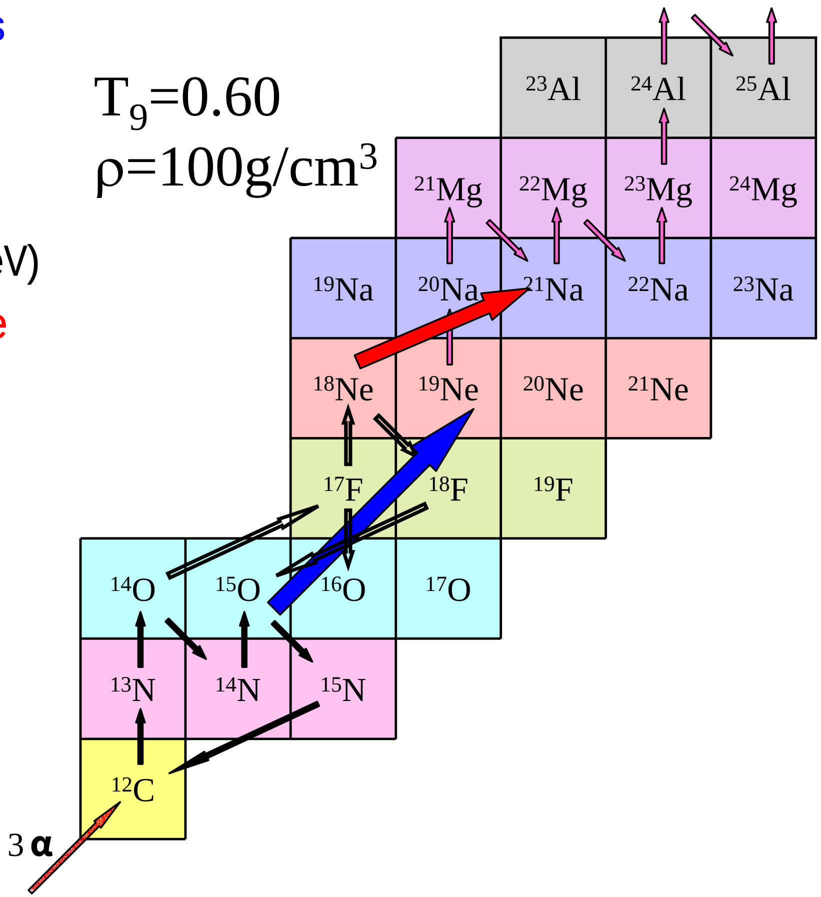
Level Scheme of ^{22}Mg

- Level scheme of ^{22}Mg is determined by the ^{21}Na+p reaction
  - Inverse kinematics
- Levels at E_x=8-10.6 MeV are unknown
- If there are some levels,
  - breakout of CNO cycle is accelerated through ^{18}Ne(α,p)^{21}Na at T_9=0.8



Breakout from CNO Cycle

- **At T_9=0.60**
  - Breakout from CNO cycle is mainly via $^{16}O(\alpha,p)^{19}Ne$
- **At T_9=0.8**
  - If there are some levels in low energy region (E_x>8 MeV)
  - ⇒Breakout from CNO cycle is accelerated through $^{18}Ne+\alpha \rightarrow ^{22}Mg^* \rightarrow ^{21}Na+p$



