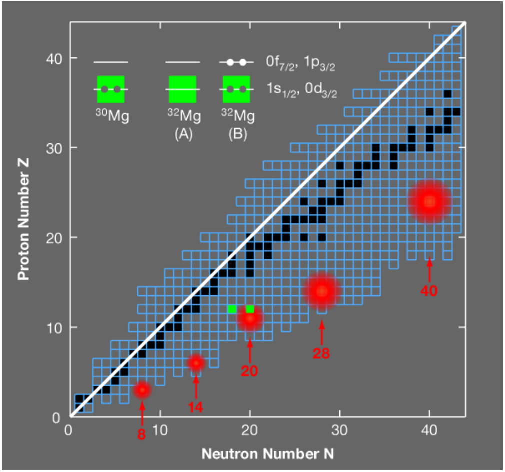
Electromagnetic Transition Rate Studies in ^{28}Mg

Matthew S. Martin for the TIP/TIGRESS Collaborations

Department of Physics, Simon Fraser University

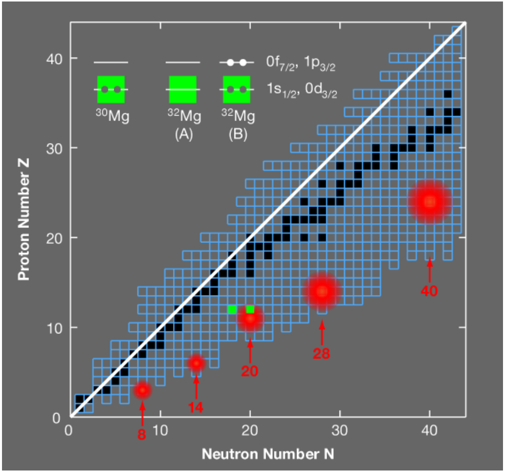
18 February, 2023

Shell Model and the Island of Inversion



- Shell model works very well near stability

B. A. Brown, Physics **3** 104 (2010).



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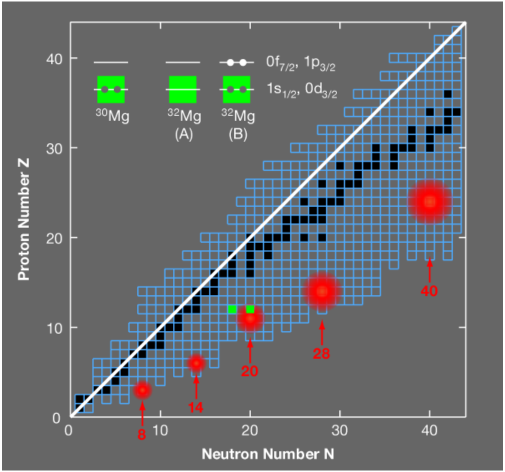

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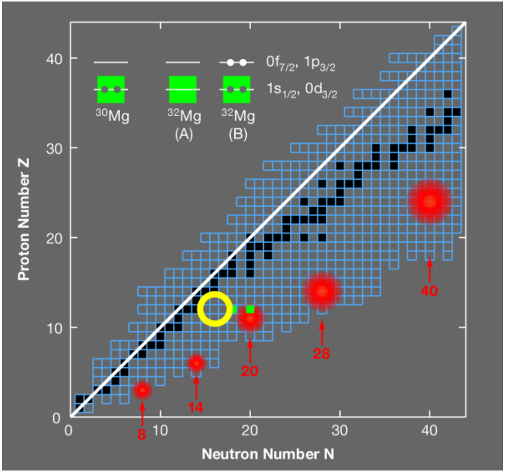

- Shell model works very well near stability
- Far from stability, $N = 20$ shell closure broken
- Intruder states present in low-energy configuration of island of inversion nuclei
- These states appear at high excitation energy closer to stability

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Electromagnetic Transition Rates

SFU

- Nuclear structure theories model strong force between nucleons
  - Predict nuclear wavefunctions
  - Can calculate theoretical matrix elements

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- Can compare lifetimes, transition strengths, etc.
  - Really comparing matrix elements

$$\left\langle \psi_{\text{ground}} \middle| \hat{E}2 \middle| \psi_{\text{excited}} \right\rangle$$

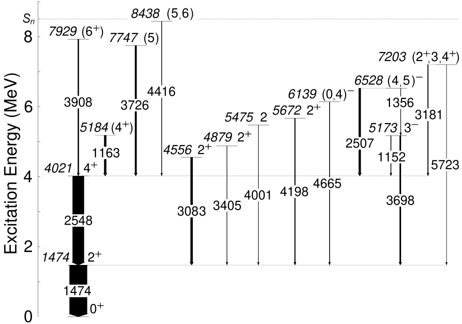
Previous Measurement of ^{28}Mg

SFU

PHYSICAL REVIEW C **100**, 014322 (2019)

Structure of ^{28}Mg and influence of the neutron *pf* shell

J. Williams,[1,*] G. C. Ball,[2] A. Chester,[1] T. Domingo,[1] A. B. Garnsworthy,[2] G. Hackman,[2] J. Henderson,[2] R. Henderson,[2] R. Krücken,[2,3] Anil Kumar,[4] K. D. Launey,[5] J. Measures,[2,6] O. Paetkau,[2] J. Park,[2,3] G. H. Sargsyan,[5] J. Smallcombe,[2] P. C. Srivastava,[4] K. Starosta,[1,†] C. E. Svensson,[7] K. Whitmore,[1] and M. Williams[2]



- Doppler Shift Attenuation Method (DSAM) used to determine lifetimes
- Not sensitive to $\tau \gtrsim 1$ ps
- No precise measurement of 2_1^+ state lifetime

$2^+ \rightarrow 0^+$ Lifetime - Theoretical Discrepancy

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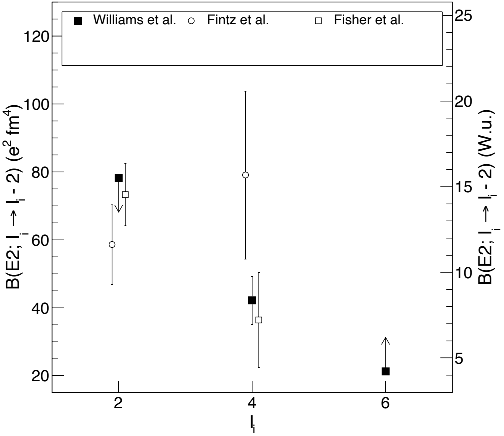

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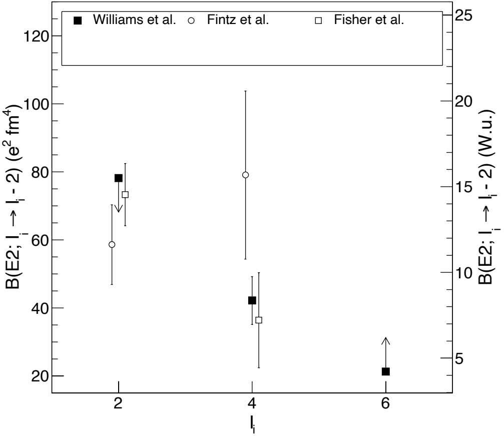

