Doppler shift lifetime measurements in $^{94}$Sr using the TIGRESS Integrated Plunger

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CAP Congress
Ottawa, ON
13-17 June 2016
Selected goals of nuclear science research

- Understand the mechanisms of shell evolution in medium-mass and heavy nuclei as a function of isospin.
- Develop a theoretical framework that is able to make accurate predictions of nuclear properties.

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.

\[
\tau(E2; 2^+_1 \rightarrow 0^+_1) = \lambda(E2; 2^+_1 \rightarrow 0^+_1)^{-1} \\
\lambda(E2; 2^+_1 \rightarrow 0^+_1) \propto E(2^+_1)^5 \times B(E2; 2^+_1 \rightarrow 0^+_1) \\
B(E2; 2^+_1 \rightarrow 0^+_1) = \frac{1}{5} \langle 2^+_1 | |E2| |0^+_1 \rangle^2 \propto \beta^2
\]
The Recoil Distance Method (RDM)

\[ c = 300 \, \mu m/ps \quad \beta = \frac{v}{c} \sim 0.05 \quad 1 \, ps \sim 15 \, \mu m \]

- Doppler shift of emitted gamma rays depends on the decay position.

- The lifetime can be inferred from the ratio of peak intensities if the recoil velocity is known.

- The velocity is measured from the Doppler shift.
The TIGRESS Integrated Plunger (TIP) device

TIP: calibrating target/degrader separation

\[ f(x) = \frac{(x-d_0)}{D} + \alpha \frac{(x-d_0)^2}{D^2} \]

- \( x_{\text{min}} = 2.94488 \text{ mm} \)
- \( d_0 = 2.93128 \text{ mm} \)
- minimum separation distance = 13.6 \( \mu \text{m} \)
RIB production at TRIUMF

ISAC-I and ISAC-II Facility
TIGRESS at TRIUMF

- TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) is an array of up to 16 segmented HPGe detectors.
- Each detector consists of 4 crystals with 8 segments/crystal with sub-segment position sensitivity.
- TIGRESS can be run in multiple configurations utilizing BGO shielding and optional X-ray absorbers.
Coulomb excitation (inverse kinematics)

\[ \beta = \frac{v}{c} \]

Impact parameter \( b \)  

Scattering angle \( \theta \)

Coulomb excitation followed by gamma-ray emission
TIP commissioning experiment

- Goal: measurement of the $2^+_1 \rightarrow 0^+_1$ lifetime in $^{84}$Kr.

- Previous measurement: 5.84(18) ps.

- TIP and 11 TIGRESS detectors in a 3/5/3 configuration with 24-element CsI(Tl) wall.

- Excited state populated via partially unsafe Coulex reaction.

- Data acquired using a TIGRESS/CsI(Tl) coincidence trigger.

TIP with the CsI(Tl) wall
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) $\to + A_F \left[ 1 - \exp \left( \frac{-t - t_0}{\tau_F} \right) \right] \exp \left( \frac{-t - t_0}{\tau_{RC}} \right)$

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

(PIN rise time) $\to + A_R \left[ 1 - \exp \left( \frac{-t - t_0}{\tau_R} \right) \right] \exp \left( \frac{-t - t_0}{\tau_{RC}} \right)$

TIGRESS detector waveform fits

![Graph showing waveform fits](image)

- **Partial risetime fit**
- **Baseline**
TIGRESS/CsI(Tl) array timing plot
TIGRESS/CsI(Tl) array: time correlated events only
Identifying $^{84}$Kr Coulex recoils

![Graph showing the distribution of protons, alphas, and heavy particles based on amplitude and PID value.

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Lifetime measurements with TIP  
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Effect of target/degrader separation

TIGRESS ring 1
θ = 38°

Energy [keV]
Counts [1 keV/ch]

Target/degrader separation: 20 μm

60 μm

120 μm
$^{84}$Kr decay curve

$\tau_{\text{lit.}} = 5.84(18)$ ps
$\tau_{\text{exp.}} = 5.87(4)$ ps

Preliminary
TIP Geant4 simulations

- User-defined reaction mechanism (Coulex) followed by gamma-ray decay.
- Analytic solutions for single step $E2$ process (Coulex kinematics, cross sections, angular distributions).
- Gamma-ray sensitive detectors ported from GRIFFIN/TIGRESS code originating from Guelph.
- Simulate lineshapes $\rightarrow$ extract lifetimes.

Simulated Doppler shift map for $^{84}$Kr

Doppler shift factor = $\frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \theta}$
Doppler shift groups for lineshape analysis

![Doppler shift factor graph]

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13-17 June 2016
RDM lineshape fits for $^{84}$Kr

Experiment
Simulation

$\tau_{\text{sim.}} = 5.84$ ps

Group 1

Group 2

Group 3

Group 4

Group 5

Counts $[1$ keV/ch$]$

Energy [keV]

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Lifetime measurements with TIP
Coulex/RDM at TRIUMF: the case for $^{94}$Sr

\[
B(E2; 2^+ \rightarrow 0^+) \left[ e^2 b^2 \right]
\]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{Mass number (Sr, Z = 38)}
\end{figure}

- Mach et al. (1991)
- Clement et al. (2016)
- Pritychenko et al. (2016)
- Mach et al. (1989)
- Ohm et al. (1987)
- Lhersonneau et al. (1990)
Based on the success of the commissioning run, a $^{94}$Sr lifetime measurement experiment was performed from December 9–14 at TRIUMF.

