サイクロトロンでの物理

若狭 智嗣
大阪大学核物理研究センター
Overview

- Overview of the Experimental Facility
- Overview of the Physics Programs
- Physics Topics at RCNP
  - Nuclear medium effects
  - Quark ($\Delta$) 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
  - 2nd FPP
  - NPOL2

East experimental hall

West experimental hall

Neutron Course

Ring Cyclotron

AVF Cyclotron
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
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
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 $\Delta$ in Nuclei
- 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
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

RCNP Ring Cyclotron Facility

Energy region covered by RCNP

![Graph showing cross sections](image)
Spin-Isospin Modes

- Filtering to Spin-Isospin Modes in Charge Exchange Reactions
  - Momentum transfer = 0
- For L=0 (GT vs Fermi)
  \[ \sigma_{GT} = K_{GT} N_{GT} |J_{\sigma r}|^2 B(GT) \]
  \[ = K_{GT} \hat{\sigma}_{GT} B(GT) \]
  \[ \sigma_{F} = K_{F} N_{F} |J_{r}|^2 B(F) \]
  \[ = K_{F} \hat{\sigma}_{F} B(F) \]
  \[ R^2 = \frac{\hat{\sigma}_{GT}}{\hat{\sigma}_{F}} \]
  \[ = \left| \frac{J_{\sigma r}}{J_{r}} \right|^2 \left( \frac{N_{GT}}{N_{F}} \right) \]

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


---

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

- Total Spin Transfer $\Sigma$
  \[\Sigma(0^\circ) = \frac{3 - \left[2 D_{NN}(0^\circ) + D_{LI}(0^\circ)\right]}{4}\]
  \[= 0 (\Delta S = 0) \text{ or } 1 (\Delta S = 1)\]

- Experimental Results
  - $\Sigma$ in GTGR = 0.99\textsubscript{±}0.01
  - $\Sigma$ 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
Two-Arm Spectrometers

- **Grand Raiden**
  - Resolution = 37,000
  - Momentum Byte = 1.05
  - Acceptance = 5.6 msr
  - Max. $B\rho$ = 5.4 Tm
  - Weight = 600 t

- **Large Acceptance Spectrometer**
  - Resolution = 6,000
  - Momentum Byte = 1.35
  - Acceptance = 20 msr
  - Max. $B\rho$ = 3.2 Tm
  - Weight = 150 t
Polarization Measurement

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

\[ D_{ij} \propto \frac{1}{A_y (Y_L(U) - Y_R(D))} \frac{Y_L(U) - Y_R(D)}{Y_L(U) + Y_R(D)} \]

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

2nd level trigger:
- Use FPGA (Field Programmable Gate Array)
- Reject the events scattered at forward angles which is not necessary to determine \(D_{ij}\)
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
Medium Effects in $A_y$

- **Pauli Blocking effects**
  - G-matrix (NN int. in nuclei)
    - *Amos Group*
      - *Fully microscopic*
    - *Kelly Group*
      - *Empirical*
  - Not reproduce $A_y$

- **Hadron Mass Reduction**
  - Reduction of nucleon mass (In strong scalar potential)
    \[ m_N^* = m_N + S(r) \]
  - Reduction of meson mass
  - Reduction of coupling const.
    \[ \frac{m_N^*}{m_N} = \frac{m_\sigma^*}{m_\sigma} = \frac{m_\omega^*}{m_\omega} = \frac{m_p^*}{m_p} = 0.7, \quad \frac{g_\sigma^*}{g_\sigma} = \frac{g_\omega^*}{g_\omega} = 0.75 \]
  - Well reproduce $A_y$

Reproduce the density dependence of $A_y$ 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 ansatz)
- $D_{ij}$ is sensitive to one meson mass scaling
  (mass and coupling constant)

- $D_{ij}$ 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
  - Framework
    - Nucleon, pion (meson), and Δ (quark spin-flip)
    - Interactions
      - Long-range OPE
      - Middle-range heavy-meson exchange ($\rho, \omega, \sigma, \ldots$)
      - 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
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)**
  - $\Delta N^{-1}$ 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