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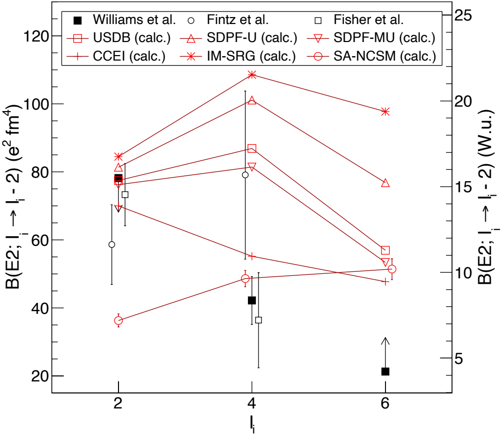

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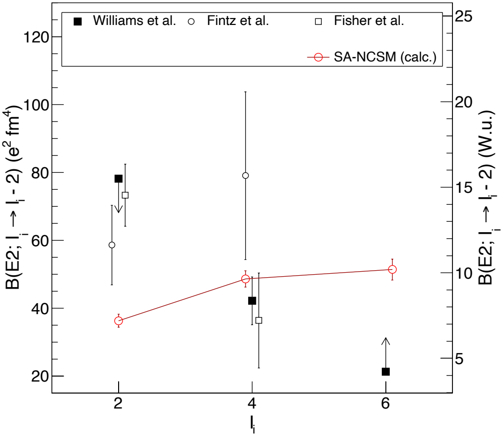

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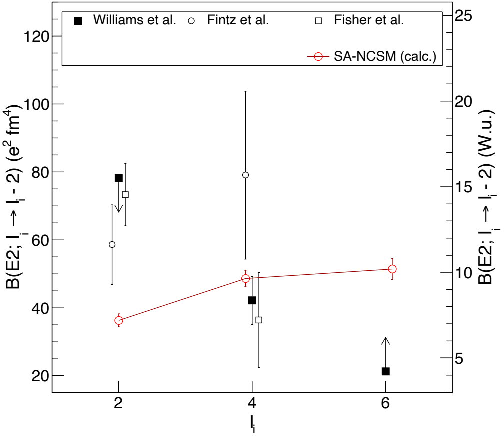

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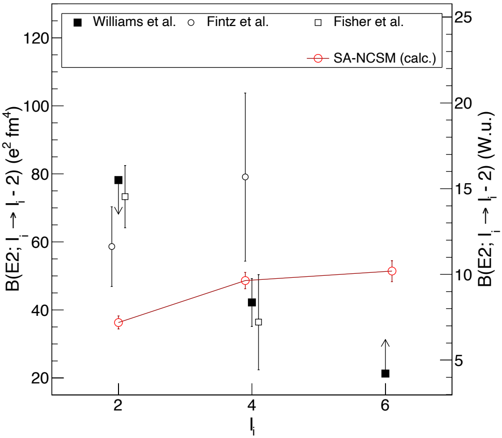
- Disagrees with previous measurements of $2^+ \rightarrow 0^+$ transition
- Provide different conclusions on nuclear properties



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ISAC at TRIUMF

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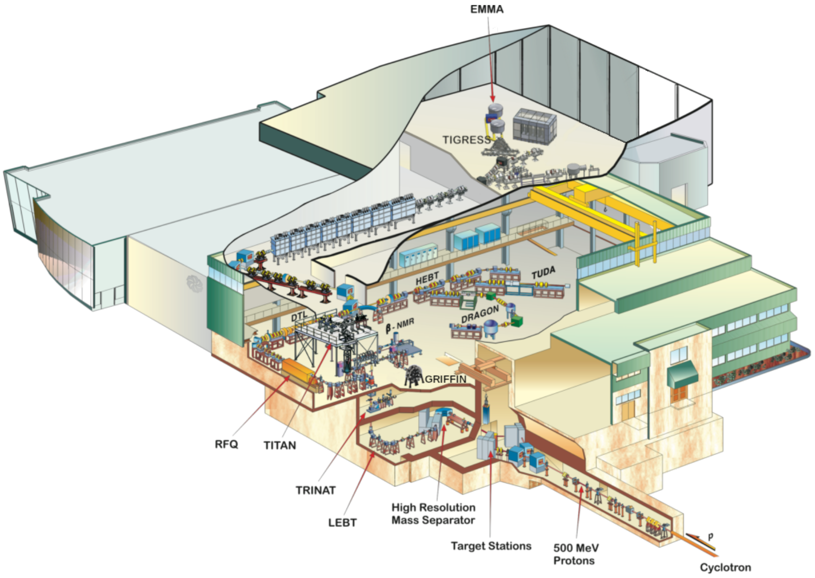
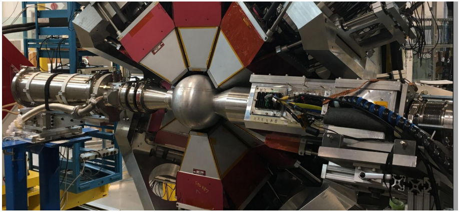
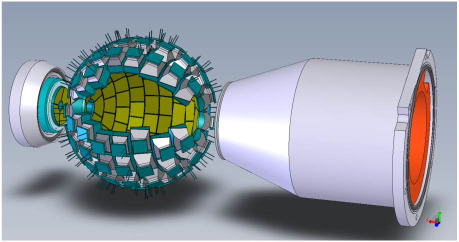


Detectors





- Gamma ray detection with TIGRESS HPGe clovers
  - All 16 clovers
- Charged particle detection with CsI Ball
  - 128 detectors
  - Nearly 4π coverage

J. Williams. PhD Thesis. Simon Fraser University (2019).

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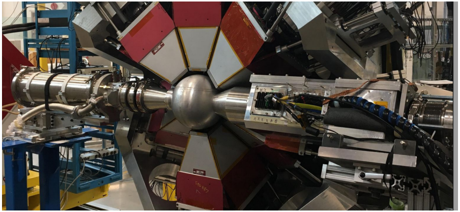

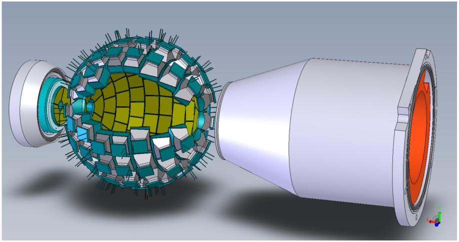

- Gamma ray detection with TIGRESS HPGe clovers
  - All 16 clovers
- Charged particle detection with CsI Ball
  - 128 detectors
  - Nearly 4π coverage
- Particle-Gamma coincidences allows for selective triggering and offline analysis
  - Essential for isolating low cross-section reactions
  - i.e. $\sim 1/1000$ reactions results in ^{28}Mg

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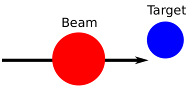
Fusion Evaporation

$$^{18}\text{O}\left(^{12}\text{C}, 2\text{p}\right)^{28}\text{Mg}$$



- Beam impinges on target with energy above Coulomb barrier

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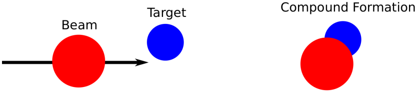

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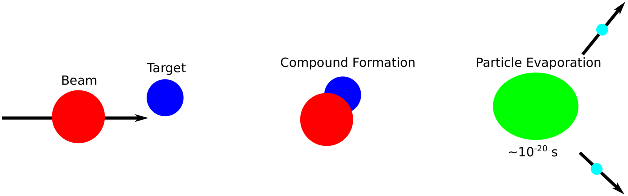

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- On order of $\sim 10^{-20}$ s, particles evaporate
  - Result is excited state of residual nucleus