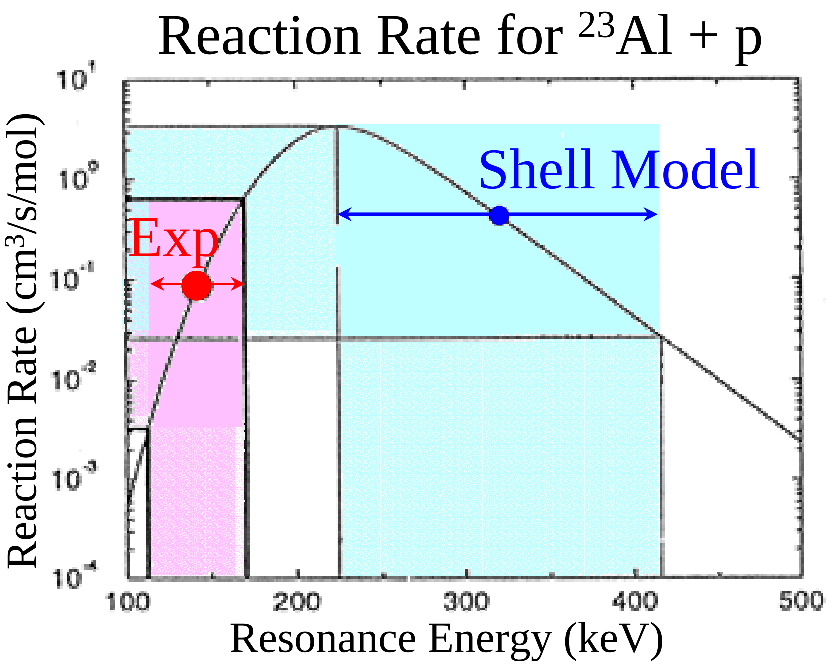
Requirement for High-Resolution Spectroscopy

- **Reaction cross section**

$$\sigma = \frac{\Gamma^2}{(E - E_R)^2 + (\Gamma/2)^2}$$

E_R: Resonance energy
Γ: Resonance Width

- **Luminosity**
  - Boltzmann distribution with stellar temperature
- **Reaction rate is sensitive to resonance energy**
  - E_R should be determined experimentally with high accuracy (high resolution)
- **Experimentally determined reaction energy E_R**
  - significantly different with theoretical one



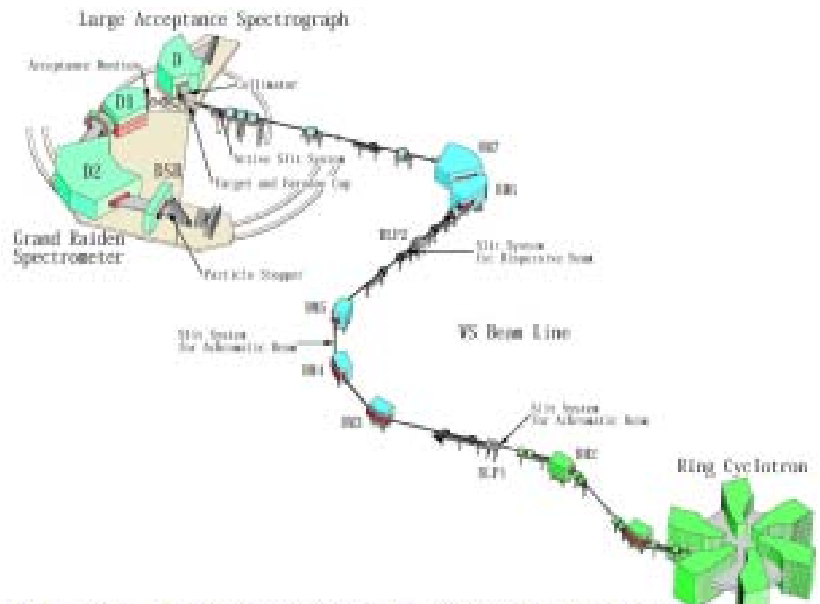
WS Beam Line at RCNP

West Experimental Hall at RCNP

- RCNP new beam line for GR/LAS
- Constructed in 1999-2000
- Experiments with WS after April 2000
- Complete matching with GR
- Double achromatic mode is also available

