Study of M1 Excitations
via High-Resolution ($p,p'$) Scattering Experiment

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Introduction
Introduction

1. Systematic study of M1 strengths and their quenching

Gamow-Teller (GT) quenching problem:
The observed GT strengths are systematically smaller the sum-rule value.

\[
\text{GT sum rule : } \quad S_{\beta^-} - S_{\beta^+} = 3(N - Z)
\]

60% 90% of the strength is observed in \(^{90}\text{Zr}\) upto \(E_x = 50\) MeV

T. Wakasa et al., PRC55(1997)2909 \( (p,n) \) reaction
K. Yako et al., PLB615(2005)193 \( (n,p) \) reaction

How about M1 strengths? Common with GT

Quenching is observed in \(T=0,1\) M1 strengths in \(^{28}\text{Si}\).

N. Anantaraman et al., PRL52(1984)1409

Almost no quenching is observed in \(^{24,26}\text{Mg}, \; ^{28}\text{Si}, \; ^{32}\text{S}\) for the sum of \(T=0\) and \(T=1\) strengths.

G.M. Crawley et al., PRC39(1989)311

High quality data are required.
2. Mechanism of Fragmentation of M1 Strengths.

- Many candidates of fragmented M1 strengths are found in the $^{48}$Ca($p,p'$) data at IUCF at the foot of the prominent $1^+$ peak at 10.22 MeV.
- Many small M2 and M1 strengths have been identified from the $^{48}$Ca($e,e'$) data at Darmstadt
  P. von Nuemann-Cosel et al., PRL82(1999)1105

$^{48}$Ca($p,p'$) at IUCF at 0 deg. analyzed by Y. Fujita et al.
3. Nuclear matrix element of neutrino inelastic scattering ($\nu,\nu'$)
   - dynamic processes in supernovae
     nucleosynthesis

4. New or exotic type excitations in nuclei
   vortex type excitations?
Merits of measuring proton inelastic scattering at 0 deg.

- \( \frac{d\sigma}{d\Omega} \) is maximum at 0\( \square \) for \( \Delta L=0 \) excitations.
- \( \Delta L \) can be identified from the angular dependence at forward angles.
- \( \frac{d\sigma}{d\Omega} \) at 0 deg can be related to the reduced matrix elements of the transition by a simple formula.
  \[
  \frac{d\sigma}{d\Omega} = K \cdot N \cdot |J^{ST}(q)|^2 \cdot B^{ST}(q,\omega)
  \]
- \( \Delta S \) is model independently assigned by measuring polarization transfer coefficients
  \[
  D_{SS} + D_{NN} + D_{LL} = \begin{cases} 
  -1 & \text{for } \Delta S = 1 \\
  3 & \text{for } \Delta S = 0 
  \end{cases}
  \]
- High resolution experiment is feasible.
- Comparison of the data with other reactions such as \((d,d')\), \((^3\text{He}, t)\), and \((e,e')\) is important for extracting detailed property of excited states.
Experiment
The RCNP Facility
Beam line WS-course

Grand-Raiden Spectrometer

High-dispersive WS-course

RCNP Ring Cyclotron

T. Wakasa et al., NIM A482 ('02) 79.
Experimental Setup (0-deg.)

medium under focus mode:
- good vertical scatt.
- angle resolution
- background subtraction

Large Acceptance Spectrometer (LAS)

As a beam spot monitor in the vertical direction

Intensity: 3 ~ 8 nA
Target: natSi (1.9 mg/cm²)

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Beam Tuning

- Beam energy spread
  \( {}^{197}\text{Au}(p,p_0) \) elastic scattering
  achromatic transport mode

  \( \sim 40 \text{ keV (FWHM)} \) at \( E_p=295 \text{ MeV} \)

  It corresponds to a beam spot size of
  \( \sim 3\text{mm (FWHM)} \) on target
  in the dispersive transport mode.

- Halo free beam tuning at 0 deg. (achro. beam)
  Single turn extraction of the AVF cyclotron

- Tuning of dispersion matching
  It takes about 2 days for the beam tuning.
Analysis
Angle calibration

Sieve slit data:
$^{58}\text{Ni}(p,p_0)$ reaction at 14°

Horizontal:
$\Delta = 0.15$ deg

Vertical:
$\Delta = 0.5$ deg at $E_x = 6$ MeV.
$0.8$ deg at $E_x = 20$ MeV.

$\Delta = 0.5 \sim 0.8$ [deg]
Background subtraction

$^{28}\text{Si}(p,p')$ at $E_p=295$ MeV

After calibration

Counts/Channel

$Y$ at the focal plane of $Y$ [mm]

Counts/Channel

Excitation Energy [MeV]
Analysis

Detailed calibrations and analyses are in progress (H. Matsubara and A. Tamii)

• Calibration of the scattering angle, solid angle. \( \Delta \theta = 0.5\text{-}0.8 \) depending on \( E_x \).