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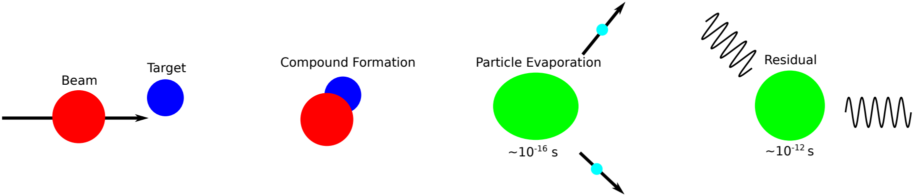

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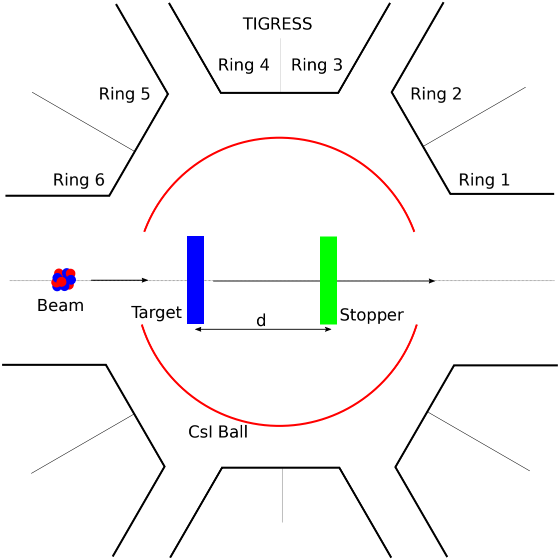
  - Result is excited state of residual nucleus
- Residual nucleus de-excites by emission of gamma ray(s)

The Recoil Distance Method (RDM)



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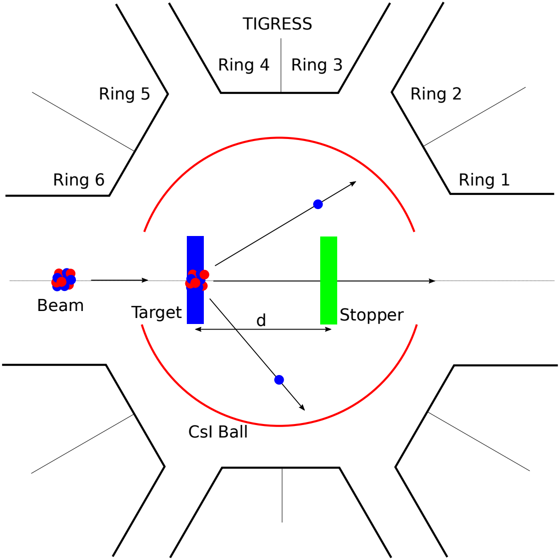

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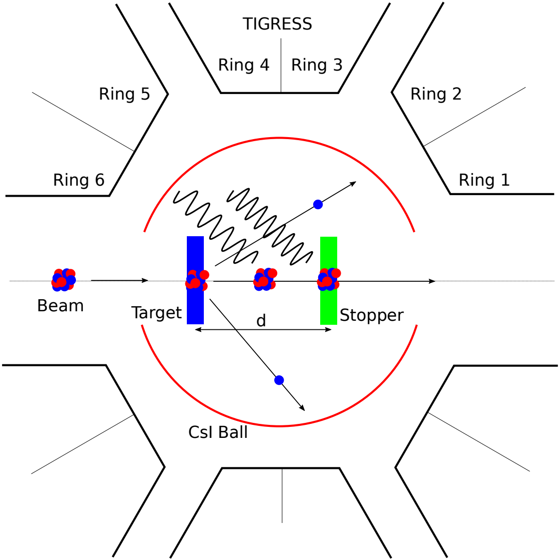

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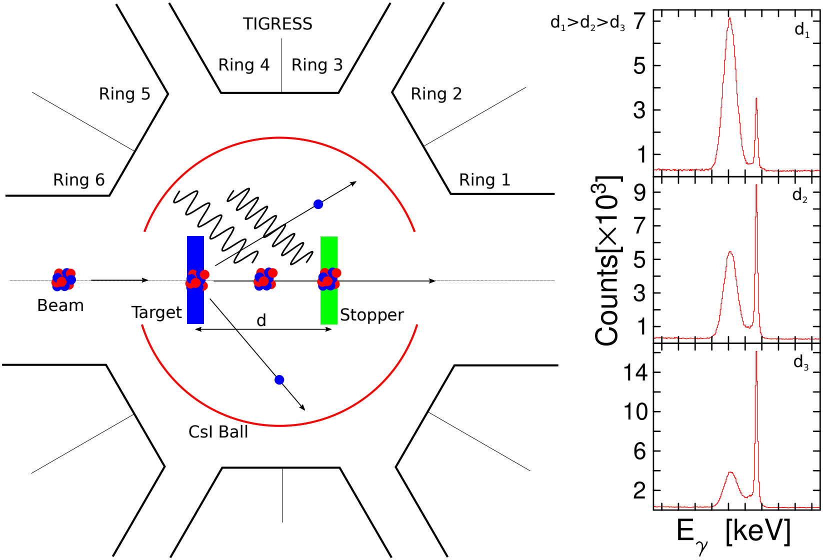
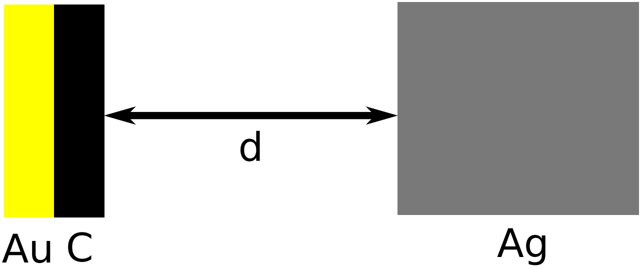
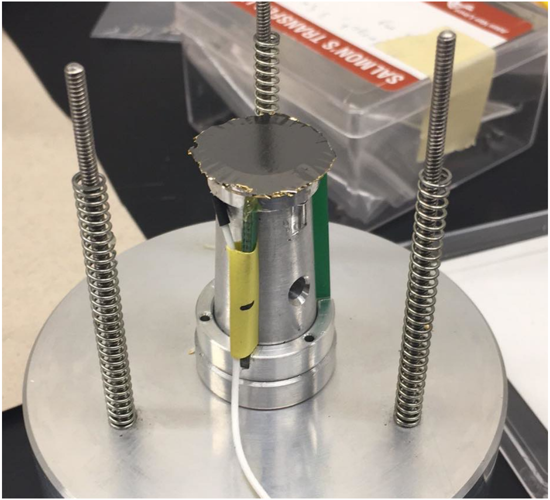


Target-Stopper Scales

- Target and stopper are not "thin films" on the scale of the distance
  - Target: 2.5 μm Au backing with 2.5 μm C target
  - Distance: 17 μm and up
  - Stopper: 12 μm Ag
- Flatness needs to be on the micron scale