- Combination of SOL1 and SOL2
  - S, N, L-types p-beam
- SOL1 (p-spin: N → S)
- SOL2 (p-spin: N → S)
- Combination of BLP1 & BLP2
  - Determine \( p_S, p_N, p_L \)
- BLP1 (polarimetry: \(^1\text{H}(p,p)^1\text{H})\)
- BLP2 and Swinger
- Beam Pulsing Device 1/9
- Combination of BLP1 & BLP2
- Determine \( p_S, p_N, p_L \)
- RING cyclotron (single-turn ext.)
- AVF cyclotron (N-type p-beam)
- n-Polarimeter NPOL II
Neutron Polarimeter 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  $4.6 \times 10^{-5}$ @160 MeV
  - LAMPF  $2.3 \times 10^{-4}$ @500 MeV
  - RCNP  $4.9 \times 10^{-4}$ @300 MeV

- High Efficiency of Neutron Detection
  - RCNP  0.15 @150-400 MeV
Result of MDA and B(GT) Strength in the Continuum

\[ \sum B(GT) \left[ E_x \leq 50 \text{ MeV} \right] = 28.0 \pm 1.6(\text{MDA}) \pm 5.4(\hat{\sigma}_{\text{GT}}) \]

= 93\% of minimum sum-rule : \(3(N - Z) = 30\)
Quasi-elastic Scattering

- **QES Process**
  - Momentum Transfer: $q$
  - Energy Transfer: $\omega$
  - Spin Transfer: $\Delta S$
    - Longitudinal ($\pi$) vs. Transverse ($\rho$)
  - Isospin Transfer: $\Delta T$

- **Simple Reaction Mechanism**

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

  \[
  D_{ij} \rightarrow \text{(distortion)} \otimes \text{(NN interaction)} \otimes \text{(response)}
  \]

- **Kinematics**

  \[
  \omega = \frac{\left(q + \vec{k}_F\right)^2}{2m} - \frac{\left(\vec{k}_F\right)^2}{2m}
  \]

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

  - peak
  - width
Pionic Correlations in Nuclei

- **Model Interaction**
  - Spin-longitudinal ($\pi$) interaction
    - Attractive at $q > 0.8 \text{ fm}^{-1}$
  - Spin-transverse ($\rho$) interaction
    - Repulsive

- **Nuclear Spin Response**
  - Longitudinal Response
    $$ R_L \propto \left| \langle n | \sigma \cdot q | 0 \rangle \right|^2 $$
    - Enhancement and Softening
  - Transverse Response
    $$ R_T \propto \left| \langle n | \sigma \times q | 0 \rangle \right|^2 $$
    - Quenching and Hardening

$$ \Rightarrow \text{ enhancement of } \frac{R_L}{R_T} $$
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 $\rho$-exchange model is OK

- **“No” Quenching of $R_T$**
  - Reaction Mechanisms
    - Spin-dependent distortion effects
    - Two-step processes
  - Relativistic Effects

\[ m^*(r=0) = 0.7 m_N \]
\[ g'_{NN} = 0.6 \]
\[ g'_{NA} = 0.3 \]
\[ g'_{AA} = 0.5 \]
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
  - New \( g' \) parameters with
    - \( g'_{N\Delta} = 0.2 \)
    - \( g'_{NN} = 0.6 / m^* = 0.8m \)
  - Old \( g' \) parameters with universality:
    - \( g'_{N\Delta} = g'_{NN} = 0.6 - 0.8 \)
2N Forces and Triton Binding Energy

- Hamiltonian of Many Body System

\[ H = \sum_i \frac{p_i^2}{2m} + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \ldots \]

- 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

<table>
<thead>
<tr>
<th></th>
<th>B of $^3$H</th>
<th>$\chi^2/N$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nijm II</td>
<td>7.6 MeV</td>
<td>1.0</td>
<td>local</td>
</tr>
<tr>
<td>Reid 93</td>
<td>7.6 MeV</td>
<td>1.0</td>
<td>local</td>
</tr>
<tr>
<td>Argonne AV18</td>
<td>7.6 MeV</td>
<td>1.1</td>
<td>local</td>
</tr>
<tr>
<td>Nijm I</td>
<td>7.7 MeV</td>
<td>1.0</td>
<td>non-local</td>
</tr>
<tr>
<td>CD Bonn</td>
<td>8.0 MeV</td>
<td>1.0</td>
<td>non-local</td>
</tr>
<tr>
<td>CD Bonn</td>
<td>8.2 MeV</td>
<td>1.0</td>
<td>relativistic &amp; non-local</td>
</tr>
<tr>
<td>Exp.</td>
<td>8.5 MeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

