Structure of neutron-rich Mg isotopes explored by beta-decay of spin-polarized Na isotopes

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Osaka Univ., KEK\textsuperscript{A}, TRIUMF\textsuperscript{B}

\beta-\gamma coincidence
\beta-\gamma-\gamma coincidence

polarization

spin-parity assignments

\beta-\gamma coincidence
\beta-\gamma-\gamma coincidence
Systematic measurements for Mg isotopes

$^{28}\text{Mg}$, $^{29}\text{Mg}$, $^{30}\text{Mg}$, $^{31}\text{Mg}$, $^{32}\text{Mg}$
$N = 16, 17, 18, 19, 20$

$\beta$-decay of $^{28,29,30,31,32}\text{Na}$ (polarized)

spin-parity assignments of the levels in $^{28,29,30,31,32}\text{Mg}$

structure of $^{28,29,30,31,32}\text{Mg}$

vanishing of $N=20$ magicity

intruder configurations
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Experiments at TRIUMF

Results with $^{28}\text{Na}$ Beam: $^{28}\text{Mg}$ Structure

Results with $^{29}\text{Na}$ Beam: $^{29}\text{Mg}$ Structure

Comparison with Shell Model Calculations

Summary

use of spin-polarized radioactive beam
β-decay from a spin-polarized nucleus

β-decay angular distribution

\[ W(\theta) \sim 1 + AP \cos \theta \]

A: asymmetry parameter of allowed β-decay

P: polarization of the parent nucleus

A takes very different values depending on the final state spin.

\[ \tau = \frac{C_V \langle 1 \rangle}{C_A \langle \sigma \rangle} \sim 0 \]

\[
A(I_i, I_f) = \begin{cases} 
\pm 1 & \text{for } I_f = I_i - 1, \\
\pm 1/(I_i + 1) - 2\tau \sqrt{I_i/(I_i + 1)} & \text{for } I_f = I_i, \\
\mp I_i/(I_i + 1) & \text{for } I_f = I_i + 1.
\end{cases}
\]

<table>
<thead>
<tr>
<th></th>
<th>( I_i )</th>
<th>( I_f )</th>
<th>( A(I_i, I_f) )</th>
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</thead>
<tbody>
<tr>
<td>( ^{28}\text{Na} )</td>
<td>1(^+)</td>
<td>1(^+)</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0(^+)</td>
<td>-1.0</td>
</tr>
<tr>
<td>( ^{29,31}\text{Na} )</td>
<td>3/2(^+)</td>
<td>3/2(^+)</td>
<td>-0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1/2(^+)</td>
<td>-1.0</td>
</tr>
<tr>
<td>( ^{30}\text{Na} )</td>
<td>2(^+)</td>
<td>3(^+)</td>
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<tr>
<td></td>
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<td>( ^{32}\text{Na} )</td>
<td>(4(^-))</td>
<td>5(^-)</td>
<td>0.8</td>
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<td>2(^-)</td>
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<td></td>
<td></td>
<td>2(^-)</td>
<td>-1.0</td>
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$P$ can be evaluated from $AP$ value for a transition to the known spin state.
In the case of cascade feeding

Deduced $A$ from $\beta$-$\gamma$ coincidence is affected by the feeding from upper levels.

\[
A_1 = A_1^\gamma \times \frac{I_{\gamma_1}}{I_{\beta_1}} - A_2 \times \frac{I_{\gamma_3}}{I_{\beta_1}},
\]

measured from $\beta$-$\gamma_1$ coincidence

\[
A_1^\gamma = A_2 \times \frac{I_{\gamma_3}}{I_{\gamma_1}} + A_1 \times \frac{I_{\beta_1}}{I_{\gamma_1}},
\]

known

unknown
required statistics in $AP$ measurement

\[
\frac{\Delta (AP)}{AP} = \frac{\sqrt{1 - (AP)^2}}{AP \sqrt{Y_{\beta\gamma}}} \quad Y_{\beta\gamma} : \beta\gamma \text{ total yields}
\]

Large polarization is important

Experimental $AP$ value fluctuates statistically.