Specifications of WS

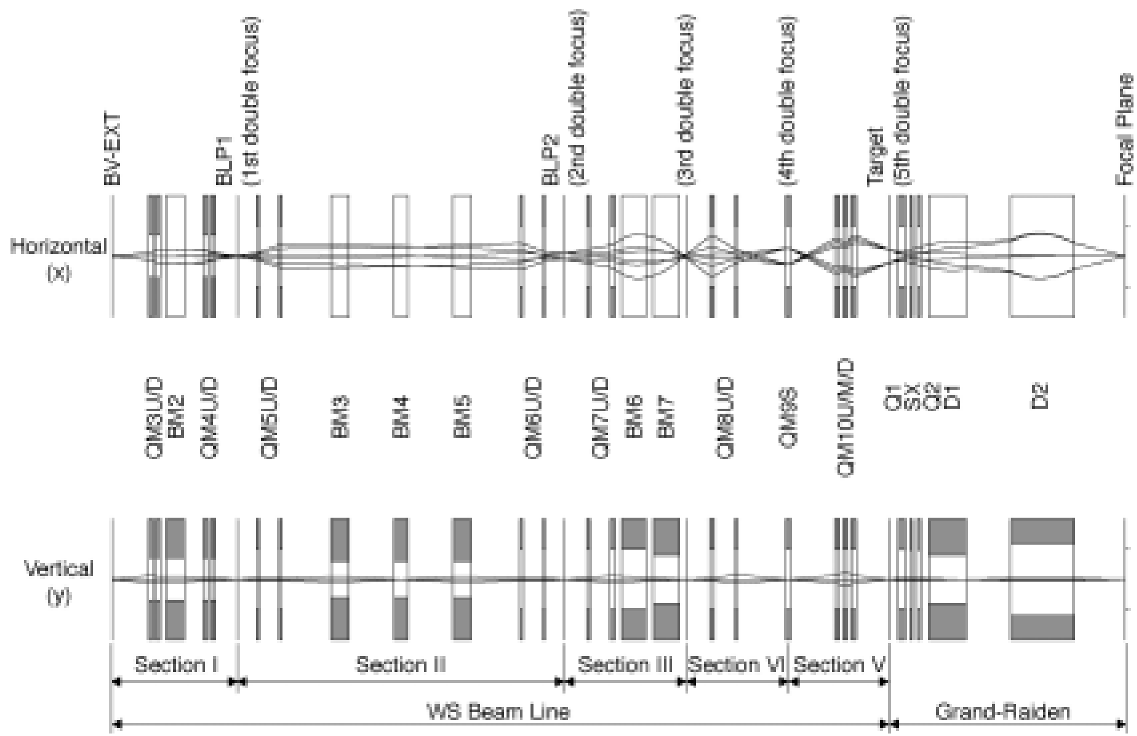
- Total length: 65.46m
- Total bending angle: 270 °
- Five double-focus points (Two for BLP)
- **Dispersive mode**
  - ***Dispersion: 37.1 m***
  - ***Angular dispersion: 20.0 rad***
  - ***Compete matching with GR***
- **Achromatic mode**
  - ***Lateral dispersion: 0 m***
  - ***Angular dispersion: 0 rad***
  - ***Double achromatic beam***



