Electromagnetic Transition Rate Studies in ^{28}Mg

Matthew S. Martin for the TIP/TIGRESS Collaborations

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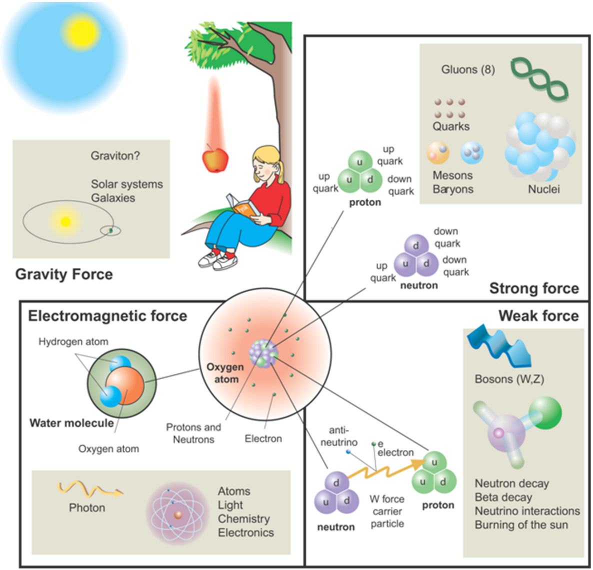
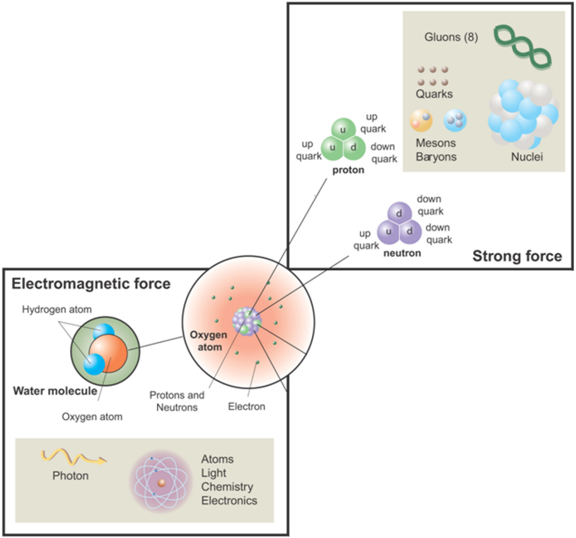
8 June, 2022

Fundamental Interactions



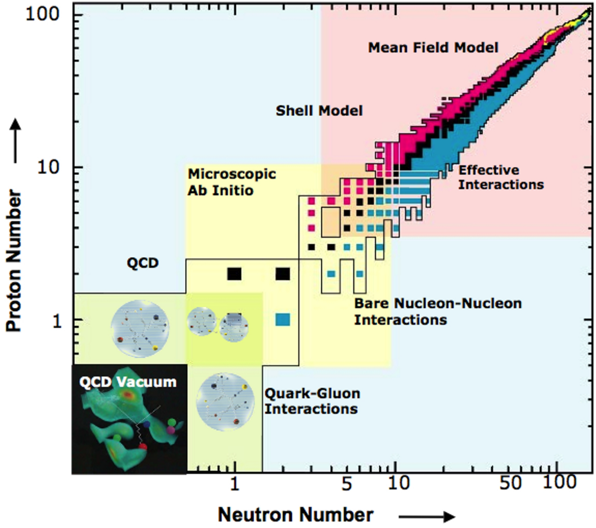

Gluons (8)
Quarks
Mesons
Baryons
Nuclei
up quark
up quark
down quark
proton
down quark
up quark
down quark
neutron
Strong force
Electromagnetic force
Hydrogen atom
Water molecule
Oxygen atom
Oxygen atom
Protons and Neutrons
Electron
Photon
Atoms
Light
Chemistry
Electronics

