Doppler Shift Attenuation Method: The experimental setup at the MLL and the lifetime measurement of the 1st excited state in $^{31}\text{S}$

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Doppler Shift Attenuation Method: The experimental setup at the MLL and the lifetime measurement of the 1\textsuperscript{st} excited state in $^{31}\text{S}$

1. Motivation

2. Method, setup and experiment

3. Analysis: simulation and line shape calculation

4. Results and conclusion
1. Motivation

- H-rich material accumulates on surface of white dwarf (C/O or O/Ne core)
- energy production via pp-chain ($e \sim T^4$)
- CNO sets in ($e \sim T^{17}$) pressure overcomes degeneracy $\rightarrow$ ejection of the envelope
- proton capture up to $A=40$
- competition: p-capture / b decay

(classical nova illustration)
1. Motivation

(p,g) vs. b decay reaction rates
1. Thermonuclear Resonant Reaction Rate

\[
\langle ov \rangle = \left( \frac{8}{\pi \mu} \right)^{1/2} (kT)^{3/2} \int_0^\infty E \sigma(E) \exp \left( \frac{-E}{kT} \right) dE
\]

\[
\langle ov \rangle = \left( \frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \sum_i \omega \gamma_i \exp \left( \frac{-E_i}{kT} \right)
\]

Resonance strength

\[
\omega \gamma_i = \frac{2J_i + 1}{(2J_p + 1)(2J_X + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma}
\]

\[
= g(l - B_p) B_p \frac{\hbar}{\tau_i}
\]

\[
= g(l - B_\gamma) B_\gamma \frac{\hbar}{\tau_i}
\]

Life time

\[
\mu \ - \ reduced \ mass
\]

\[
J_i, J_p, J_X \ - \ Spins \ of: \ resonance \ state/ \ projectile/ \ target
\]

\[
T \ - \ temperature
\]

\[
E_i \ - \ relative \ energy \ of \ state \ (to \ Q)
\]

\[
\Gamma_p, \Gamma_\gamma \ - \ partial \ width \ of \ p- / \gamma- \ decay
\]

\[
B_p = \Gamma_p / \Gamma \ - \ branching \ ratio
\]
2. Lifetime measurements

- Population of the state
  - $t = 0s$
  - $10fs < \tau < 1ps$
  - $1ps < \tau < 100ps$
  - $100ps < \tau$

- Fast electronic timing:
  - Start-stop measurements
  - Counting measurements

- Doppler Shift Attenuation Method
- Recoil-Distance Doppler Shift Method
2. Doppler Shift Attenuation Method

Setup:

\[ \beta(t) = \frac{v_{\text{ion}}(t)}{c} \]

\[ E_{\gamma}^{\text{obs}} = E_{\gamma}^{0} \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \alpha} \approx E_{\gamma}^{0} (1 + \beta \cos \alpha) \]
2. Doppler Shift Attenuation Method

\[ \beta(t) = \frac{v_{ion}(t)}{c} \]

\[ E_{\gamma}^{obs} = E_{\gamma}^{0} \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \alpha} \approx E_{\gamma}^{0}(1 + \beta \cos \alpha) \]

**Setup:**
- Ion beam
- Thick target
- HPGe at 0°

**Graph:**
- Activity vs. time in [ps]
- E\(_{\gamma}\) in [keV]
- \(\tau = 1.000\) ps
2. DSAM setup at the MLL

Setup:
- HPGe at 110°
- Thick target

Beam:
- \( ^{32}\text{S} \) at 85 MeV

Target:
- \( ^{3}\text{He} \) implanted Au (stops \( ^{31}\text{S} \))

Recoils:
- \( ^{31}\text{S} \) with \( E_{ex} = 1.25 \text{ MeV} \)
- \( ^{4}\text{He} \) for PID & coinc.

Reaction: \( ^{32}\text{S}(^{3}\text{He},^{4}\text{He})^{31}\text{S}^* \)
2. Commissioning experiment: $^{32}\text{S}(^{3}\text{He},^{4}\text{He})^{31}\text{S}^*$

Reaction: $^{32}\text{S}(^{3}\text{He},^{4}\text{He})^{31}\text{S}^*$

Beam: $^{32}\text{S}$ at 85 MeV

Low trans. strength:
$2^{\text{nd}} \rightarrow 1^{\text{st}}, 3^{\text{rd}} \rightarrow 1^{\text{st}}$

High trans. strength:
$4^{\text{th}} \rightarrow 1^{\text{st}}, 5^{\text{th}} \rightarrow 1^{\text{st}}$

levels nicely separated
Detector response function known
known lifetime
no feeding

Russbach, 13/03/13
2. DSAM setup at the MLL

- Condensation tube
- Cooled target ladder rotated by \( \theta = 54^\circ \)
- Si detectors at \( \theta = 39^\circ \)

Russbach, 13/03/13
2. DSAM setup at the MLL
2. DSAM setup at the MLL

Features: beam diagnostic

- mini cup with suppressing voltage
- optional collimator in Cu tube
- CsI crystal for visual diagnostic
2. DSAM setup at the MLL