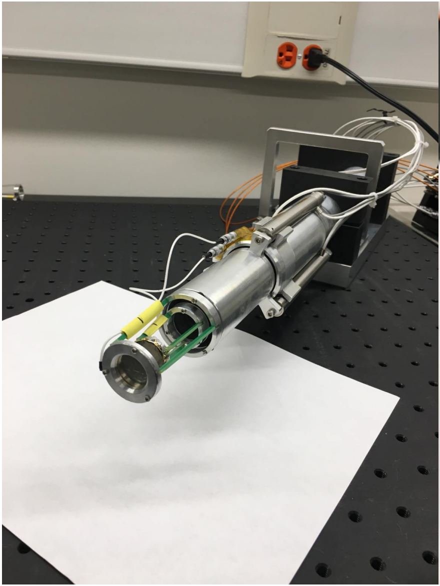


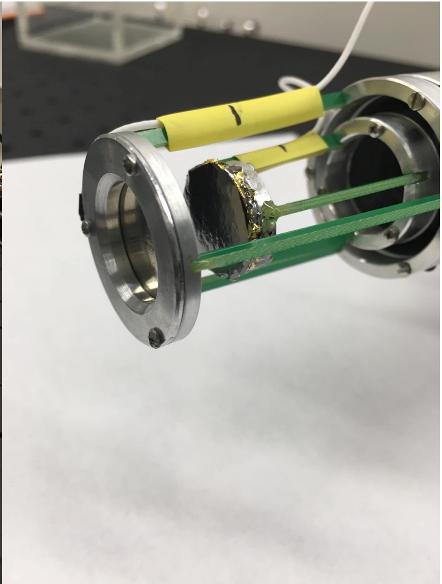
Carbon Target



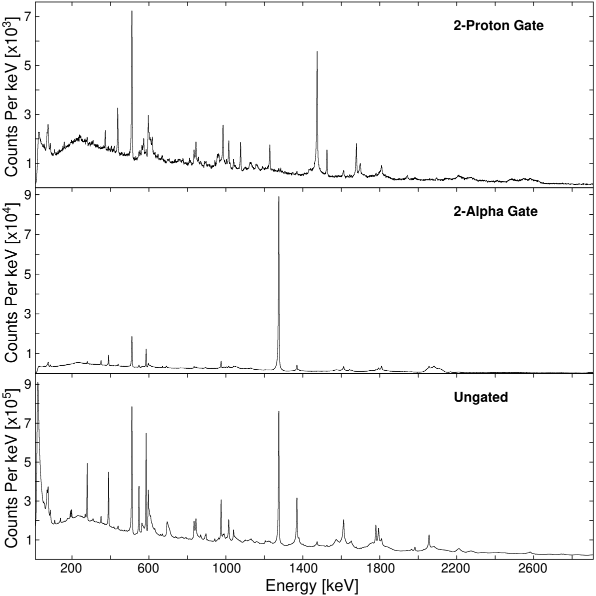
Plunger

SFU





Particle-Gated Spectra



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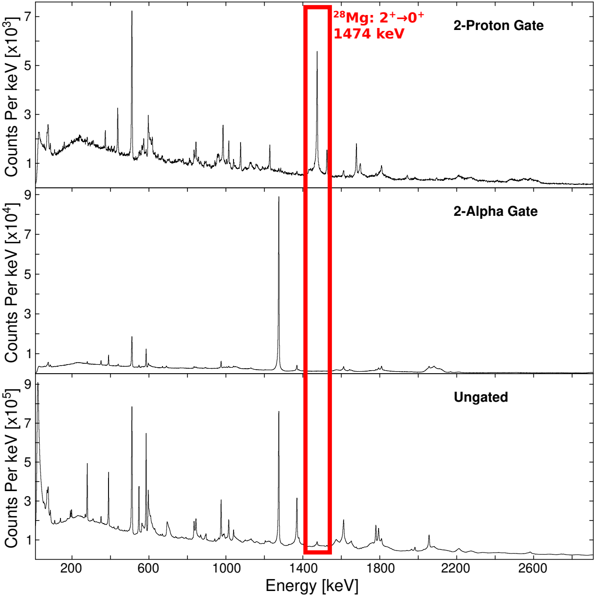

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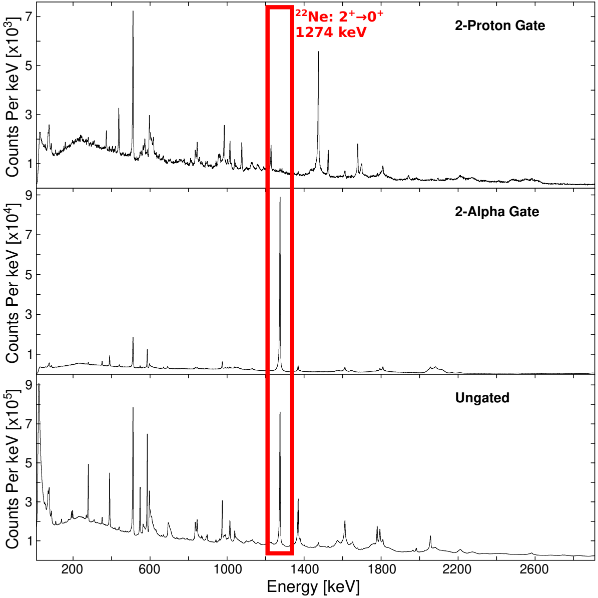
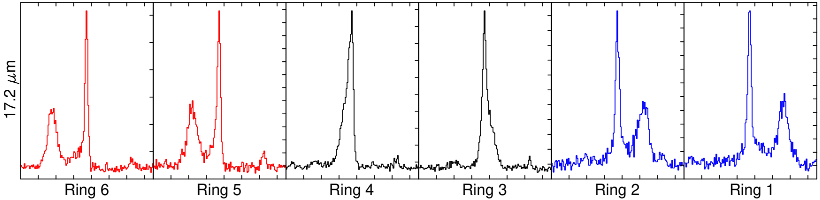
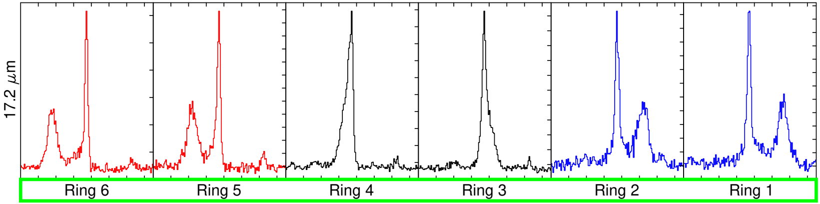
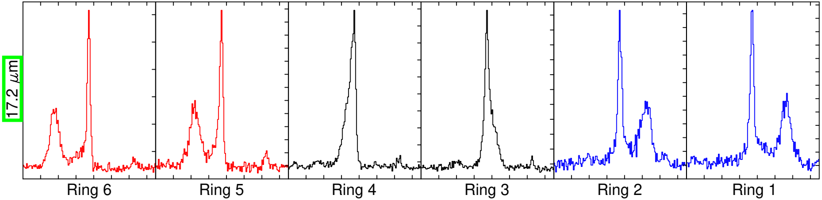



17.2 μm
Ring 6
Ring 5
Ring 4
Ring 3
Ring 2
Ring 1

Experimental RDM Spectra

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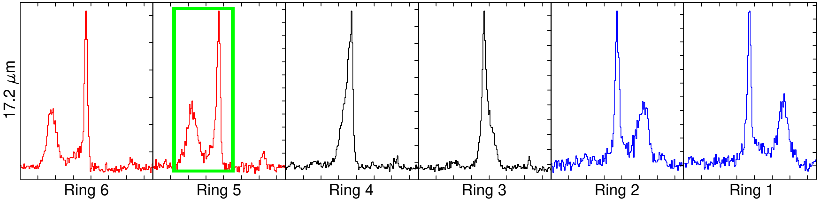