• Calibration for the energy high resolution data. \( \Delta E \approx 20 \text{ keV} \)

• Background Subtraction working well

• Absolute cross section and angular distribution.

• Analysis of elastic scattering and optical potential.
Spectra and Preliminary Results
$^{12}\text{C}(p,p')$ at $E_p = 295$ MeV

- Preliminary
- $\theta = 0 - 0.5^\circ$
- Underfocus mode
- With b.g. subtraction
- 30 mg/cm$^2$

Excitation Energy [MeV]

Counts/Channel

FWHM 50 keV
$^{12}\text{C}(p,p')$ at $E_p=295$ MeV

- Preliminary
- $\theta=0-0.5^\circ$
- Underfocus mode
- With b.g. subtraction
- 30 mg/cm$^2$

Counts/Channel vs. Excitation Energy [MeV]
A typical spectrum of $^{28}$Si($p,p'$) at 0-deg.

Background events were subtracted reasonably.
$^{48}\text{Ca}(p, p')$

$^{48}\text{Ca}(p, p')$ at $E_p=295$ MeV

$\theta=0-1^\circ$
underfocus mode
w/o b.g. subtraction
1.9 mg/cm$^2$
$^{64}\text{Ni}(p,p')$

$^{64}\text{Ni}(p,p')$ at $E_p = 295$ MeV

- $\theta = 0^\circ$, full acceptance
- underfocus mode
- with b.g. subtraction
  - $4.7$ mg/cm$^2$

$^{64}\text{Ni}(p,p')$ at $E_p = 295$ MeV

- $\theta = 2.5^\circ$, full acceptance
- underfocus mode
- with b.g. subtraction
  - $4.7$ mg/cm$^2$

$^{64}\text{Ni}(p,p')$ at $E_p = 295$ MeV

- $\theta = 4.5^\circ$, full acceptance
- underfocus mode
- with b.g. subtraction
  - $4.7$ mg/cm$^2$
$^{90}\text{Zr}(p, p')$


at 200 MeV and 4 deg

present data

$^{90}\text{Zr}(p,p')$ at $E_p=295$ MeV

$\theta=0^\circ$, full acceptance
underfocus mode
with b.g. subtraction
30 min. data acq.

1.0 mg/cm$^2$
Inelastic Scattering from $^{208}\text{Pb}$

$^{208}\text{Pb}(p,p')$ at $E_p = 295$ MeV

Preliminary

$\theta = 0.0 - 0.5^\circ$

underfocus mode

with b.g. subtraction

5.2 mg/cm$^2$, 90 min
The elastic data are perfectly consistent with the one reported in spin 94 (A. Tamii et al.) Optical potential of Jones et al., PRC50(1994)1982 (LAMPF, at 318 MeV) well reproduces the data.
Inelastic Scattering from $^{12}$C

Sakemi et al. PRC51(1995)3162 used the FL325 parameter set for $E_p=300$ MeV. They reported that the c.s. ratio of $1^+; T=0$ to $1^+; T=1$ is well described by the DWBA calculation at $E_p=300$ MeV. It is reconfirmed.

The calculations of DW81 and DWBA91 are consistent to each other (small difference exists). The Franey Love interaction parameter set at 325 MeV better describes the data than that at 270 MeV.
Inelastic Scattering from $^{12}\text{C}$

The DWBA calculation well describes the data. The exists some difference between the calculations of DW81 and DWBA91.
A typical spectrum of $^{28}\text{Si}(p,p')$ at 0-deg.

Background events were subtracted reasonably.
Distinction between IS and IV

DWBA calculation

Trans. density : A. Willis et al., PRC 43(1991)5 (by OXBASH in sd shell only)

From angular distribution, isospin value is identified.
Other states identified as $I^+$

Preliminary

$9.72\text{MeV}$

$10.91\text{MeV}$

$12.33\text{MeV}$

$13.20\text{MeV}$

$15.10\text{MeV}$

$10.60\text{MeV}$

$11.15\text{MeV}$

$12.96\text{MeV}$

$13.30\text{MeV}$

$15.44\text{MeV}$

$10.73\text{MeV}$

$11.94\text{MeV}$

$13.03\text{MeV}$

$13.76\text{MeV}$

$15.70\text{MeV}$

$10.81\text{MeV}$

$12.24\text{MeV}$

$13.18\text{MeV}$

$14.03\text{MeV}$

$15.88\text{MeV}$
$B(\sigma)$ Strength distribution

$B(\sigma)$ at 9.50 and 11.45 MeV were normalized to the data of Crawley using $d\sigma/d\omega$. These ratios were applied to other states. Unit cross section