Electromagnetic Transition Rates

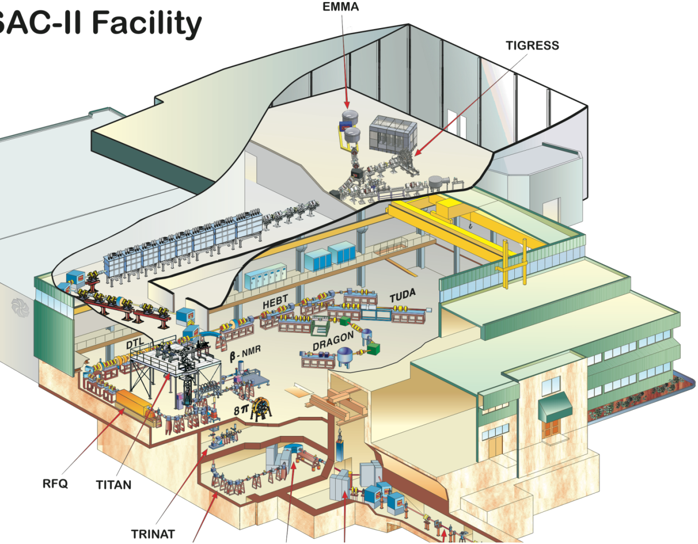
- Nuclear structure theories model strong force between nucleons
  - Predict nuclear wavefunctions
- Lifetime of nuclear states

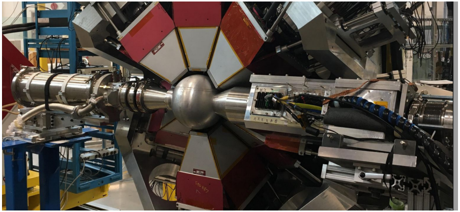
$$\frac{1}{\tau_{theory}} \propto \left| \left\langle \psi_{\text{ground}} \middle| \hat{E}2 \middle| \psi_{\text{excited}} \right\rangle \right|^2$$

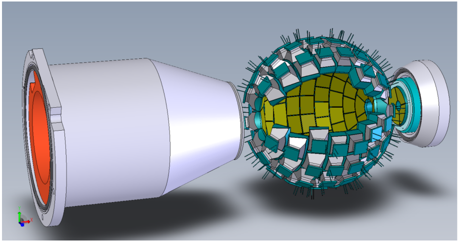
- Allows comparision between τ_{theory} and τ_{exp}



- Nuclear force is a residual of the strong interaction
  - No complete theory of nuclei
- Many theoretical approaches
  - Address various regions of the nuclear landscape
- Measurements needed to test and guide theory


ISAC-I and ISAC-II Facility
EMMA
TIGRESS
HEBT
TUDA
DRAGON
DTL
β - NMR
8π
RFQ
TITAN
TRINAT

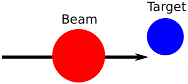




- Gamma ray detection with TIGRESS HPGe clovers
- Charged particle detection with CsI Ball
- Particle-Gamma coincidences allows for selective trigger and offline analysis
    - Essential for isolating low cross-section reactions
    - i.e. $\sim 1/1000$ reactions results in ^{28}Mg

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

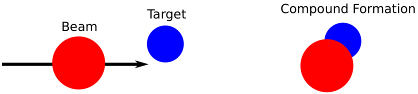
$$^{18}\mathrm{O}\left(^{12}\mathrm{C}, 2\mathrm{p}\right)^{28}\mathrm{Mg}$$



- Beam impinges on target with energy above Coulomb barrier

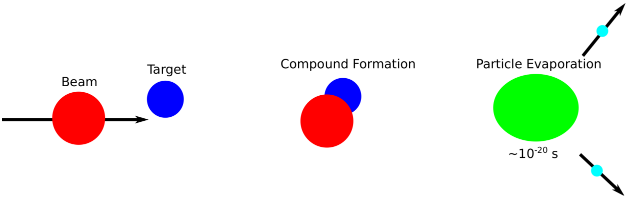
Fusion Evaporation

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



- Beam impinges on target with energy above Coulomb barrier
- Fusion occurs, forming compound nucleus

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



- Beam impinges on target with energy above Coulomb barrier
- Fusion occurs, forming compound nucleus
- On order of $\sim 10^{-20}$ s, particles evaporate
  - Result is excited state of residual nucleus

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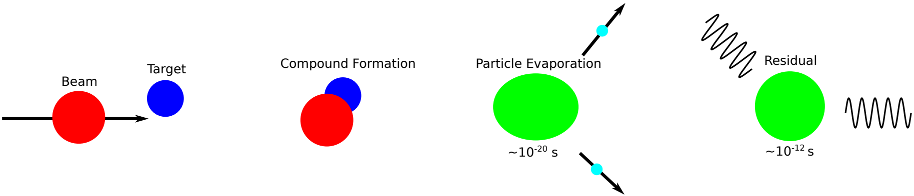
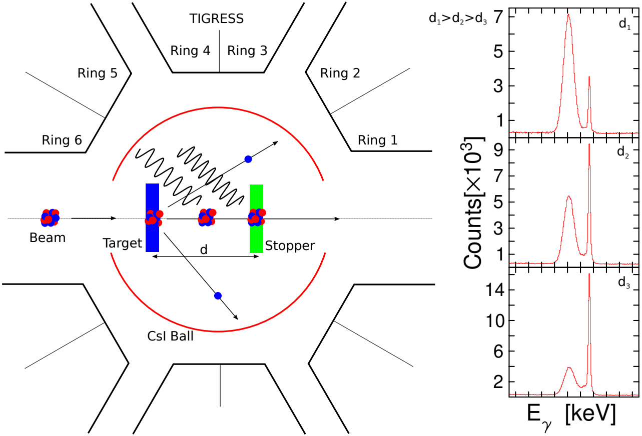