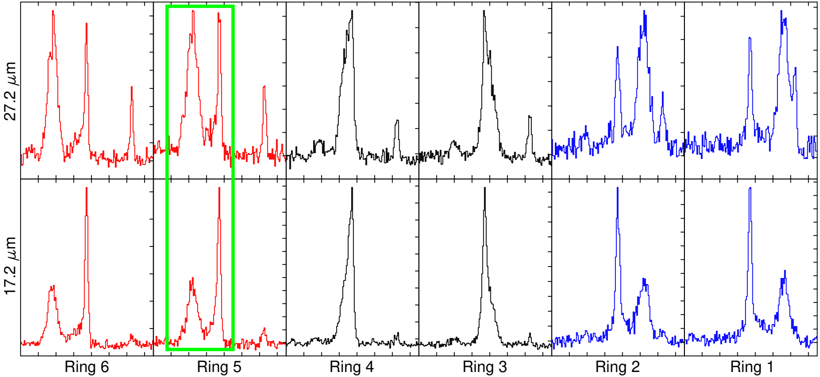
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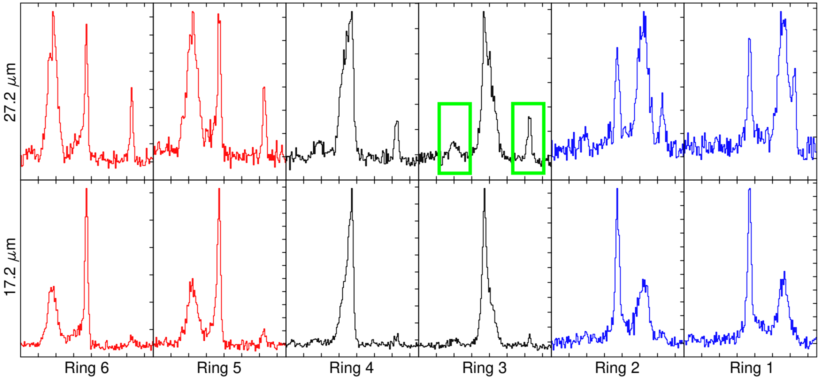

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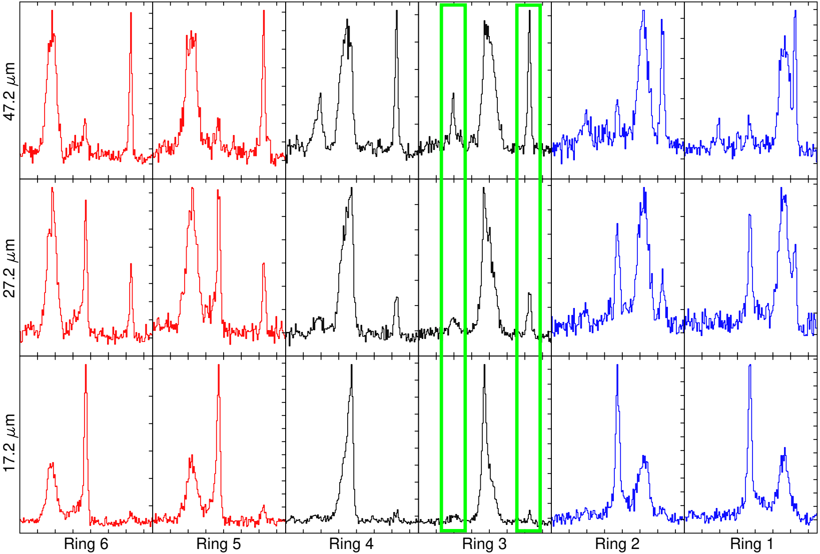

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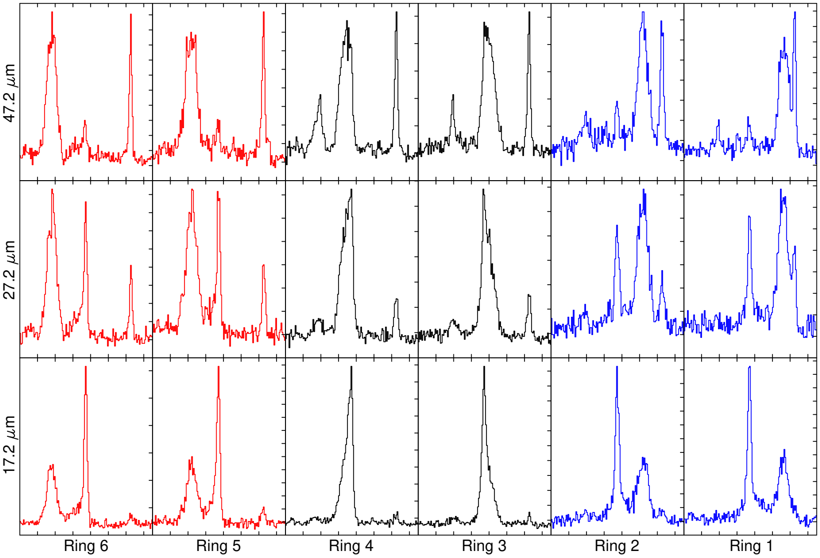
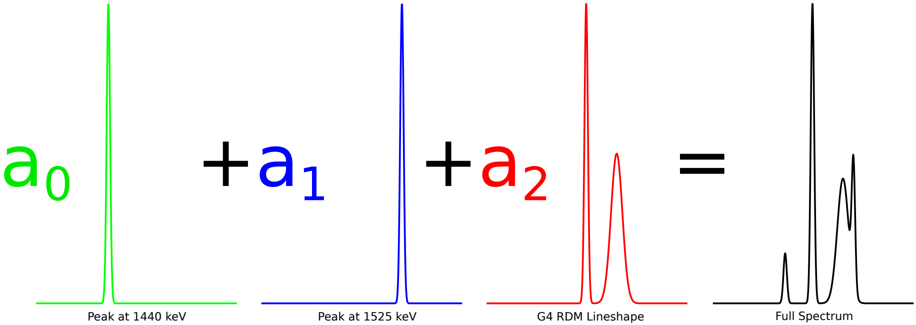


Simulated RDM Spectra



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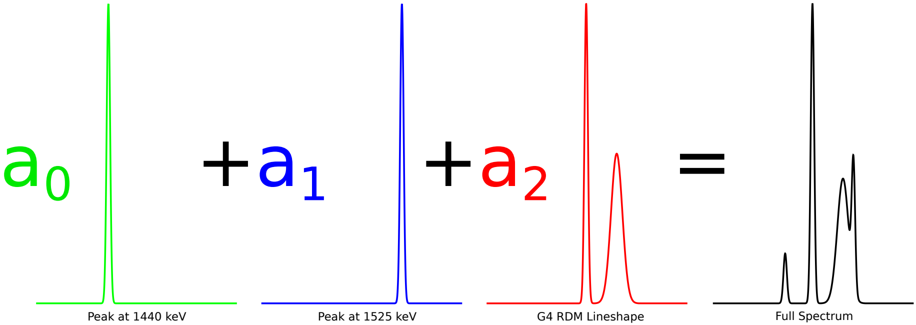

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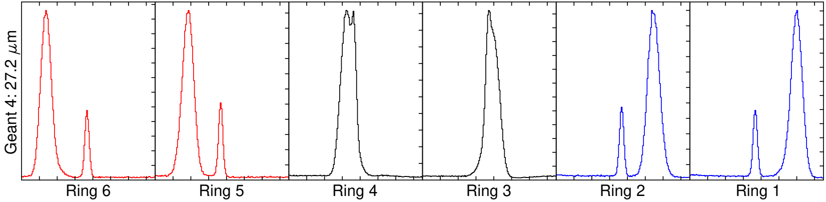
- Linear combination can then be compared to data
  - Statistical methods applied
  - Best-fit lifetime determined