<table>
<thead>
<tr>
<th>$I_i$</th>
<th>$I_f$</th>
<th>$A(I_i, I_f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Na)</td>
<td>(Mg)</td>
</tr>
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<td>(28\text{Na})</td>
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<td></td>
</tr>
<tr>
<td>(1^+)</td>
<td>(2^+)</td>
<td>+0.5</td>
</tr>
<tr>
<td>(0^+)</td>
<td>(1^+)</td>
<td>-0.5</td>
</tr>
<tr>
<td>(0^+)</td>
<td>(0^+)</td>
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<tr>
<td>(29,31\text{Na})</td>
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<tr>
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<td>+0.6</td>
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<tr>
<td>(3/2^+)</td>
<td>(3/2^+)</td>
<td>-0.4</td>
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<tr>
<td>(1/2^+)</td>
<td>(1/2^+)</td>
<td>-1.0</td>
</tr>
<tr>
<td>(30\text{Na})</td>
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<td></td>
</tr>
<tr>
<td>(2^+)</td>
<td>(3^+)</td>
<td>+0.67</td>
</tr>
<tr>
<td>(1^+)</td>
<td>(2^+)</td>
<td>-0.33</td>
</tr>
<tr>
<td>(1^+)</td>
<td>(1^+)</td>
<td>-1.0</td>
</tr>
<tr>
<td>(32\text{Na})</td>
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<td></td>
</tr>
<tr>
<td>((4^-))</td>
<td>(5^-)</td>
<td>+0.8</td>
</tr>
<tr>
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<td>(4^-)</td>
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<tr>
<td>(3^-)</td>
<td>(2^-)</td>
<td>-0.25</td>
</tr>
<tr>
<td>(2^-)</td>
<td>(2^-)</td>
<td>-1.0</td>
</tr>
</tbody>
</table>
Monte Carlo simulation

Beta-rays were generated according to

\[ W(\theta) \simeq 1 + AP \cos \theta \]
where to perform the experiment?

TRIUMF ISAC in Canada

polarized radioactive beam

world-highest polarization
Principle of Measurement

Experiments at TRIUMF

Results with $^{28}$Na Beam: $^{28}$Mg Structure

Results with $^{29}$Na Beam: $^{29}$Mg Structure

Comparison with Shell Model Calculations

Summary
Isotope Separator / ACcelerator

radioactive nuclear beams produced in target fragmentation induced by a 500 MeV 100 $\mu$A proton beam

commissioned in Aug. 2001
TRIUMF ISAC Polarized Beam Line

collinear optical pumping

neutralizer

polarized $^{\text{A} \text{Na}^0}$

re-ionizer

polarized $^{\text{A} \text{Na}^+}$

1.9 m

B $\rightarrow$ 10 Gauss

10Gauss

beam velocity tuning

unpolarized $^{\text{A} \text{Na}^+}$

30 keV

Kiefl 80% pol $^8\text{Li}$: transverse $\beta$-NMR condensed matter physics

Shimoda 30–50% pol $^{\text{A} \text{Na}}$: transverse $^7\text{Li}$: transverse decay spectroscopy

Kiefl 80% pol $^8\text{Li}$: longitudinal $\beta$-NMR condensed matter physics

C.D.P. Levy et al.
Nucl. Instr. and Meth.
B204 (2003) 689

pumping within 2.6$\mu$s
pumping the two ground-state hyperfine levels in order to achieve high polarization.

without hyperfine int.

$\vec{F} = \vec{J} + \vec{I}$

atom 1/2  nucleus 3/2

905 MHz

D1 673 nm

$^{11}\text{Li} (I=3/2^-)$
Achieved polarization

Phil Levy @TRIUMF

$^8\text{Li}$: 80%, $^9\text{Li}$: 56%, $^{11}\text{Li}$: 55%,

$^{20}\text{Na}$: 57%, $^{21}\text{Na}$: 56%, $^{26}\text{Na}$: 55%,
$^{27}\text{Na}$: 51%, $^{28}\text{Na}$: 45%,

$^{28}\text{Na}$: 28%, $^{29}\text{Na}$: 36%

Corrected for spin-relaxation

Uncorrected for spin-relaxation
Preset work

Pumping for $^{11}\text{Be}^+$ beam is in progress.
9 HPGe detectors + plastic scintillator telescopes