- Beam impinges on target with energy above Coulomb barrier
- Fusion occurs, forming compound nucleus
- On order of $\sim 10^{-20}$ s, particles evaporate
  - Result is excited state of residual nucleus
- Residual nucleus de-excites by emission of gamma ray

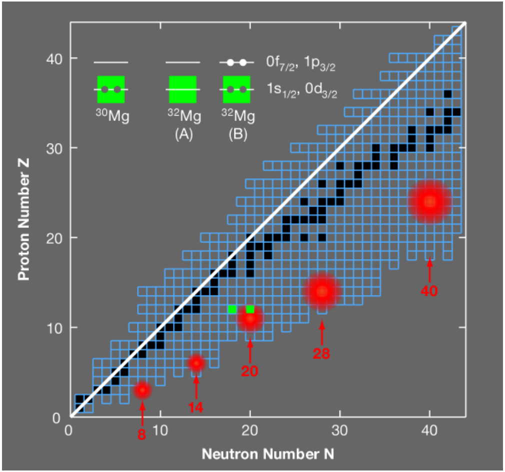
The Recoil Distance Method

SFU



- Charged particles detected by CsI Ball
- Gamma rays Doppler shifted if decay in flight
- Compare counts of shifted vs non-shifted gamma rays

Shell Model and the Island of Inversion



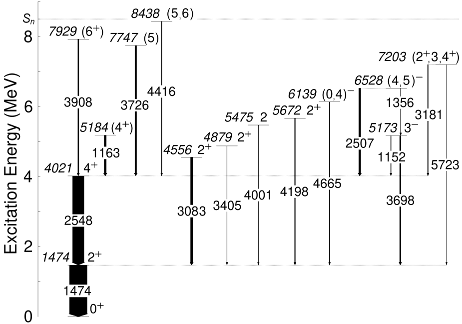
- Nucleons are placed into single particle energy shells
- Shell model works very well near stability
- Nuclear models are parametrized using data near stability
- $N = 20$ shell closure broken far from stability

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

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]

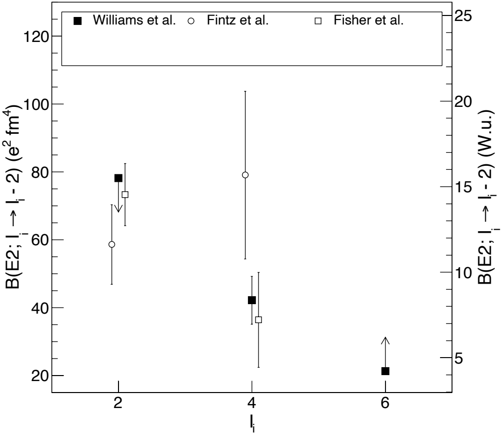


- Doppler Shift Attenuation Method (DSAM) used to determine lifetimes
- Not sensitive to $\tau \gtrsim 1$ ps
- No precise measurement of 2_1^+ state lifetime

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

SFU

- Measurement resolved discrepancy in $4^+ \to 2^+$ transition



J. Williams *et al.* PRC **100** 014322 (2019).

P. Fintz *et al.* Nucl. Phys. A **197** 423 (1972).

T.R. Fisher *et al.* PRC **7** 1878 (1973).