GEANT4 Setup

- Experimental setup has been constructed in GEANT4
- Can simulate experiment and produce spectra



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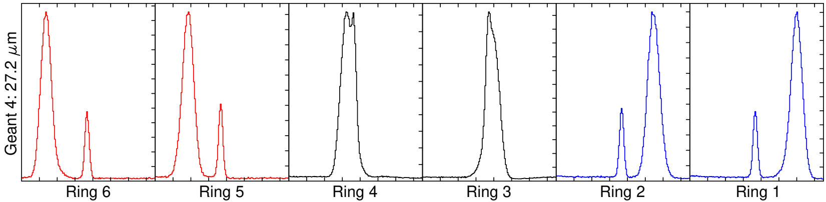
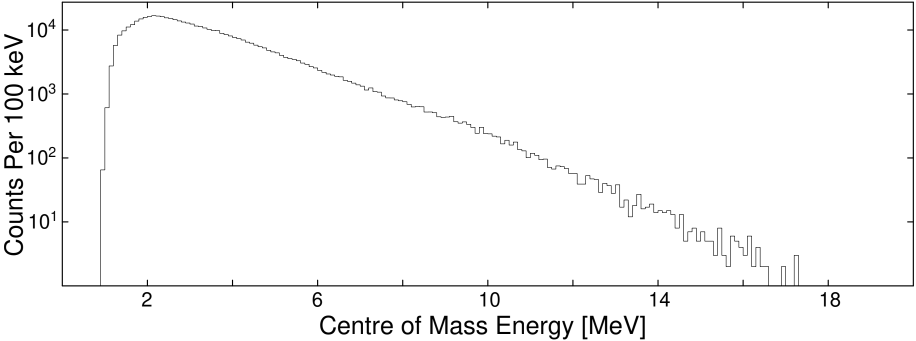
- Working to reproduce particle energy spectra
  - Particle energy spectra determines resdiual velocity distribution
  - Essential to reproduce in order to get correct Doppler shifts



CsI Particle Energy

- Use reconstructed centre of mass energy spectra of particles to determine reaction parameters
- Can actually extract a temperature of the fusion-evaporation reaction
  - $kT \sim 2$ MeV



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  - 11 total distances
- Apply maximum likelihood method for comparison of simulation and data to determine lifetimes

Acknowledgements

Thank you to all those who helped with the experiment

H. Asch[1], A. B. Garnsworthy[2], C. J. Griffin[2], G. Hackman[2], G. Leckenby[2,3], J. Liang[2,4], R. Lubna[2], C. R. Natzke[2,5], C. Pearson[2], A. Redey[6], K. Starosta[7], S. Upadhyayula[2], K. van Wieren[8], V. Vedia[2], J. Williams[2], A. Woinoski[1], F. Wu[7], and D. Yates[2,3]

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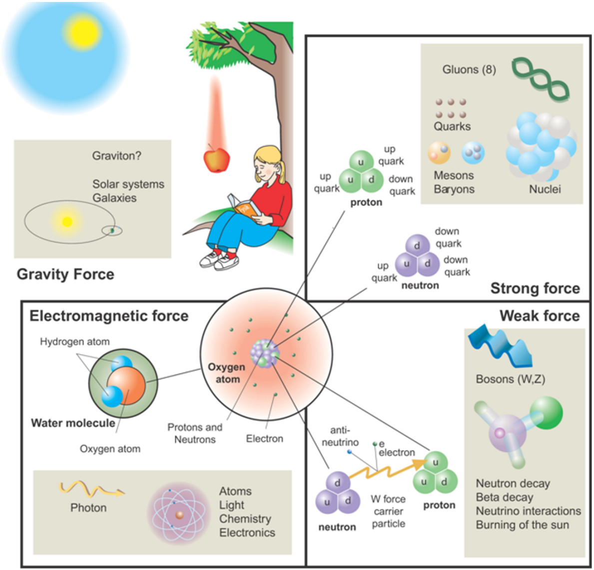
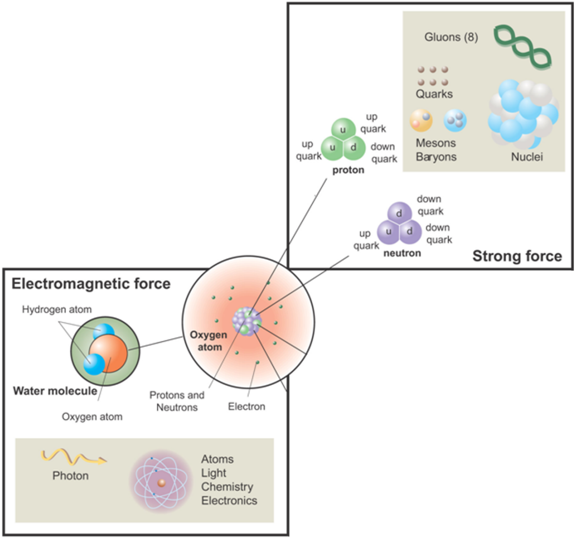
[2] TRIUMF
[3] Department of Physics and Astronomy, University of British Columbia
[4] Department of Physics and Astronomy, Saint Mary's University
[5] Department of Physics, Colorado School of Mines
[6] School of Engineering Science, Simon Fraser University
[7] Department of Chemistry, Simon Fraser University
[8] Science Technical Centre, Simon Fraser University

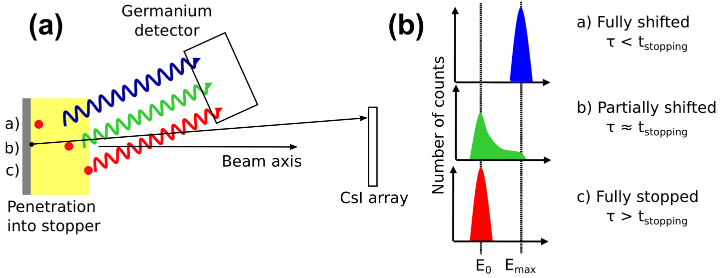

Graviton?
Solar systems
Galaxies
Gravity Force
Gluons (8)
Quarks
Mesons
Baryons
Nuclei
up quark
up quark
down quark
proton
down quark
down quark
up quark
neutron
Strong force
Electromagnetic force
Hydrogen atom
Water molecule
Oxygen atom
Oxygen atom
Protons and Neutrons
Electron
Photon
Atoms
Light
Chemistry
Electronics
Weak force
Bosons (W,Z)
anti-neutrino
e electron
neutron
W force carrier particle
proton
Neutron decay
Beta decay
Neutrino interactions
Burning of the sun

Fundamental Interactions



- Radioactive beam facility on Canada's west coast
- Produce a wide array of stable and radioactive beams
- Houses the TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) array for in-beam reaction measurements

$$\lambda = \frac{8\pi\alpha c}{e^2} \sum_{\sigma L} \frac{L+1}{L[(2L+1)!!]^2} \left(\frac{E}{\hbar c}\right)^{2L+1} B(\sigma L; I_i \to I_f) \qquad (1)$$



- Charged particles detected by CsI Ball
- Residual nucleus gradually slowed in backing
- Doppler shift dependent on how far into backing residual nucleus gets before emitting gamma ray
- Determine lifetime using statistical methods comparing lineshape from experimental data to simulations using GEANT4