β- and γ-rays

β-asymmetry: β−γ, β−γ−γ, γ−γ

β energy threshold: eliminates Al contaminants from trigger
β energy: assigns β-decay branch

28,29,30,31,32Na decay at TRIUMF

total efficiency 1.7% @1333keV

28Na and 29Na in Nov. 2007

plastic scintillators (1.5 mm)

β-asymmetry, 60%

L: β−asymmetry, 60%

Na beam 30.4 keV

β−γ, 60%

40%

60%

45%

30%

60%

Pt stopper

LEPS

polarization

B~85mT

50%

R: β−asymmetry, 60%

30.4 keV

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Principle of Measurement
Experiments at TRIUMF

Results with $^{28}$Na Beam: $^{28}$Mg Structure

Results with $^{29}$Na Beam: $^{29}$Mg Structure

Comparison with Shell Model Calculations

Summary
system check with polarized $^{28}$Na beam and search for something new

800 particles per sec
New transition? 

$^{28}\text{Na} \rightarrow ^{28}\text{Mg}$ 

2389.2 keV 

B.G. 2614 

3083.4 keV 
3087.4 keV 
Single escape 

$\gamma$-ray spectrum with all Ge detectors
New level in $^{28}\text{Mg}$

1473 keV

gated by 2907 keV $\gamma$-ray

3083 keV

new 7461 keV

5269 keV

g.s.

2192 keV

gated by 5269 keV $\gamma$-ray

$^{28}\text{Mg}$

2907 keV

2192 keV

1473 keV

4557 keV

5269 keV
polarization of $^{28}\text{Na}$

Select ground-state transition.

$AP = -0.283(5)$

$1^+ \rightarrow 0^+ : A = -1.0$

$\Rightarrow P = 0.283(5)$

uncorrected for spin-relaxation
**Spin assignments of the levels in $^{28}$Mg**

<table>
<thead>
<tr>
<th>$I_i^\pi$ (Na)</th>
<th>$I_f^\pi$ (Mg)</th>
<th>$A(I_i, I_f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2+</td>
<td>+0.5</td>
<td></td>
</tr>
<tr>
<td>1+</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>0+</td>
<td>-1.0</td>
<td></td>
</tr>
</tbody>
</table>

2389 keV $\gamma$-ray peaks (3862 $\rightarrow$ 1473) coincident with $\beta$-rays

$AP = -0.25 \pm 0.01 \Rightarrow A = -0.89 \pm 0.05 \Rightarrow I^\pi = 0^+$

**Successful assignments**
spin assignment of new level at 7.461 MeV

2192 keV $\gamma$-rays was too weak to determine $A_{7.461}$

$A_{5269}^{\gamma}$ is affected by the $\beta$-decay
Asymmetry to the 7.461 MeV level

$$A_{5269}^{\gamma} = A_{5.269} \times \frac{I_{5269}^{\beta}}{I_{5269}^{\gamma}} + A_{7.461} \times \frac{I_{2192}^{\gamma}}{I_{5269}^{\gamma}}.$$

+0.5 or -0.5 or -1.0

7.464 MeV level $\rightarrow$ 2+

<table>
<thead>
<tr>
<th></th>
<th>$I_i^\pi$ (Na)</th>
<th>$I_f^\pi$ (Mg)</th>
<th>$A(I_i, I_f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28}\text{Na}$</td>
<td>1$^+$</td>
<td>1$^+$</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>-1.0</td>
</tr>
</tbody>
</table>

$^{28}\text{Mg}$
Revised Decay Scheme of $^{28}$Na and New Levels in $^{28}$Mg

Levels and gamma rays
- Red: newly observed ones
- Blue: previously observed in (t, p) reaction and newly observed in 28Na β decay

Spins and parities
- Red: newly assigned
- Green: previously reported, and confirmed by present work
- Black: previously reported

Diagram showing the decay scheme with levels and energies for $^{28}$Na and $^{28}$Mg, along with log ft and $I_\beta$ values.
Principle of Measurement
Experiments at TRIUMF
Results with $^{28}$Na Beam: $^{28}$Mg Structure
Results with $^{29}$Na Beam: $^{29}$Mg Structure
Comparison with Shell Model Calculations
Summary
$^{29}$Na decay
spin-parity assignments of
$^{29}$Mg levels

