Doppler shift lifetime measurements using the TIGRESS Integrated Plunger device

Aaron Chester on behalf of the TIP and TIGRESS teams

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Nuclear structure studies far from stability

\[ N = Z \]

\( ^{16}\text{O} \)
\( ^{48}\text{Ca} \)
\( ^{78}\text{Ni} \)
\( ^{100}\text{Sn} \)
\( ^{40}\text{Ca} \)
\( ^{56}\text{Ni} \)
\( ^{208}\text{Pb} \)
\( ^{132}\text{Sn} \)
Along the $N = Z$ line, shells open or close simultaneously and in the same way for protons and neutrons.

Closed shells are spherical and inert.

Proton-neutron interactions develop for partially filled proton and neutron shells, driving shape deformation.

This gives rise to the phenomenon of shape evolution along the $N = Z$ line.
Studying nuclear structure using the electromagnetic force

- The electromagnetic force provides a convenient non-intrusive probe of nuclear systems bound by the strong force.
- Lifetime measurements using gamma-ray spectroscopy provide:
  1. An observable sensitive to nuclear structure.
  2. A sensitive benchmark for nuclear model calculations.

\[
\tau(E2; 2_1^+ \to 0_1^+) = \frac{1}{\lambda(E2; 2_1^+ \to 0_1^+)}
\]
\[
\lambda(E2; 2_1^+ \to 0_1^+) \propto E(2_1^+)^5 \times B(E2; 2_1^+ \to 0_1^+)
\]
\[
B(E2; 2_1^+ \to 0_1^+) \propto \langle 2_1^+ | |E2| |0_1^+ \rangle^2
\]
\[
B(E2; 2_1^+ \to 0_1^+) \propto \beta^2
\]
Motivation: Why $^{68}\text{Se}$?

Model calculations

<table>
<thead>
<tr>
<th>Model</th>
<th>Interaction</th>
<th>Hartree-Bogoliubov</th>
<th>Self-consistent</th>
<th>Excited</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell Model</td>
<td>$B(E2, 2^+_1 \rightarrow 0^+_1) \ [e^{2}\text{fm}^4]$</td>
<td>$100^1$</td>
<td>$500^3$</td>
<td></td>
</tr>
<tr>
<td>Interacting</td>
<td></td>
<td>$280^2$</td>
<td>$725^4$</td>
<td></td>
</tr>
<tr>
<td>Hartree-Bogoliubov</td>
<td></td>
<td></td>
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<td>Self-consistent</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$B(E2, 2^+_1 \rightarrow 0^+_1) \ [e^{2}\text{fm}^4]$</th>
<th>$\tau \ [\text{ps}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coulex $^6$</td>
<td>432(58)</td>
</tr>
<tr>
<td>RDM $^7$</td>
<td>392(70)</td>
</tr>
</tbody>
</table>


Recent measurements

A compound system forms with large angular momentum and recoil speed.

The system decays first by the emission of particles, then by gamma-ray emission.

Exotic recoil products can be studied provided a proper channel selection method is realized.
Doppler shift attenuation method lifetime measurements

- a) Fully shifted \( \tau < t_{stopping} \)
- b) Partially shifted \( \tau \approx t_{stopping} \)
- c) Fully stopped \( \tau > t_{stopping} \)

Penetration into stopper

Particle detector

Germanium detector

Number of counts
TIP DSAM configuration

Camera

Collimator

LED

Rotating Rod

Target Wheel
Objective: Observation of $^{68}$Se and possible lifetime measurement via DSAM.

Detectors:
- 24-element CsI(Tl) downstream wall for particle detection.
- 13 TIGRESS HPGe and 3 GRIFFIN HPGe for gamma-ray detection.

An $^{36}$Ar beam was reacted on a $^{40}$Ca target in a variety of backings and running conditions.

The $^{76}$Sr compound nucleus has 2α evaporation channel to $^{68}$Se.

