Investigation of Single-Particle Structure in $^{26}$Na using the new SHARC Array

Gemma Wilson
Talk outline

Motivations and previous work

Experimental setup

Detector performance

Analysis technique

Results
  - proton angular distributions
  - new level scheme

Conclusions
The Experiment

• $^{25}\text{Na}(d,p)^{26}\text{Na}$ in inverse kinematics

• 12 days of 5 MeV/nucleon $^{25}\text{Na}$ beam, between $10^4$-$10^7$ pps, delivered by ISAC-II at TRIUMF

• SHARC used with TIGRESS and a trifoil, a zero degree detector used to separate beam-like particles and fusion evaporation products
Why $^{26}$Na?

- Brand new setup, using a new silicon array
- New analysis technique developed of gating on $\gamma$ rays to extract proton distributions
- Low-lying excited quartet of $\nu d_{3/2} \otimes \pi d_{5/2}$ at around 1.5MeV
  - Disappearance of N=20 magic number?
- Closely spaced states will test our setup in terms of efficiency and resolution
- Setup since been used for $^{24}$Na(d,p)$^{25}$Na - A. Knapton, W.N. Catford, N. Timofeyuk

$^{27}$Mg(d,p)$^{28}$Mg has been approved - W.N. Catford
$^{26}\text{Na Level Scheme}$

$^{14}\text{C}({}^{14}\text{C}, d)^{26}\text{Na}$ at FSU


Previous work:

- $^{26}\text{Mg}(t, {}^{3}\text{He})^{26}\text{Na}$

- $^{25}\text{Na}(d,p)^{26}\text{Na}$

- $\beta$-decay of $^{26}\text{Ne}$
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Mass excess, energies of excited states
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New levels and spin assignments
233- and 407-keV states inferred to be $2^+$
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Mass excess, energies of excited states

New levels and spin assignments

233- and 407-keV states inferred to be $2^+$

Ground state quartet seen. No spin and parity assignments, no angular distributions

New levels. Branching ratios also suggest 2+ for 233- and 407-keV states. Other spins and parities assigned based on decay
Disappearance of the N=20 magic number

- $^{30}\text{Si}$ close to N=Z; has expected magic number at N=20
- $^{24}\text{O}$ is an exotic nucleus; has a magic number at N=16

T. Otsuka et al
Shell-model calculations

Calculations using USD and s-p-sd-pf model spaces
s-p-sd-pf done with 0.7 MeV gap reduction between sd- and pf-shells [1,2]

Schematic

**TIGRESS resolution and decay scheme**

**Downstream box**
- Elastically scattered p and d

**Trifoil**
- Tags recoil events
- All beam goes through

**30μm Al foil**
- Catches fusion evaporation products from carbon

**Upstream box**
- Ejected protons

**CD detector**
- Ejected protons

**CD₂ target**

**25Na beam at 5AMeV**
SHARC

- Silicon Highly Segmented Array for Reactions and Coulex
- Upstream box of 4 DSSSDs
- Downstream box of up to 4 dE-E
- Upstream CD of 4 DSSSDs
- High spatial resolution
- Large solid angle coverage
- Designed to work inside TIGRESS

• TRIUMF-ISAC Gamma-Ray Escape-Suppressed Spectrometer
• Array of up to 16 HPGe detectors
• Each detector has 4 crystals in a common cryostat
• Each clover has 32-fold segmentation
• Can run in two modes: high efficiency or fully suppressed

• Downstream of SHARC
• 10µm scintillation foil with active area of 40mm x 40mm
• Mounted with 30µm Al foil to stop fusion evaporation products
• Has three phototubes, with a coincidence required on two
Setup

TIGRESS

SHARC

Beam direction
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Doppler Correction
Doppler Correction

Resolution of $\gamma$ ray from transfer reaction: 19 keV at 1800 keV
Efficiency of TIGRESS

Efficiency measured initially with $^{56}$Co, $^{152}$Eu and $^{133}$Ba
- Dead time affected!
Efficiency of TIGRESS

Efficiency measured initially with \(^{56}\text{Co},^{152}\text{Eu}\) and \(^{133}\text{Ba}\)
- Dead time affected!