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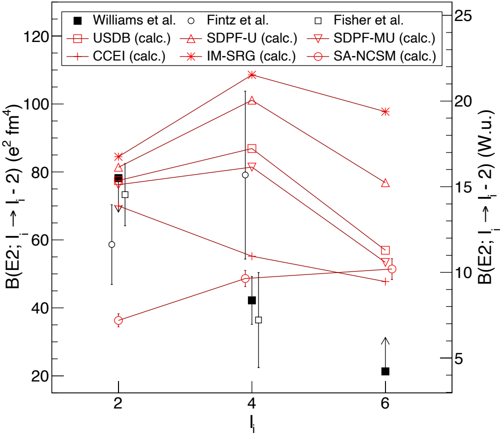

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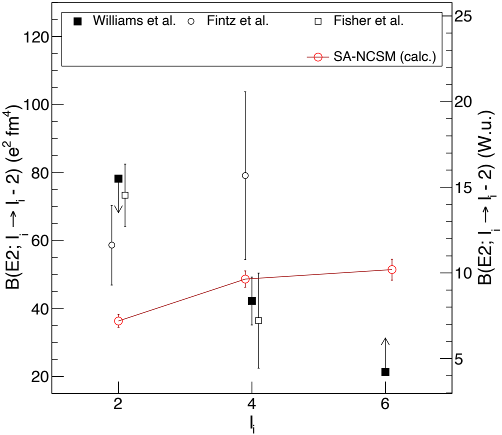
- NCSM agrees with $B(E2; 4^+ \rightarrow 2^+)$ measurement
- Disagrees with previous measurements of $2^+ \rightarrow 0^+$ transition



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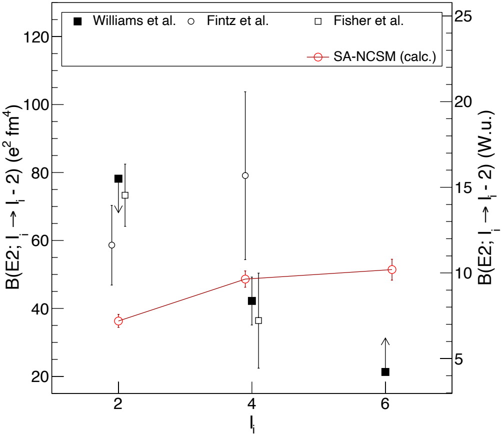
- Disagrees with previous measurements of $2^+ \rightarrow 0^+$ transition
- Provide different conclusions on nuclear properties



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Experiment Run May-June 2021

SFU

- RUN 1: Calibration of CsI Ball

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- RUN 2: DAQ Shakedown
  - New free-flowing DAQ with no global trigger
  - Requires reconstruction of events from individual fragments

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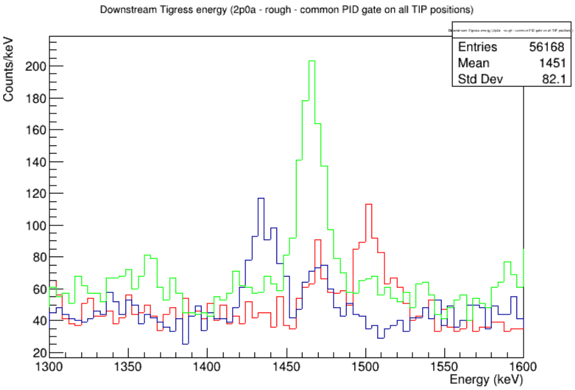
SFU

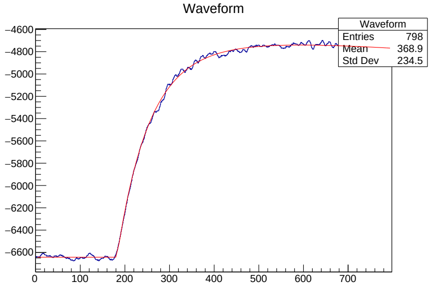
- RUN 1: Calibration of CsI Ball
- RUN 2: DAQ Shakedown
  - New free-flowing DAQ with no global trigger
  - Requires reconstruction of events from individual fragments
- RUN 3: Production Run
  - DSAM run with lead-backed target
    - Sensitive to shorter-lived states
    - Represents the "zero-separation"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

Online Analysis



- Able to isolate ^{28}Mg using online PID gates
- Can see separation of shifted-to-stopped peaks
  - Blue: Upstream
  - Green: Corona
  - Red: Downstream