Features: target ladder

- 5+2 positions
- linear translator
- rotation angle 54°
- coolable to $T = -100 \, ^\circ C$
2. DSAM setup at the MLL

Features: Silicon telescopes
- $E/E$ (50 $\mu$ m/1mm) for PID
- polar angles: $25^\circ < \theta < 60^\circ$
- distance: 32 mm
- $20 \times 20$ mm$^2$
- position sensitive
2. DSAM setup at the MLL

- target chamber base
- copper tube
- target ladder
- Silicon telescopes
3. Analysis: Simulation and lineshape calculation

Three major analysis steps:

3.1 Proceeding the acquired data of the experiment
   → calibration
   → background reduction in the $E_g$ spectra

3.2 Simulation of the Stopping process: Geant4

3.3 Line shape analysis: Fitting with APCAD
3.1 Proceeding the experimental data

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3.1 Proceeding the experimental data

Raw data:

- ~90 hours (with 2.3 pnA) \( ^{32}\text{S} \rightarrow \text{“}^{3}\text{He} + \text{Au}” \) target

- ~30 hours (with 6.3 pnA) \( ^{32}\text{S} \rightarrow \text{“} \text{Au-only}” \) target

- global trigger on charged particles in the Si telescopes
3.1 Proceeding the experimental data

Proceeding:

• Particle identification in the dE/E Si telescopes
• Background subtraction
3.1 $E_\gamma$ background subtraction

\[
\text{scaling} = \frac{\text{Integral}^{3\text{He}}_{[1350.0, 1700.0]}}{\text{Integral}^{\text{Au}}_{[1350.0, 1700.0]}}
\]

- Dotted line: $^3$He data
- Dotted line: Au only data
3.1 $E_\gamma$ spectra for lineshape analysis

![Graphs showing $E_\gamma$ spectra for different angles: 110°, 90°, and 0°.](image-url)
Three major analysis steps:

3.1 Proceeding the acquired data of the experiment → calibration → background reduction in the $E_g$ spectra

3.2 Simulation of the Stopping process: Geant4

3.3 Line shape analysis: Fitting with APCAD
3.2 Simulation of the stopping process: Geant4

Monte Carlo simulation:

- beam:
  - energy
  - elliptical spot

- target:
  - 1st layer: $^3$He in gold
  - 2nd layer: Au only
  - rotation

- transfer reaction
3.2 Simulation of the stopping process: Geant4

Output file:

- if transfer reaction occurs:
  - save $^{31}$S vector
  - save $^4$He vector
  for each time step
3.1 Proceeding the experimental data

Three major analysis steps:

3.1 Proceeding the acquired data of the experiment
   → calibration
   → background reduction in the \( E_g \) spectra

3.2 Simulation of the Stopping process: Geant4

3.3 Line shape analysis: Fitting with APCAD
3.3 Line shape analysis: APCAD

**Analysis Program for Continuous Angle DSAM**

- Christian Stahl, TU Darmstadt, AG Pietralla

**Idea:**

1. Simulate stopping process $v_{\text{ion}}(t)$
2. Determine observed Doppler Shift distribution $m_{\text{det}}(t)$
3. Assume lifetime and convolve it with $m_{\text{det}}(t)$
4. Fit experimental line shape by varying assumed lifetime
3.3 Fitting the experimental data

HPGe detector at $\Theta = 110^\circ$
3.3 Fitting the experimental data
3.3 Fitting the experimental data

HPGe detector at $\psi = 0^\circ$
3.3 Fitting the experimental data

- simultaneous fit of all angles

$$\tau = \left(964 \pm 19_{\text{stat}} \pm \text{Error}_{\text{syst}}\right) \text{fs}$$

preliminary
4. Results and error discussion

geometry of the setup

preliminary

stopping power

16%

2.4%
4. Conclusion and outlook

• Successful commissioning of the new DSAM setup at the MLL

• 1\textsuperscript{st} excited state in $^{31}$S:

$$\tau = \left( 964 \pm 19_{\text{stat}} \pm 89_{\text{syst}} \right) \text{fs}$$

• The error is dominated by systematic uncertainties of the stopping power

Outlook:

• Neutron detector for access to additional reaction channels

• DAQ: digitizer

• Ice target (hydrogen target)

• Miniball @ MLL

• CRYRING @ GSI
5. Additional slides
5.1 previous measurements:

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32S(^3He,^4He)^{31}S, 7MeV, direct kinematic

2-step fragmentation, 
40Ca+^9Be->^{37}Ca

^{37}Ca+^9Be->^{31}S

Miniball,

Fusion evaporation, 
20Ne+^{12}C->^{31}S+n
5.2 feeding

High trans strength: $4^{\text{th}} \rightarrow 1^{\text{st}}, 5^{\text{th}} \rightarrow 1^{\text{st}}$