**T=0 : IS**

- oxbash
- kuo

**T=1 : IV**

- oxbash
- wildenthal

- kuo
- wildenthal

- preliminary

- exp

- exp
Running sum of $B(\square)$

$T=0$ : IS

$T=1$ : IV
0-degree facility at iThemba LABS, South Africa
Ion optical calculation by TRACK

Beam Stopper

Target

Quad

D1

D2

Detector
1st spectrum of $^{12}\text{C}(p,p')$ at 200MeV and 0-degree

**12C data (2nd Weekend)**
- run268
- corrected TOF + Y gated

Observable $E_x$: 6.4~22.4MeV
$\Delta E_x \approx 32\text{keV}$ (FWHM)
Summary

• Development of the experimental technique of high-resolution \((p,p')\) measurements at forward angles including zero degrees is successfully advancing.

• Reasonably good vertical scattering angle resolution \((\Delta \theta = 0.5-0.8 \degree)\) and background subtraction technique were simultaneously achieved by using a GR ion optics of 'medium under focus' mode.

• An energy resolution of \(\Delta E = 20\) keV has been achieved.

• Measurement of the \(^{208}\text{Pb}(p,p')\) scattering is now feasible.

• Detailed calibration and analysis are in progress.

• Same type experimental technique is now developing at iThemba lab. We succeeded in measuring \(^{12}\text{C}(p,p')\) at 0 deg. at \(E_p = 200\) MeV.
Summary

• Next steps
  - further calibration and establishment of the analysis procedure
  - Extraction of the angular distribution and $J^\pi$ assignment of each peak.
  - Extraction of M1 strengths and their distribution.
• A project of improving the injector cyclotron is now performed.
  - Flat topping of the acceleration voltage is achieved by applying additional RF power with 5 times higher frequency.
  - Better stability and more intensity is expected with the same energy resolution.
  - Measurement of heavy target is now feasible.
• Further applications
  - Other inelastic scattering experiments such as $(d,d')$ and $(\alpha,\alpha')$ reactions are feasible.
  - Complete polarization transfer coefficients of $(p,p')$ reaction can be measured, which are useful for $J^\pi$ assignments.
medium under focus mode for
• good vertical scatt. angle resolution
• background subtraction

Grand Raiden spectrometer in the 0 deg exp. set up.

Another spectrometer LAS was used to monitor the vertical position of the beam spot.
Experimental Conditions

Beam Energy: $E_p = 295$ MeV

Beam Intensity: 1~5 nA at 0 deg-FC (0 deg)
~8 nA at Q1-FC (2.5 and 4.5 deg)
~12 nA at SC-FC (6.0 deg)
0.2~15 nA at SC-FC (elastic)

Polarization: unpolarized beam from Neomafios (inelastic)
polarized beam from HIPIS, ~71% (elastic)

Solid Angle: full acceptance (inelastic 0-4.5 deg)
20H 30V (inelastic 6.0 deg, elastic)

WS: dispersive (inelastic)
achromatic (a few inelastic at 0deg, elastic)

GR optics: underfocus mode (inelastic and elastic)

Trigger Rate: 6kcps (90% DAQ clock live)
## Targets and Angles

<table>
<thead>
<tr>
<th>Thickness (mg/cm²)</th>
<th>natC</th>
<th>mylar</th>
<th>¹³CH₂</th>
<th>²⁴Mg</th>
<th>²⁵Mg</th>
<th>²⁶Mg</th>
<th>²⁷Al</th>
<th>natSi</th>
<th>⁴⁰Ca</th>
<th>⁴⁸Ca</th>
<th>⁵⁸Ni</th>
<th>⁶⁴Ni</th>
<th>⁹⁰Zr</th>
<th>¹²⁰Sn</th>
<th>²⁰⁸Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 (partly 1.1)</td>
<td>10</td>
<td>0.7</td>
<td>1.8</td>
<td>4.00</td>
<td>1.55</td>
<td>1.8</td>
<td>1.86 (58.5 a part of elastic)</td>
<td>13</td>
<td>1.9</td>
<td>4</td>
<td>4.7</td>
<td>1.0</td>
<td>2.6</td>
<td>5.2</td>
</tr>
</tbody>
</table>

- ... measured,  - ... good statistics,  - ... poor statistics,  - ... not measured

### Amount of Data

- Oct-2004: 145 runs, 141 GBytes
- Jul-2005: 149 runs, 238 GBytes
$^{24}\text{Mg}(p,p')$

$^{24}\text{Mg}(p,p')$ at $E_p = 295$ MeV

$\theta = 0^\circ$, full acceptance
underfocus mode
with b.g. subtraction
$1.8 \text{ mg/cm}^2$
$^{26}\text{Mg}(p,p')$