200 particles per sec
first observation of β-decay to the 1st excited state (0.055 MeV)

- $T_{1/2} = 44.9$ ms, $3/2^+$
- $Q_β = 13280(90)$ keV

Excluded gate for β-ray energy spectrum

Energy loss was estimated by using GEANT4

γ rays coincidence with the β ray

54.6 keV
Polarization of $^{29}$Na

The ground state of $^{29}$Mg (3/2+) is the only spin-known state.

It is not possible to exclude the transition to the 55-keV level by setting a gate on $\beta$-ray energy.

![Beta-ray energy spectrum graph](image)
Ratio of $AP$ values

\[ \frac{A_1^\gamma P}{A_2^\gamma P} = \frac{A_1^\gamma}{A_2^\gamma} \]
Spins and parities of the 2.615 MeV & 3.224 MeV levels

Select the β rays in coincidence with each γ rays

\[ \frac{A_{2560}^\gamma P}{A_{1586}^\gamma P} = \frac{A_{2560}^\gamma}{A_{1586}^\gamma} = 2.19 \pm 0.59 \]
In allowed transition …

\[
\begin{array}{c|c|c}
\hline
I^\pi_{29\text{Na}} & I^\pi_{29\text{Mg}} & A(I^\pi_{29\text{Na}}, I^\pi_{29\text{Mg}}) \\
\hline
\frac{3}{2}^+ & \frac{3}{2}^+ & +0.6 \\
\frac{3}{2}^+ & \frac{5}{2}^+ & -0.4 \\
\frac{5}{2}^+ & \frac{5}{2}^+ & -1.0 \\
\hline
\end{array}
\]

\[\frac{A_{2560}^\gamma P}{A_{1586}^\gamma P} = \frac{A_{2560}^\gamma}{A_{1586}^\gamma} = 2.19 \pm 0.59\]

\[A\] ratio takes \(3 \times 3\) patterns

\[
\begin{array}{cccc}
A_{2560} & +0.6 & -0.4 & -1.0 \\
A_{1586} & (l_f = 5/2^+) & (l_f = 3/2^+) & (l_f = 1/2^+) \\
\hline
+0.6 & 1 & -0.67 & -0.6 \\
-0.4 & -1.5 & 1 & \text{2.5} \\
-1.0 & -0.6 & -0.4 & 1 \\
\hline
\end{array}
\]

Exp. result
Polarization of $^{29}$Na

\[ A_\gamma^{1586} = -0.4 \ (I_f^\pi : 3/2^+), \ A_\gamma^{2560} = +0.6 \ (I_f^\pi : 1/2^+) \]

\[ P_{1586} = \frac{A_\gamma^{1586} P}{A_\gamma^{1586}} = 0.40 \pm 0.11 \]

\[ P_{2560} = \frac{A_\gamma^{2560} P}{A_\gamma^{2560}} = 0.35 \pm 0.02 \]

\[ P = 0.36 \pm 0.11 \]

Polarization of $^{29}$Na \ldots 36\pm11\%
Spin-parity of 3.227 -MeV Level
Spin-parity of 3.227 -MeV Level

\[
A_{\text{doublet}} P = A_{3223.6} P \times \frac{I_{3223.6}}{I_{3223.6} + I_{3227.4}} + A_{3227.4} P \times \frac{I_{3227.4}}{I_{3223.6} + I_{3227.4}}
\]

\[
A_{3227.4} = 0.27 \pm 0.68
\]