WS Beam Line and Two-Arm Spectrometers at RCNP

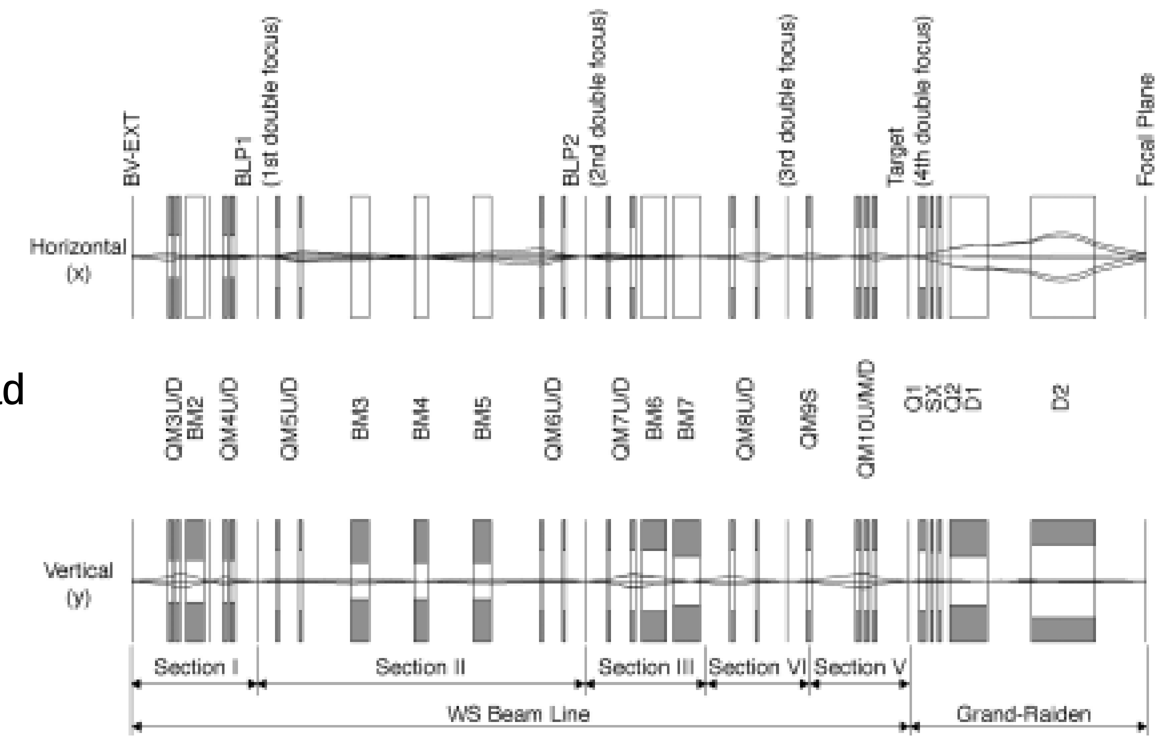
WS Beam Line and Grand Raiden in Dispersive Mode

- **Beam Envelopes**
  - P: ±0.03%
  - θ: ±2mrad
  - ϕ: ±2 mrad
- **Ion-optical properties**
  - M_x: 0.41
  - D: 0 m
  - $(\theta|p)$: 0 rad



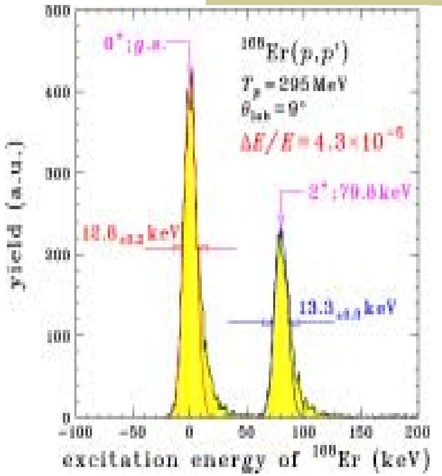
WS Beam Line and Grand Raiden in Achromatic Mode

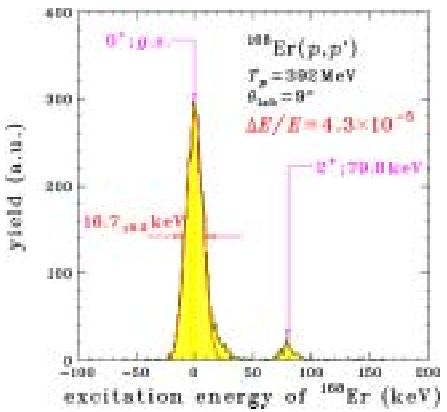
- **Beam Envelopes**
  - P: ±0.03%
  - θ: ±2mrad
  - ϕ: ±2 mrad
- **Ion-optical properties**
  - M_x: 0.41
  - D: 15.1 m
  - (θ|p): 1.13 rad