$^{26}\text{Mg}(p,p')$ at $E_p = 295$ MeV

$\theta = 0^\circ - 1^\circ$

underfocus mode

w/o b.g. subtraction

1.6 mg/cm$^2$
\[ ^{40}\text{Ca}(p, p') \]

\[ ^{40}\text{Ca}(p, p') \text{ at } E_p = 295 \text{ MeV} \]

\( \theta = 0^\circ \), full acceptance underfocus mode with b.g. subtraction 13.3 mg/cm\(^2\)
$^{64}$Ni($p, p'$)


at 200 MeV and 4 deg

present data
Inelastic Scattering from $^{208}\text{Pb}$

$^{208}\text{Pb}(p,p')$ at $E_p=295$ MeV

Preliminary

$\theta=0.5-1.5^\circ$
underfocus mode
with b.g. subtraction
5.2 mg/cm$^2$, 90 min
Inelastic Scattering from $^{208}$Pb

$^{208}$Pb($p,p'$) at $E_p = 295$ MeV

$\theta = 1.5\text{–}2.5^\circ$
underfocus mode
with b.g. subtraction
5.2 mg/cm$^2$, 90 min
Inelastic Scattering from $^{12}\text{C}$
Inelastic Scattering from $^{12}$C

The data taken in inelastic runs and in elastic runs are consistent.

DWBA calculations require to include coupling channel and deformation effect. Not yet done.
Inelastic Scattering from $^{12}\text{C}$

The shape of the peak is not well fit by a Gaussian+linear b.g. The data of inelastic runs might be underestimating the c.s. in a level of 10%.
Inelastic Scattering from $^{208}$Pb
New beam stop installation
Present developments

New wire chambers for Y information.

New VME electronics for faster and cleaner data taking.

Halo monitor in the beamline.

Internal beam stop for (p,t) reaction at 0-degree
Study of $M1$ Quenching in $^{28}\text{Si}$ by a $(p,p')$ Measurement at zero-degrees

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Introduction

GT quenching problem

- Less strength is observed than predicted with sum rule.

**GT sum rule:** \[ < 0 | [Y_+, Y_-] | 0 | = 3(N - Z) \]

60 % 90% of the strength is observed.

T. Wakasa et al., PRC55(1997)2909 (\(p,n\)) reaction
K. Yako et al., PLB615(2005)193 (\(n,p\)) reaction

How about M1 strengths? \(\sigma, \sigma_\tau\) Common with GT

**Quenching is observed** in \(T=0,1\) M1 strengths in \(^{28}\text{Si}\).
N. Anantaraman et al., PRL52(1984)1409

**Almost no quenching is observed** in \(^{24,26}\text{Mg}, \text{Si, S}\).
G.M. Crawley et al., PRC39(1989)311

Improvement of the data quality is required.

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Interesting point in M1 Quenching

Two mechanisms were proposed to explain the quenching.

- many-particle-many-hole configurations (np-nh)
- \(\square\)-hole excitations (\(\square\)-h)

M1 transition: \(\square\) \(T = 0\) or \(1\)

<table>
<thead>
<tr>
<th></th>
<th>(\square) (T = 0) (IS)</th>
<th>(\square) (T = 1) (IV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>np-nh</td>
<td>possible</td>
<td>possible</td>
</tr>
<tr>
<td>(\square)-h</td>
<td><strong>impossible</strong></td>
<td>possible</td>
</tr>
</tbody>
</table>

Is each quenching factor the same value or not?

Another aspect of the quenching can be found.
G.M. Crawley et al, PRC39(1989)311, at Orsay

Present data

$^{nat}Si(p,p'), E_P = 201$ MeV, $\Theta_{lab} = 3^\circ$

$^{nat}Si(p,p'), E_P = 295$ MeV, $\Theta_{lab} = 0^\circ$

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Optical potential of $^{28}$Si

Target thickness was also calibrated using silicon wafer.
Strength distribution

$B(\beta^-)$ at 9.50 and 11.45 MeV were normalized to the data of Crawley using $d\beta^-/d\theta$. These ratios were applied to other states. ∆ Unit cross section
Total sum of $B(\square)$

$T=0 : IS$

$T=1 : IV$

preliminary
Summary

- We realized a $^{28}$Si$(p, p')$ measurement at 0-degrees with high resolution.
  - A scattering angle resolution of 0.5 ~ 0.8 deg.
  - An energy resolution of 20 keV in FWHM.

- Using angular distributions, $I^+$ states were selected and IS and IV transition were identified.

- Strength distribution and total sum of $B(γ)$ were compared with shell-model calculations using unit cross section.

Future

- Deducing the $B(γ)$ with absolute value.

- Comparing with recent sophisticated shell-model calculations.