Similarly

\[
A_{2132.8} = 1.03 \pm 1.89
\]
Relative intensity of $\gamma$-rays from 3.224 MeV and 3.227 MeV levels

\[
\begin{array}{c|c|c|c|c|c}
\text{Level} & I^\pi & E & \text{Exp.} & \text{USD} \\
\hline
3/2^+ & 3/2^+ & 0.055 & 3223 & 3/2^+ & 0.039 \\
1/2^+ & 3/2^+ & 0.055 & 3223 & 1/2^+ & 0 \\
(5/2^+) & 1/2^+ & 2.614 & 3223 & 3/2^+ & 0 \\
& 3/2^+ & 2.614 & 3223 & 5/2^+ & 2.438 \\
(5/2^+) & 1/2^+ & 2.614 & 3223 & 3/2^+ & 2.192 \\
& 3/2^+ & 2.614 & 3223 & 7/2^+ & 2.107 \\
5/2^+ & 3/2^+ & 3.227 & 3196 & 5/2+ & 3.039 \\
& 1/2^+ & 3.227 & 3196 & 1/2^+ & 2.438 \\
& 3/2^+ & 3.227 & 3196 & 3/2^+ & 2.192 \\
& 5/2+ & 3.227 & 3196 & 5/2+ & 2.107 \\
& 1/2^+ & 3.227 & 3196 & 1/2^+ & 2.438 \\
& 3/2^+ & 3.227 & 3196 & 3/2^+ & 2.192 \\
& 5/2+ & 3.227 & 3196 & 5/2+ & 2.107 \\
\end{array}
\]
Revised Decay Scheme of $^{29}$Na and Spin-Parity Assignments of $^{29}$Mg Levels I

Levels and gamma rays
- **Red**: newly observed
- **Blue**: previously observed in 30Na $\beta$-n decay and transfer reactions; newly observed in 29Na $\beta$ decay

$^{29}$Na

- $3/2^+ \quad 0.0 \quad 44.9$ ms
- $Q_\beta = 13.28 (9)$ MeV

- $5.8 (1) \quad 0.76 (18) \quad (1/2 \text{ to } 3/2^+)$
- $5.5 (1) \quad 2.5 (5) \quad (5/2^+)$
- $4.9 (1) \quad 11 (2)$

- $4.5 (1) \quad 36 (6) \quad 1/2^+$

- $> 6.1 \quad < 1.5 \quad ?$
- $7.3 (2) \quad 0.10 (5)$
- $> 6.5 \quad < 0.65 \quad ?$

$^{29}$Mg

- $\log f_t \quad I_\beta \quad \frac{1}{2} \pi$
- $3/2^+$
- $E_x [\text{MeV}]$

- $1.638 \quad 1.430 \quad 1.095 \quad 0.555 \quad 0.0$
Finding of the 1583 keV $\gamma$-ray for the first time

Relative intensity is the clue to spin assignment.
0.055 MeV and 1.638 MeV levels are suggested to be 1/2+ and 5/2+, respectively.
Revised Decay Scheme of $^{29}$Na and Spin-Parity Assignments of $^{29}$Mg Levels II

Levels and gamma rays
- **Red**: newly observed
- **Blue**: previously observed in $^{30}$Na $\beta$-n decay and transfer reactions; newly observed in $^{29}$Na $\beta$ decay

Spins and parities
- **Red**: newly assigned
- **Green**: assigned tentatively by $\gamma$ ray transition probability

Graph showing energy levels and transitions between $^{29}$Na and $^{29}$Mg levels with spin and parity assignments.
Systematics (Exp.)
Z=12

Systematics (Exp.)
N=17


\begin{align*}
27\text{Ne} & (3/2^+) \\
29\text{Mg} & 3/2^+ \\
31\text{Si} & 3/2^+ \\
33\text{S} & 3/2^+ \\
35\text{Ar} & 3/2^+
\end{align*}
Either one reproduces the experimental intensity ratio, if the above hindrance factors are assumed.
Revised Decay Scheme of $^{29}$Na and Spin-Parity Assignments of $^{29}$Mg Levels III

Levels and gamma rays
- Red: newly observed
- Blue: previously observed in $^{30}$Na $\beta$-n decay, and transfer reactions; newly observed in $^{29}$Na $\beta$ decay

Spins and parities
- Red: newly assigned
- Green: assigned tentatively by $\gamma$ ray transition probability

$log f/t$ $I_\beta$ $J^\pi$ $\beta^-$ $Q_\beta$ $E_x$ [MeV]

- $2^{+}$
- $3/2^-$
- $5/2^-$
- $7/2^-$

$^{29}$Na $Q_\beta = 13.28 (9)$ MeV

$^{29}$Mg $E_x$ [MeV]