Typical Spectrum of ^{168}Er(p,p') after Employing Dispersion Matching

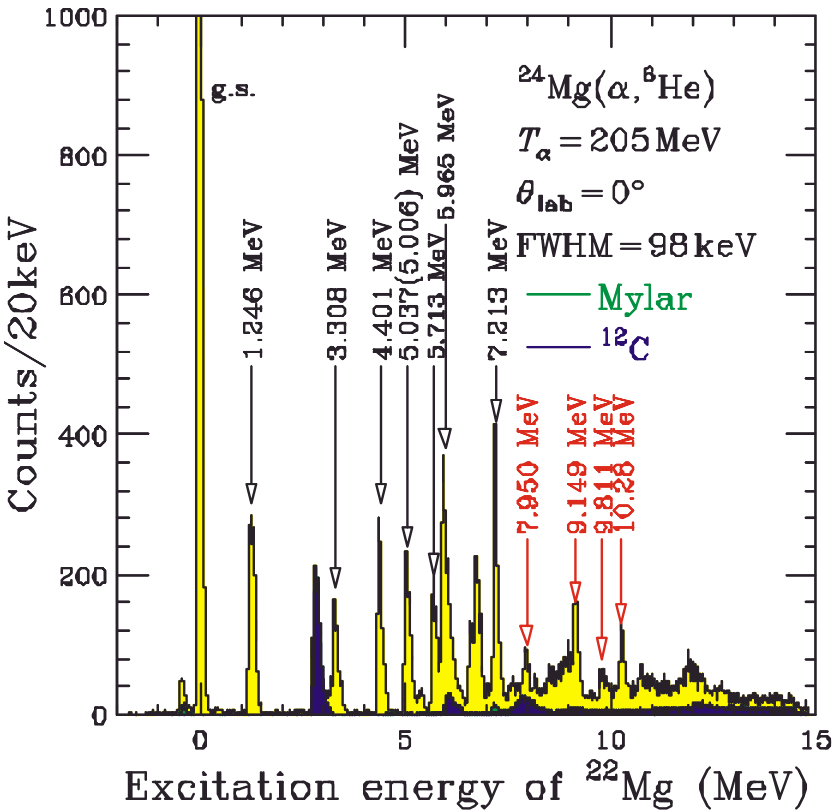
- **Bean energy**
  - 295 MeV (April 2000)
  - 392 MeV (June 2000)
- **Beam energy spread**
  - ΔE: 150 keV(FWHM)
- **Target**
  - ^{168}Er: 2 mg/cm^2
- **Energy resolution**
  - 13.0 keV for 295 MeV
  - 16.7 keV for 392 MeV
- **Energy resolutions are consistent with the resolving power limit of Grand Raiden**





Levels of ^{22}Mg

- **Resonance states in ^{22}Mg studied via the ^{24}Mg(α,^{6}He)^{22}Mg reaction**
- **Experimental conditions**
  - ^{22}Mg: 1.8 mg/cm^2
  - α-beam: 205 MeV, 80enA
  - Beam resolution: >150 keV
  - Final resolution after dispersion matching: 98 keV (determined by target multiformity)
- **Several levels have been observed**
- **Peak assignment (E_R and Γ) is now in progress**



Summary

- **The RCNP is a unique facility for**
  - High resolution/quality beams and detectors
  - Polarization phenomena with polarized beams and polarimeters
  - Double-arm spectrometer system
- **Nuclear Physics to Investigate**
  - Nuclear medium effects
  - Spin-Isospin modes in nuclei
  - Few-body systems and 3NF effects
  - Giant Resonances and their fine structure
- **Hadron properties in nuclear medium**
  - Mass/coupling-const. reduction in nuclei
  - Precursor phenomena (enhancement) of pion condensation
  - 3NF effects