Goal: measurement of the $2_{1}^{+} \rightarrow 0_{1}^{+}$ lifetime in $^{94}$Sr.

Previous measurement: 10(4) ps.

TIP and 16 TIGRESS detectors in a 4/8/4 configuration with 24-element CsI(Tl) wall.

Reaction mechanism, trigger settings and analysis techniques established during commissioning run.

$^{94}\text{Sr}$ RDM spectrum: 100 µm
Identifying $^{94}$Sr Coulex recoils

![Graph showing PID value against amplitude for identifying $^{94}$Sr recoils. The graph displays different categories such as Electrons, Heavy particles, and Al recoils.](image-url)
PID gated $^{94}$Sr RDM spectrum: 100 $\mu$m

TIGRESS ring 1
$\theta = 38^\circ$

Counts [4 keV/ch]

Energy [keV]

Counts [4 keV/ch]

Energy [keV]

Counts [4 keV/ch]

Energy [keV]

Counts [4 keV/ch]

Energy [keV]
Simulated Doppler shift map for $^{94}$Sr

Doppler shift factor $= \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \theta}$
RDM lineshape fits for $^{94}\text{Sr}$

100 μm

$\tau_{\text{sim.}} = 10.0$ ps

Experiment

Simulation

Group 1

Group 2

Group 3

Group 4

Group 5
Acknowledgments

TIP Design
R. Henderson, TRIUMF

Simon Fraser University
C. Andreoiu, D. Cross, T. Domingo, J. Pore, U. Rizwan, K. Starosta, P. Voss, J. Williams

SFU Science Machine & Electronics Shops
R. Holland, P. Kowalski, J. Shoults, K. Van Wieren

TRIUMF

University of Guelph
E. T. Rand, C. Svensson

University of Toronto
T. E. Drake

University of Surrey
L. Evitts, S. Hallam

St. Mary’s University
R. A. E. Austin
TIP commissioning experiment

\[ ^{84}\text{Kr properties} \]

\begin{align*}
E_\gamma & \quad 881.615 \text{ keV} \\
\tau_{\text{lit.}} & \quad 5.84(18) \text{ ps}
\end{align*}

Plunger setup

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [mg/cm^2]</th>
<th>Thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Al</td>
<td>1.07(4)</td>
</tr>
<tr>
<td>Degrader</td>
<td>Cu</td>
<td>3.90(16)</td>
</tr>
</tbody>
</table>

\[ ^{84}\text{Kr beam properties} \]

<table>
<thead>
<tr>
<th>Energy [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coulomb barrier</td>
</tr>
<tr>
<td>Safe Coulex</td>
</tr>
<tr>
<td>Beam energy</td>
</tr>
</tbody>
</table>
$^{94}\text{Sr}$: Previous results

Timing spectrum and observed centroid shift for $^{90}\text{Sr}$.

### 94Sr: Previous results

<table>
<thead>
<tr>
<th>Time [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centroid shift</td>
</tr>
<tr>
<td>RD correction</td>
</tr>
<tr>
<td>Compton correction</td>
</tr>
<tr>
<td>$\tau_{2^+_1 \to 0^+_1}$</td>
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</tbody>
</table>

- Timing spectrum FWHM is 96 ps.
- These measurements are at the limit of the applicability of the fast timing technique.
- Is the onset of deformation in the Sr isotopes truly as sudden as it appears?

TIP: capacitance stabilization

![Graph of amplitude ratio (%) over time (Hr:Min)](image1)

![Graph of temperature (V) over time (Hr:Min)](image2)
TIP: capacitance stabilization

![Graph showing amplitude ratio and temperature changes over time.](image-url)
HPGe/BGO hit map
HPGe/BGO suppression map

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Compton suppression results

![Graph showing Compton suppression results for different detectors with and without BGO suppressors.](image)

- **TIGRESS detector**
  - With BGO suppressors
  - Energy range: 200 keV to 1800 keV
  - Counts [1 keV/ch]: Ranged from 0 to 2000

- **GRIFIN detector**
  - Without BGO suppressors
  - Energy range: 200 keV to 1800 keV
  - Counts [1 keV/ch]: Ranged from 0 to 2000

Legend:
- Black line: Rejected
- Red line: Accepted

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Add-back procedure

$E_1 > E_2$
Add-back procedure

\[ E = E_1 + E_2 \] assigned to white

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Add-back factor $= 1.37$ (37% more counts in add-back) at 889 keV.