Experiment Breakdown

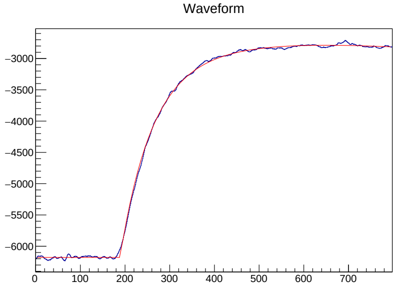
SFU

- RUN 1: Calibration of CsI Ball
- RUN 2: DAQ Shakedown
  - New free-flowing DAQ with no global trigger
  - Requires reconstruction of events from individual fragments
- RUN 3: Production Run
  - DSAM run with lead-backed target
    - Sensitive to shorter-lived states
    - Represents the "zero-separation" measurement
  - RDM run after
    - 11 plunger distances
    - 17 μm through 400 μm
    - $\sim$16 hours per distance to build statistics

Event Reconstruction

- With newly installed GRIFFIN DAQ at TIGRESS, there is no global trigger number
  - Fragments are written with individual timestamps
  - Events need to be reconstructed from individual fragments
- Fragments come from various detector types
  - CsI Ball
  - TIGRESS
    - Central contacts
    - Individual segments
    - BGO suppressors
- Fragment timing is dependent on detector type
  - Time coincidence gates must be applied separately

Waveform Analysis



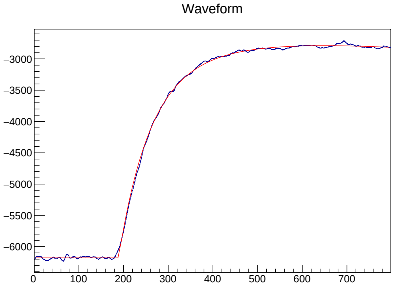
- Can fit waveforms from data

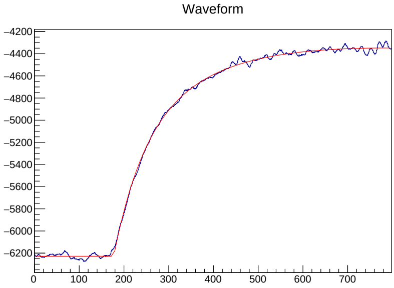
$$W(t) = C + A_F(1 - e^{-(t-t_0)/\tau_F})e^{-(t-t_0)/\tau_{RC}} + A_S(1 - e^{-(t-t_0)/\tau_S})e^{-(t-t_0)/\tau_{RC}}$$

- Ratio of slow-to-fast risetime amplitudes $[(A_S/A_F) * 100 + 100]$ used for particle identification
- More precise determination of t_0

Waveform Analysis

- First step in analysis is proper PID
  - Requires determination of particle type

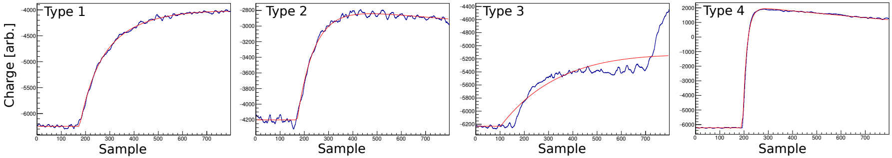




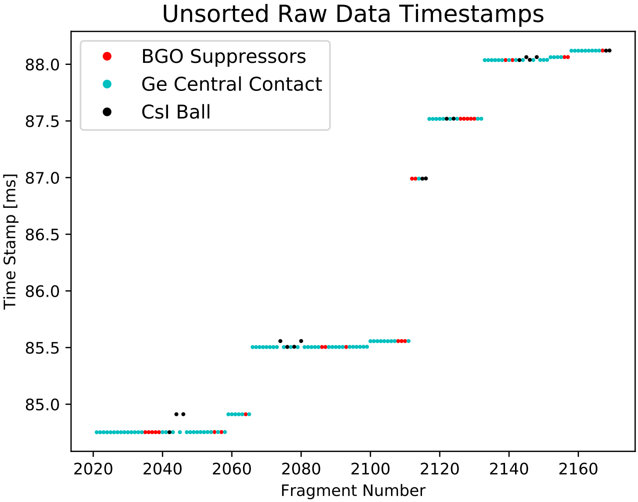
- Alphas (left) and protons (right) result in different waveforms
- Least-squares fit applied to each waveform
  - Ratio of slow-to-fast risetime amplitude used to determine particle type

SFU

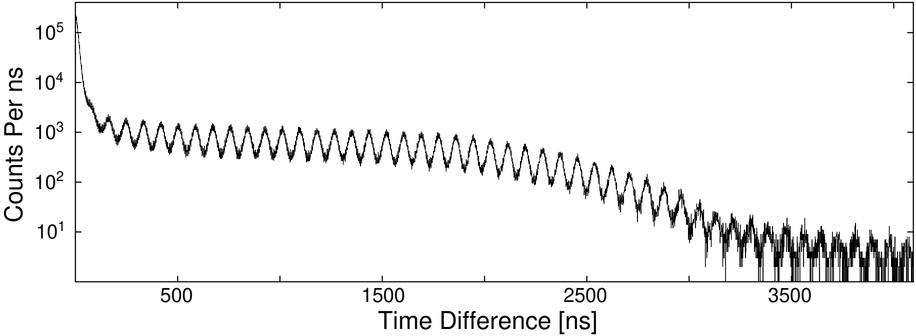
There are different types of waveforms



Disordered Fragment Timing



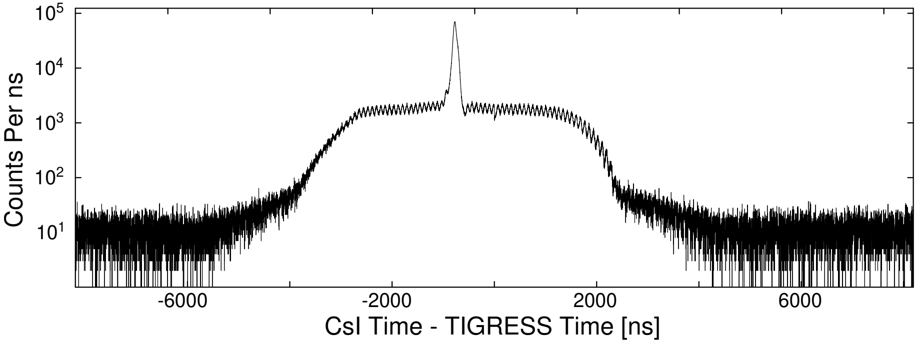
TIGRESS-TIGRESS Timing



- Coincidence peak ends $\lesssim$ 150 ns
- Resolution allows observation of beam bunches