Coincidence method used - determined the efficiency of \(\gamma_2\) by gating on \(\gamma_1\).

\[56\text{Co}\]
Efficiency of TIGRESS

Separate efficiencies for clovers at 90° and 135°

\[ \varepsilon_{\gamma} (846 \text{ keV}) \text{ at } 90^\circ = (1.73\pm0.017)\% \]

\[ \varepsilon_{\gamma} (846 \text{ keV}) \text{ at } 135^\circ = (1.70\pm0.017)\% \]

\[ \varepsilon_{\gamma} (1238 \text{ keV}) \text{ at } 90^\circ = (1.49\pm0.011)\% \]

\[ \varepsilon_{\gamma} (1238 \text{ keV}) \text{ at } 135^\circ = (1.47\pm0.011)\% \]
Use of Trifoil for vetoing $\gamma$ rays

![Graph showing the use of Trifoil for vetoing gamma rays with peaks at 407 keV, 511 keV, 837 keV, 974 keV, 1266 keV, 1509 keV, 1612 keV, and 1806 keV. The graph compares counts per 2 keV without and with trifoil.]
The effect of the Trifoil on particles

Projections of thin slices of these plots can be taken to measure the performance of the Trifoil:
The effect of the Trifoil on particles

Projections of thin slices of these plots can be taken to measure the performance of the Trifoil:

\[ 105^\circ < \theta < 107^\circ \]
The effect of the Trifoil on particles

Projections of thin slices of these plots can be taken to measure the performance of the Trifoil:

\[ 105^\circ < \theta < 107^\circ \]

\[ 129^\circ < \theta < 131^\circ \]
Measuring Trifoil performance

105° < θ < 107°

129° < θ < 131°

Ungated

Trifoil gated
Measuring Trifoil performance

- 80% of protons tagged
- Signal to background improved by factor of 10
Measuring Trifoil performance

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Protons

\[ 105^\circ < \theta < 107^\circ \]

\[ 129^\circ < \theta < 131^\circ \]

Ungated

Trifoil gated

Gamma rays

From one clover
Measuring Trifoil performance

- 80% of protons tagged
- Signal to background improved by factor of 10

- $\gamma$-rays from (d,p) events tagged with 67% efficiency
- Random coincidences (from beam decay): 11%
- $\gamma$-rays not from (d,p) suppressed by factor of 6
- Peak to background improved by factor of 40
Trifoil Efficiency

A measure of efficiency taken by looking at slices in $r$
Trifoil Efficiency

![Graph showing efficiency as a function of r (cm)]

- 85-95 UD1
- 175-185 UD2 CD3
- 265-275 UD3 CD4
- 350-0 UD4 CD4
- 29-39 UD4 CD1
- 135-145 UD2 CD2
The trifoil cannot be used for quantitative analysis.
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Using $\gamma$ rays to separate states
Decays straight to the ground state
Using the Ex vs Eγ plot to identify γ rays

Using the $E_x$ vs $E_Y$ plot to identify $\gamma$ rays
Using the $E_x$ vs $E_Y$ plot to identify $\gamma$ rays
Using the Ex vs E\textgamma plot to identify \textgamma rays
Differential cross-sections

\[ \frac{d\sigma}{d\Omega} = \frac{N}{\varepsilon \, d\Omega \, I_t} \]

- Measured
- Calculated for each angle bin
- From elastic scattering cross-sections
Elastic scattering normalisations

Elastic scattering, which occurs concurrently with transfer, can provide a normalisation for the proton angular distributions.