Russbach, 13/03/13
5.2 Energy of $^4$He particles

- $^4$He ($^3_1S \rightarrow$ ground state)
- $^4$He ($^3_1S \rightarrow$ 1st state)
- $^4$He ($^3_1S \rightarrow$ 2nd state)
- $^4$He ($^3_1S \rightarrow$ 3rd state)
- $^{3_1S}$ (ground state)
- $^{3_1S}$ (1st state)
- $^{3_1S}$ (2nd state)
- $^{3_1S}$ (3rd state)

- Distance target detector: 34.65
- Target rotation: 54.00
- Beam diameter: 3.00

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5.3 Fusion evaporation

\[ {^{32}\text{S} + ^{12}\text{C}} \rightarrow X + ^{4}\text{He} \]

\[ {^{39}\text{K}} \rightarrow ^{36}\text{Ar} \]

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5.3 Fusion evaporation
2. Recoil-Distance Doppler Shift Method

\[ N_{\text{shifted}} = \int_{t=0}^{t_{\text{flight}}} N_{\text{all}} \exp \left( -\frac{t}{\tau} \right) \]

\[ E_{\gamma}^{\text{obs}} = E_{\gamma}^{0} \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \alpha} \approx E_{\gamma}^{0} (1 + \beta \cos \alpha) \]

\[ \beta = \begin{cases} \frac{v_{\text{flight}}}{c}, & t < t_{\text{flight}} \\ 0, & t > t_{\text{flight}} \end{cases} \]

\[ t_{\text{flight}} = \frac{d}{\beta_{\text{flight}} \cdot c} \]

Setup:
- Thin target
- Stopper
- HPGGe at 0°
- Ion beam
- Flight path

Where:
- \( \beta \) is the velocity of the target relative to the observer.
- \( t_{\text{flight}} \) is the flight time.
- \( d \) is the distance.
- \( \beta_{\text{flight}} \) is the flight velocity.
- \( c \) is the speed of light.
2. Recoil-Distance Doppler Shift Method

Setup:

\[ \beta = \begin{cases} \frac{v_{\text{flight}}}{c}, & t < t_{\text{flight}} \\ 0, & t > t_{\text{flight}} \end{cases} \]

\[ t_{\text{flight}} = \frac{d}{\beta_{\text{flight}} \cdot c} \]

\[ E_{\gamma}^{\text{obs}} = E_{\gamma}^{0} \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \alpha} \approx E_{\gamma}^{0} (1 + \beta \cos \alpha) \]

\[ N_{\text{shifted}} = \int_{t=0}^{t_{\text{flight}}} N_{\text{all}} \exp \left( -\frac{t}{\tau} \right) \]
3.1 TDC gate

TDC data

• common start: trigger Si telescopes

• individual stop:
  - delayed Si telescopes
  - HPGe @ 0°
  - HPGe @ 90°
  - HPGe @ 110°
3.1 charged particle identification

PID gate with E/E Si telescopes

two groups:
• protons
• $^3\text{He}$, $^4\text{He}$

$\rightarrow$ $^3\text{He}$ and $^4\text{He}$ can not be separated
3.1 charged particle identification

PID gate with E/E Si telescopes

effective thickness $d_{\text{eff}}$ of $E$ depends on ($\theta, \varphi$)

\[ d_{\text{eff}} = \frac{d_{\text{norm}}}{\vec{p} \cdot \vec{n}} \]
3.1 charged particle identification
3.1 PID $\alpha$ gate on $E_\gamma$ spectra
3.3 Projection on a HPGe detector

Observed Doppler shift is determined by the ion’s velocity component in the direction of observation

\[
E_{\gamma}^{\text{obs}} = E_{\gamma}^0 \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \alpha} \\
\approx E_{\gamma}^0 (1 + \beta \cos \alpha)
\]

\[
E_{\gamma}^{\text{obs}} = E_{\gamma}^0 (1 + m)
\]

\[
m = \frac{E_{\gamma}^0}{E_{\gamma}^{\text{obs}}} - 1 = \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \alpha} - 1
\]
3.3 Projection on a HPGe detector

![Graph showing projection on a HPGe detector at 0° and normalized Doppler shift factor.](image-url)
3.3 Doppler Shift distribution: projection
3.3 Line shape modeling

\[ \tau = 0.500 \text{ ps} \]

- Counts vs. time in [ps]
- Time after excitation in [ps]
3.3 Line shape modeling
3.3 Line shape modeling
3.3 Physical energy in the HPGe

$$E_{\gamma}^{\text{obs}} = E_{\gamma}^{0}(1 + m)$$

1st state in $^{31}$S:

$$E_{\gamma}^{0} = 1248.9\text{keV}$$
3.3 HPGe detector response
3.3 Fitting the experimental data

Optimize $\chi^2$

free parameters:
- lifetime
- transition energy $E^0_{\gamma}$
- number of events
- background offset

Fixed parameters:
- HPGe detector response
- background slope

$\tau = 500\text{fs}$