Preliminary analysis is geared towards optimizing procedures for observation of $^{68}$Se.
### $^{68}$Se DSAM experiment summary

<table>
<thead>
<tr>
<th>Beam energy</th>
<th>Target</th>
<th>Backing</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 MeV</td>
<td>250 µg/cm$^2$ Ca</td>
<td>21.7 mg/cm$^2$ Au</td>
<td>ox</td>
</tr>
<tr>
<td>110 MeV</td>
<td>250 µg/cm$^2$ Ca</td>
<td>21.7 mg/cm$^2$ Au</td>
<td>ox</td>
</tr>
<tr>
<td><strong>110 MeV</strong></td>
<td><strong>250 µg/cm$^2$ Ca</strong></td>
<td><strong>25.6 mg/cm$^2$ Pb</strong></td>
<td>ox</td>
</tr>
<tr>
<td>110 MeV</td>
<td>500 µg/cm$^2$ Ca</td>
<td>28.1 mg/cm$^2$ Pb</td>
<td>v. ox</td>
</tr>
<tr>
<td>110 MeV</td>
<td>134.2 µg/cm$^2$ Ca</td>
<td>24.36 mg/cm$^2$ Au</td>
<td>remade</td>
</tr>
<tr>
<td>105 MeV</td>
<td>134.2 µg/cm$^2$ Ca</td>
<td>24.36 mg/cm$^2$ Au</td>
<td>remade</td>
</tr>
<tr>
<td>115 MeV</td>
<td>250 µg/cm$^2$ Ca</td>
<td>27.6 mg/cm$^2$ Pb</td>
<td>remade</td>
</tr>
<tr>
<td>100 MeV</td>
<td>250 µg/cm$^2$ Ca</td>
<td>27.6 mg/cm$^2$ Pb</td>
<td>remade</td>
</tr>
</tbody>
</table>

- ox: target exhibited signs of oxidation
- v. ox: old target, very oxidized
- remade: remade by Micromatter with calcium “chunks” rather than grains
Gamma-ray spectrum: No particle identification

Strong lines from reactions on $^{16}$O!

- $^{49}$Cr $^{7/2-} \rightarrow ^{5/2-}$ $^{271.8 \text{ keV}}$
- $^{46}$Ti $^{2+} \rightarrow ^{0+}$ $^{889.3 \text{ keV}}$
- $^{49}$V $^{11/2-} \rightarrow ^{7/2-}$ $^{1021.6 \text{ keV}}$
- $^{49}$V $^{15/2-} \rightarrow ^{11/2-}$ $^{1241.7 \text{ keV}}$
- $^{46}$Ti $^{6+} \rightarrow ^{4+}$ $^{1289.1 \text{ keV}}$
- $^{46}$Ti $^{10+} \rightarrow ^{8+}$ $^{1345.1 \text{ keV}}$
CsI(Tl) detector waveform fits

Waveform fit function

for $t \leq t_0 : W(t) = C$

for $t \geq t_0 : W(t) = C$

(Csl fast) $\rightarrow + A_F \left[ 1 - \exp \left( \frac{t - t_0}{\tau_F} \right) \right] \exp \left( \frac{t - t_0}{\tau_{RC}} \right)$

(Csl slow) $\rightarrow + A_S \left[ 1 - \exp \left( \frac{t - t_0}{\tau_S} \right) \right] \exp \left( \frac{t - t_0}{\tau_{RC}} \right)$

(PIN rise time) $\rightarrow + A_R \left[ 1 - \exp \left( \frac{t - t_0}{\tau_R} \right) \right] \exp \left( \frac{t - t_0}{\tau_{RC}} \right)$
Particle identification using CsI(Tl) waveform fits

PID value = 100 × (1 + $A_S/A_F$ )
1p1α gated gamma-ray spectrum

- **47V**: 1p1α from $^{36}\text{Ar}+^{16}\text{O}$
- **46Ti**: 2p1α from $^{36}\text{Ar}+^{16}\text{O}$
- **70Se**: 2p1α from $^{36}\text{Ar}+^{40}\text{Ca}$
2p1\(\alpha\) gated gamma-ray spectrum

- * 46Ti: 2p1\(\alpha\) from \(^{36}\text{Ar}+^{16}\text{O}\)
- ‡ 70Se: 2p1\(\alpha\) from \(^{36}\text{Ar}+^{40}\text{Ca}\)

![Graph showing gamma-ray spectrum with energy in keV on the x-axis and counts in 1 keV/ch on the y-axis. Peaks marked with * indicate 46Ti: 2p1\(\alpha\) from \(^{36}\text{Ar}+^{16}\text{O}\), while peaks marked with ‡ indicate 70Se: 2p1\(\alpha\) from \(^{36}\text{Ar}+^{40}\text{Ca}\).]
<table>
<thead>
<tr>
<th>Particle type</th>
<th>eff. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>18.72(11)</td>
</tr>
<tr>
<td>Alpha</td>
<td>7(3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle type</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>14.8(4)</td>
</tr>
<tr>
<td>Alpha</td>
<td>5.5(1.5)</td>
</tr>
</tbody>
</table>