Fitting to well-known potentials allows beam current and the number of target particles to be known.
Elastic scattering normalisations

\[ \frac{d\sigma}{d\Omega} (\text{mb/Sr}) \]

\[ \theta_{\text{cm}} \text{ (°)} \]

\[ (d,d) \]

\[ (p,p) \]
Elastic scattering normalisations

(p,p): L. Rosen et al., Annals of Physics 34, 96 (1965)
Elastic scattering normalisations

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\( l.t_d = (380 \pm 10) \times 10^2 \text{ mb}^{-1} \)
Elastic scattering normalisations

(p,p): L. Rosen et al., Annals of Physics 34, 96 (1965)

$\sigma_{d/d} = (380 \pm 10) \times 10^2 \text{ mb}^{-1}$

Deuteron to proton ratio = 91.7%
SHARC solid angle

• Solid angle of SHARC needed for angular distribution normalisation
• SHARC is a box
• Dead strips need to be accounted for

For a cylindrically symmetric system:

\[ d\Omega = \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} \int_{\phi} \sin \theta \, d\theta \, d\phi = 2\pi \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} \sin \theta \, d\theta = 2\pi [\cos \theta]_{\theta_{\text{min}}}^{\theta_{\text{max}}} \]
SHARC solid angle

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For a cylindrically symmetric system:

\[
d\Omega = \int_{\theta_{\min}}^{\theta_{\max}} \int_{\phi} \sin \theta \, d\theta \, d\phi = 2\pi \int_{\theta_{\min}}^{\theta_{\max}} \sin \theta \, d\theta = 2\pi [\cos \theta]_{\theta_{\min}}^{\theta_{\max}}
\]

But \(\phi\) isn’t constant over each angle bin!
SHARC solid angle

Target position at (0,0,0)

In each detector, one of the three coordinates is constant

\[ d\Omega = \frac{d\vec{A} \cdot \hat{r}}{r^2} = \frac{d\vec{A} \cdot \vec{r}}{r^3} \]

\[ d\vec{A} = \begin{cases} 
(dx) (dz) \vec{n} & \text{for constant } y, \\
(dy) (dz) \vec{n} & \text{for constant } x.
\end{cases} \]

\[ \vec{r} = (r \sin \theta \cos \phi) \hat{i} + (r \sin \theta \sin \phi) \hat{j} + (r \cos \theta) \hat{k} \]

\[ \theta = \arccos(z/r) \]

\[ \phi = \arctan(y/x) \]
SHARC solid angle

CM frame
Downstream detector for elastic scattering
SHARC solid angle

Lab frame, 2° bins for angular distributions

CM frame
Downstream detector for elastic scattering
Gating technique
Gating technique

• Gates on both excitation energy and a $\gamma$-ray transition to the ground state

• A background gate, which accurately represents the background under the peak

  • Can vary state by state

• Data from 90° and 135° TIGRESS clovers treated separately, before combining

• Proton angular distribution and background normalised before subtraction
Angular distributions for the state and background done at $\theta_{\text{TIG}} = 90^\circ$ and $135^\circ$

Differences in:
- Doppler shift
- Efficiency
- possible anisotropy in $\gamma$-ray distribution
Angular distributions - 233 keV state

Angular distributions for the state and background done at $\theta_{\text{TIG}} = 90^\circ$ and $135^\circ$.

Differences in:
- Doppler shift
- Efficiency
- possible anisotropy in $\gamma$-ray distribution
Angular correlation effects

When a nucleus is populated in a bound excited state, it can $\gamma$ decay
• Will not generally be isotropic due to alignment of magnetic substates of the final nucleus with respect to the beam direction.
  • Detecting protons on the beam axis on a spin-zero target has exclusive $m=0$ population
• As proton angle moves away from 0 or 180°, higher substates are populated

For a non spin-zero target ($^{25}$Na), the observation of the proton at 0° will lead to a substate population in the final state that is driven by the initial (equal) substates in the target, but with the coupling of the transferred $s=^{1/2}$ nucleon.
Substate populations over proton CM angle for a 2.2 MeV state in $^{26}$Na
Substate populations over proton CM angle for a 2.2 MeV state in $^{26}$Na
Comparison of proton angular distributions with and without a γ-ray gate

Gating does not affect the shape of the angular distribution, but the size of the cross-section. Therefore an adjustment to the spectroscopic factor needs to be made.
Angular distributions - 407 keV state
Angular distributions - 407 keV state

\[ \frac{d\sigma}{d\Omega} (\text{mb/Sr}) \]

\[ \theta_{\text{lab}} (\degree) \]

\[ 0.001, 0.01, 0.1, 1, 10 \]

\[ 0, 30, 60, 90, 120, 150, 180 \]

\[ d_{3/2} \]

\[ S_{1/2} \]
Angular distributions - 407 keV state

There have been no previous direct measurements of the 233- or 407-keV states - they have only been previously deduced to be $2^+$ [1,2]

Theoretical cross-sections calculated using TWOFNR, using the zero-range ADWA method [1].