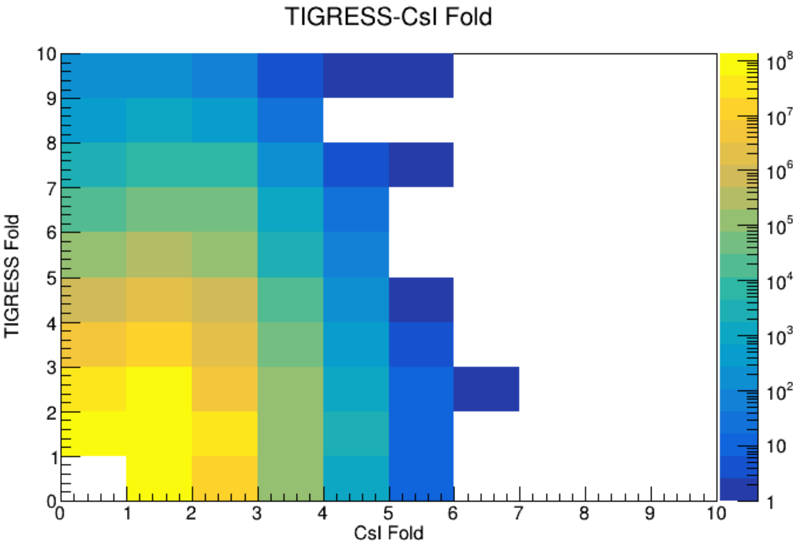
TIP-TIGRESS Timing

SFU

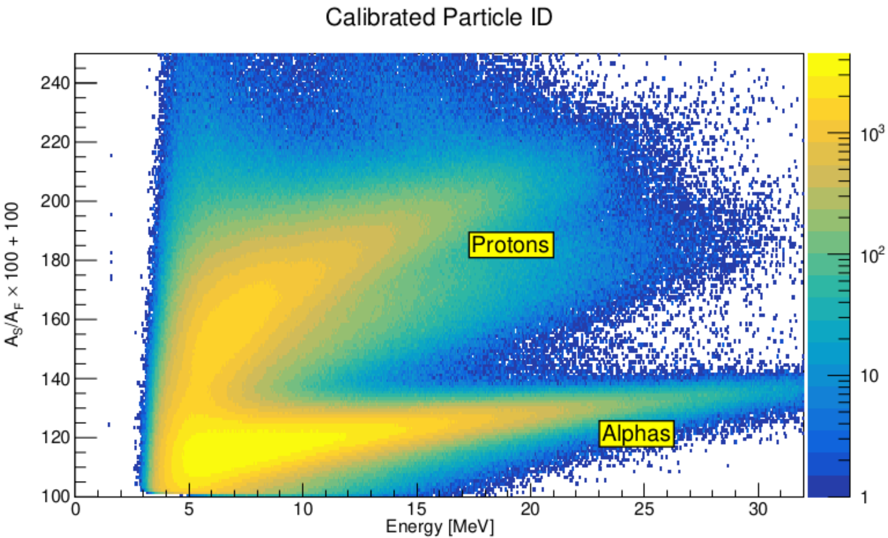


- Reconstruct complete timestamps including CFD and waveform fits
- CsI hits arrive before TIGRESS hits
- Coincidence peak at $|\Delta t| \sim 800$ ns

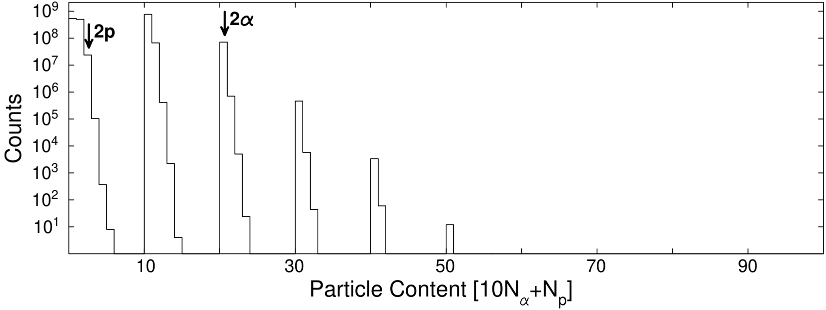
Particle-Gamma Fold



Particle Identification



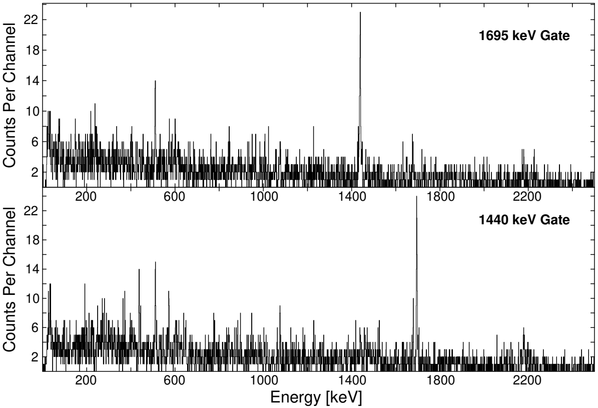
Particle Content

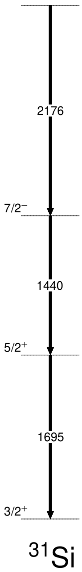


- Can group and separate events by particle content
  - **Detected** particle content
  - Some events will have particle undetected
  - Can include background particles (i.e. cosmics)
- 2p (^{28}Mg) and 2α (^{22}Ne) labelled

1440 keV: $^{16}O(^{18}O,2pn)^{31}Si$

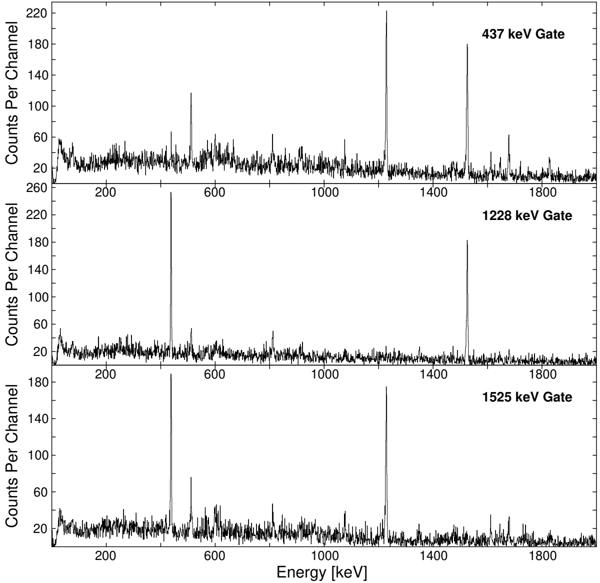
SFU

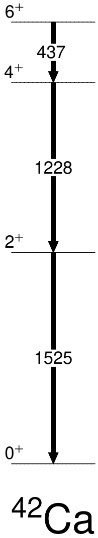




1525 keV: $^{28}Si(^{18}O,2p2n)^{42}Ca$

SFU

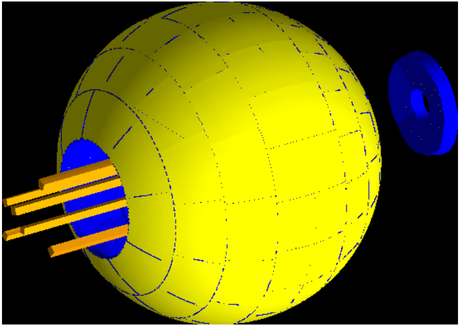




Contaminants Summary

SFU

- Two main contaminant lines interfere with RDM measurement
  - 1440 keV – ^{31}Si
  - 1525 keV – ^{42}Ca
- Additional contaminant transitions in multiple PID gates
  - ^{38}Ar lines identified in 2α
  - ^{40}Ar lines identified in α2p
- Source concluded to be desposition on target during experiment
- PID channels, high statistics, and low-cross section measurement combine to result in these transitions being substantial in spectra
  - Highly sensitive measurement technique
- Cannot remove through particle selection
  - Proton emission spectra are not substantially different
- Each is in coincidence with a "clean" transition in spectra
  - Can constrain size of contaminants using these
- Need to be accounted for in final simulated spectra



- GEometry ANd Tracking, Monte Carlo simulation framework
- Can simulate detector construction and reaction parameters

- Built plunger apparatus and CsI ball geometry
- Fusion-evaporation reactions already constructed
- Simulating experimental setup and comparing to data
- Apply maximum likelihood method for computing lifetimes