For comparison, the efficiency of Microball is $\sim 70\%$ for protons and $\sim 45\%$ for alpha particles under similar conditions.\textsuperscript{8}

DSAM lineshapes in the 2p1α gate

$^{46}$Ti
$^8 \rightarrow ^6 + 1597.5$ keV
$\tau = 0.71(9)$ ps

Counts [1 keV/ch]

Energy [keV]

ring 1

ring 2

ring 3

ring 4

ring 5

ring 6

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Add-back procedure

\[ E_1 > E_2 \]
Add-back procedure

\[ E = E_1 + E_2 \] assigned to white
Add-back factor = 1.37 (37% more counts in add-back) at 889 keV.

Reduced low energy Compton background
Compton suppression via TIGRESS/BGO hit pattern

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Future work: DSAM lineshape analysis code

- Geant4-based analysis code to extract lifetimes from DSAM lineshapes is under development.
- The TIGRESS array and TIP ancillary detectors have been implemented.
- Fusion-evaporation reaction kinematics must be implemented.
- Simulated lineshapes can be fit to experimental spectra and the best fit lifetime can be determined.
Future work: experiments with the TIP plunger

The TIP plunger device for RDM measurements, designed by Robert Henderson at TRIUMF.
Future work: TIP CsI(Tl) ball

The TIP CsI(Tl) ball, an $\sim 4\pi$ particle detector, designed by Robert Henderson at TRIUMF.
Conclusions and Summary

- Currently establishing data analysis procedures prior to attempting $^{68}$Se identification.

- BGO suppression schemes are currently under investigation.

- The analysis will be geared towards identifying $^{68}$Se and other nuclei where a contribution can be made by:
  1. Measuring lifetimes,
  2. building level schemes,
  3. measuring angular distributions,
  4. and measuring linear polarization.
Acknowledgements

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Effect of target oxidation

![Graph showing the effect of target oxidation with energy in keV on the x-axis and counts (x10^3) [1 keV/ch] on the y-axis. Two curves represent the oxidized target and the remade target.]

- Oxidized target
- Remade target

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Calculating particle detection efficiency: an example

- In general, if \( n \) particles are emitted, the probability to detect \( i \) is given by Eq. 1
  \[
P(i) = \binom{n}{i} \varepsilon^i (1 - \varepsilon)^{n-i}
  \]  
  where \( \varepsilon \) is the particle detection efficiency.

- The probability of detecting the two proton channel in the one proton gate is given by Eq. 2
  \[
P(2p \text{ in } 1p) = \binom{2}{1} \varepsilon_p^1 (1 - \varepsilon_p)^{2-1} = 2\varepsilon_p (1 - \varepsilon_p)
  \]  
  where \( \varepsilon_p \) is the proton detection efficiency.

- Similarly, the probability of detecting the two proton channel in the two proton gate is given by Eq. 3
  \[
P(2p \text{ in } 2p) = \varepsilon_p^2
  \]
Calculating particle detection efficiency: an example

- Take the ratio of probabilities and solve for $\varepsilon_p$:

\[
R = \frac{P(2p \text{ in } 2p)}{P(2p \text{ in } 1p)} = \frac{\varepsilon_p^2}{2\varepsilon_p(1 - \varepsilon_p)} = \frac{\varepsilon_p}{2(1 - \varepsilon_p)}
\]

\[
\Rightarrow \varepsilon_p = \frac{2R}{1 + 2R}
\]

- We can calculate the proton detection efficiency for the $^{36}\text{Ar} + ^{40}\text{Ca}$ reaction channel using the 1p1\(\alpha\) and 2p1\(\alpha\) gates.

- The detection probability is reflected in the number of observed gamma-rays from the nucleus of interest; in this case the 944 keV line in $^{70}\text{Se}$.

- The alpha particle detection efficiency is fixed by examining the same alpha particle gate.

69141(437) counts in the 1p1\(\alpha\) gate and 5996(121) counts in the 2p1\(\alpha\) gate $\Rightarrow \varepsilon_p = 14.8(4)\%$ from Eq. 5.