- **2π-Exchange 3NF**
  - A virtual $\Delta$ resonance induces 3NF (Fujita-Miyazawa type)
  - Extended to
    - Urbana-Argonne 3NF
    - Tucson-Melbourne 3NF
- **Urbana-Argonne 3NF**
  - $A_{2\pi}$ [2π – exchange (Fujita – Miyazawa type)]
  - $U_0$ [Short Range (Tensor type)]
  - $A_{2\pi}, U_0$: Adjustable parameters
- **Tucson-Melbourne 3NF**
  - Generated with $\pi N$ scattering amplitudes
  - One free (adjustable) cutoff parameter of $\pi NN$ vertex
- **Adjusted 3NFs reproduce triton binding energy very well**

<table>
<thead>
<tr>
<th></th>
<th>B of $^3H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD Bonn + TM-3NF</td>
<td>8.5 MeV</td>
</tr>
<tr>
<td>Nijm II + TM-3NF</td>
<td>8.5 MeV</td>
</tr>
<tr>
<td>AV18 + TM-3NF</td>
<td>8.5 MeV</td>
</tr>
<tr>
<td>AV18 + UA-3NF</td>
<td>8.5 MeV</td>
</tr>
<tr>
<td>Exp.</td>
<td>8.5 MeV</td>
</tr>
</tbody>
</table>
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
  - $\omega$-q-transfers can be controlled
  - Various observables including PTO are measureable

- **3NF Effects**
  - Effects in elastic channel are fairly large around 100 MeV
  - RCNP is a unique facility to explore 3NF effects
3NF Effects in p+d Elastic Scattering

- **2N Force only**
  - Not reproduce $\sigma$
  - Not reproduce $A_y$
  - Reproduce $D_{ij}$ fairly well

- **2N+3N Forces**
  - Reproduce $\sigma$ 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 $^{14}\text{O}(\alpha,p)^{17}\text{F}$

- At $T_9=0.5$
  - Breakout from CNO cycle through $^{15}\text{O}(\alpha,p)^{19}\text{N}$

- At $T_9=0.8$
  - Breakout from CNO cycle through $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$
Level Scheme of $^{22}\text{Mg}$

- Level scheme of $^{22}\text{Mg}$ is determined by the $^{21}\text{Na}+p$ 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 $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$ at $T_9=0.8$
Breakout from CNO Cycle

- At $T_9=0.60$
  - Breakout from CNO cycle is mainly via $^{16}\text{O}(\alpha, p)^{19}\text{Ne}$
- 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 $^{18}\text{Ne} + \alpha \rightarrow ^{22}\text{Mg}^* \rightarrow ^{21}\text{Na} + p$

$T_9=0.60$
$\rho=100\text{g/cm}^3$
Requirement for High-Resolution Spectroscopy

- Reaction cross section
  \[ \sigma = \frac{\Gamma^2}{(E - E_R)^2 + (\Gamma/2)^2} \]
  \(E_R\): Resonance energy  
  \(\Gamma\): 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

![Graph showing Reaction Rate for {23}Al + p](image)
WS Beam Line 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

West Experimental Hall at RCNP
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 Grand Raiden in Dispersive Mode

- **Beam Envelopes**
  - $P$: $\leq 0.03\%$
  - $\theta$: $\leq 2$ mrad
  - $\phi$: $\leq 2$ 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: $\leq 0.03\%$
  - $\theta$: $\leq 2$ mrad
  - $\phi$: $\leq 2$ mrad

- **Ion-optical properties**
  - $M_x$: 0.41
  - D: 15.1 m
  - $(\theta| p)$: 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**
  - $\Delta E$: 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 $^{22}\text{Mg}$

- Resonance states in $^{22}\text{Mg}$ studied via the $^{24}\text{Mg}(\alpha,^6\text{He})^{22}\text{Mg}$ reaction
- Experimental conditions
  - $^{22}\text{Mg}$: 1.8 mg/cm$^2$
  - $\alpha$-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 $\Gamma$) 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