- 3.985
- 3.674
- 3.227
- 3.224
- 2.614
- 1.638
- 1.430
- 1.095
- 0.055
Principle of Measurement

Experiments at TRIUMF

Results with $^{28}$Na Beam: $^{28}$Mg Structure

Results with $^{29}$Na Beam: $^{29}$Mg Structure

Comparison with Shell Model Calculations

Summary
Comparison with Shell Model Calculation

$^{29}$Mg

Not predicted by USD interaction
Comparison with USD calculation

Energy Level [ MeV ]

Log-\( ft \)

\( \Delta \text{log-}ft \) (calc-exp)

\( \log-ft \)

\( ^{29}\text{Mg} \)
Comparison with Shell Model Calculation 2
(Monte Carlo Shell Model by Utsuno et al.)

<table>
<thead>
<tr>
<th>State</th>
<th>MCSM</th>
<th>exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1/2 to 5/2)^+</td>
<td>3.985</td>
<td>5.8 (1)</td>
</tr>
<tr>
<td>(1/2 to 5/2)^+</td>
<td>3.674</td>
<td>5.8 (1)</td>
</tr>
<tr>
<td>(5/2)^+</td>
<td>3.227</td>
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</tr>
<tr>
<td>(5/2)^+</td>
<td>3.224</td>
<td>4.9 (1)</td>
</tr>
<tr>
<td>1/2^+</td>
<td>2.615</td>
<td>4.5 (1)</td>
</tr>
<tr>
<td></td>
<td>2.500</td>
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<td>2.266</td>
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<tr>
<td>(5/2^-)</td>
<td>1.638</td>
<td>&gt; 6.1</td>
</tr>
<tr>
<td></td>
<td>1.430</td>
<td>7.3 (2)</td>
</tr>
<tr>
<td></td>
<td>1.095</td>
<td>&gt; 6.5</td>
</tr>
</tbody>
</table>

- exp: Experimental values
- MCSM: Monte Carlo Shell Model values

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**Updated**

- **1/2^+**
  - MCSM: 0.055
  - exp: 5.4 (3)
- **3/2^+**
  - MCSM: 0.06
  - exp: 5.13
- **1/2^-**
  - MCSM: 0.06
  - exp: 6.13
- **3/2^-**
  - MCSM: 0.06
  - exp: 5.29
- **2/^-**
  - MCSM: 0.06
  - exp: 6.13


**Revised**

- **1/2^-**
  - MCSM: 0.055
  - exp: 5.4 (3)
- **3/2^-**
  - MCSM: 0.06
  - exp: 5.13
- **1/2^-**
  - MCSM: 0.06
  - exp: 6.13
- **3/2^-**
  - MCSM: 0.06
  - exp: 5.29
- **2/^-**
  - MCSM: 0.06
  - exp: 6.13

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**Conclusion**

The comparison between the experimental (exp) and Monte Carlo Shell Model (MCSM) values shows slight discrepancies in some states, particularly in the 1/2^+ and 3/2^- states. The MCSM values generally match the experimental data, with deviations likely due to the complexity of the shell model and the limitations of the experimental measurements.
Summary

◆ The decay spectroscopy with spin-polarized $^{28,29}$Na was successfully carried out at TRIUMF.

◆ The decay schemes of $^{28,29}$Na were revised drastically.
  - In $^{28}$Mg, 13 $\gamma$ rays and 9 levels were newly found in the $\beta$ decay of $^{28}$Na. Spins and parities of the 4 levels were newly proposed.
  - In $^{29}$Mg, the 336 keV, 1793 keV, and 1583 keV $\gamma$ rays were newly found in the $\beta$ decay of $^{29}$Na. Spins and parities of the 5 levels were newly proposed.

◆ The level structures of $^{28,29}$Mg were discussed by comparing with the shell model calculation (NuShell).
  - The level energies and $\log ft$ values of the levels in $^{28,29}$Mg were reasonably reproduced by the shell model calculation using USD interaction.
  - For the $^{29}$Mg, the 1.095 MeV and 1.431 MeV levels, the small $\beta$ transition suggests negative parity of these levels, being in good agreement with the MCSM calculation.
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