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Particle</th>
<th>Cross-section (mb/Sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.512</td>
<td>$p_{3/2}$</td>
<td>3.512</td>
</tr>
<tr>
<td>3.136</td>
<td>$p_{3/2}$</td>
<td>3.136</td>
</tr>
<tr>
<td>2.226</td>
<td>$d_{3/2}$</td>
<td>2.226</td>
</tr>
<tr>
<td>2.119</td>
<td>$d_{3/2}$</td>
<td>2.119</td>
</tr>
<tr>
<td>1.807</td>
<td>$d_{3/2}$</td>
<td>1.807</td>
</tr>
<tr>
<td>0.407</td>
<td>$s_{1/2}$</td>
<td>0.407</td>
</tr>
<tr>
<td>0.233</td>
<td>$s_{1/2}$</td>
<td>0.233</td>
</tr>
</tbody>
</table>


Hoping to redo this with the help of N. Timofeyuk [IoP, 2013]
26Na
This work

Energies in keV

Branching ratios in red
26 Na
This work

Energies in keV
Branching ratios in red

* Negative parity states
## Final Spectroscopic Factors

<table>
<thead>
<tr>
<th>E* (MeV)</th>
<th>coupling</th>
<th>S.F.</th>
<th>J^π</th>
<th>E* (MeV)</th>
<th>coupling</th>
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</tr>
</thead>
<tbody>
<tr>
<td>3.512</td>
<td>p_{3/2}</td>
<td>0.54</td>
<td>4^-</td>
<td>3.613</td>
<td>p_{3/2}</td>
<td>0.431</td>
<td>4^-</td>
</tr>
<tr>
<td>3.136</td>
<td>p_{3/2}</td>
<td>0.098</td>
<td>3^-</td>
<td>3.377*</td>
<td>p_{3/2}</td>
<td>0.147</td>
<td>3^-</td>
</tr>
<tr>
<td>2.226</td>
<td>d_{3/2}</td>
<td>0.432</td>
<td>4^+</td>
<td>1.648</td>
<td>d_{3/2}</td>
<td>0.59</td>
<td>4^+</td>
</tr>
<tr>
<td>2.119</td>
<td>d_{3/2}</td>
<td>0.216</td>
<td>4^+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.807</td>
<td>d_{3/2}</td>
<td>0.216</td>
<td>3^+</td>
<td>1.247</td>
<td>d_{3/2}</td>
<td>0.32</td>
<td>3^+</td>
</tr>
<tr>
<td>0.407</td>
<td>s_{1/2}</td>
<td>0.337</td>
<td>2^+</td>
<td>0.231</td>
<td>s_{1/2}</td>
<td>0.19</td>
<td>2^+</td>
</tr>
<tr>
<td>0.233</td>
<td>s_{1/2}</td>
<td>0.144</td>
<td>2^+</td>
<td>0.05</td>
<td>s_{1/2}</td>
<td>0.22</td>
<td>2^+</td>
</tr>
</tbody>
</table>

*This state also has an f_{7/2} component, S.F. = 0.168*
Findings

The energies of the negative parity states in $^{26}$Na agree with predictions, to within $\sim$100 keV when the gap between the $sd$- and $pf$-shells was reduced by 0.7 MeV relative to WBP in the $s$-$p$-$sd$-$pf$ calculation.

This systematic lowering of the shell gap was also applicable in the study of $^{25}$Ne[1] and $^{27}$Ne[2].

As previously seen in $^{25}$Ne [1], we see the $\nu(d_{3/2})$ states $\sim$0.5 MeV higher than predicted than WBP (which uses USD in the $sd$-shell).

Therefore the shell gap between the $sd$- and $pf$-shells is found to reduce by 1.2 MeV relative to nuclei closer to stability.

These findings should motivate improvements to the shell model interactions to remove the need for ad hoc adjustments of single particle levels.

Collaborators

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