Waveform Analysis

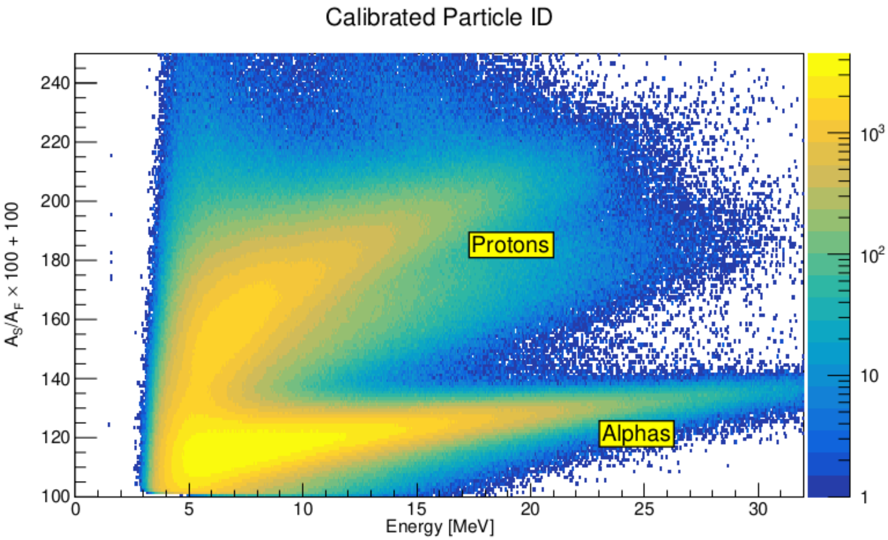


- Can fit waveforms from data

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

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

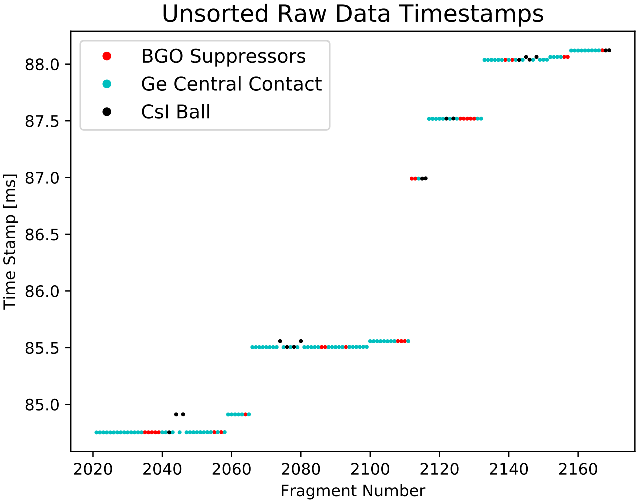
Particle Identification



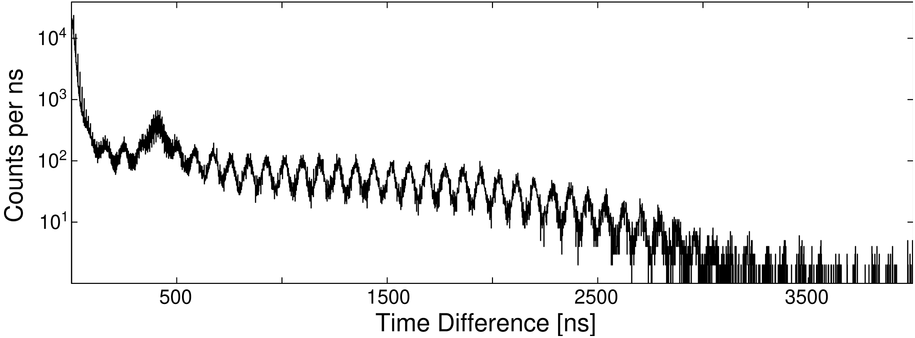
Event Reconstruction

- 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 timing type
  - Time coincidence gates must be applied separately

Disordered Fragment Timing



TIGRESS-TIGRESS Timing



- Coincidence peak ends $\lesssim$ 150 ns
- Second peak at $\sim$ 410 ns
- Resolution allows observation of beam bunches

TIP-TIGRESS Timing

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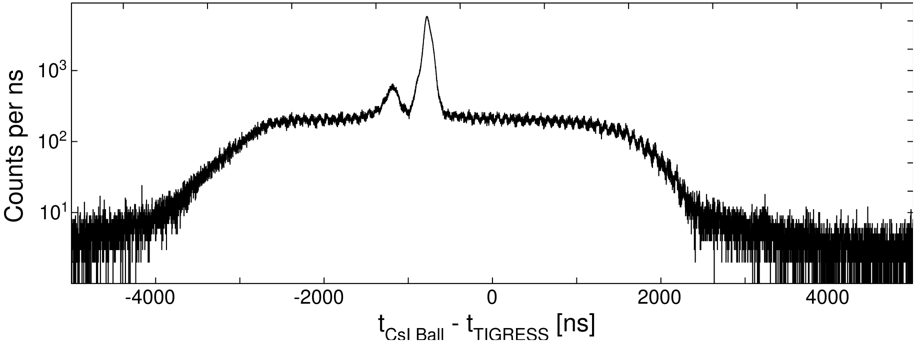
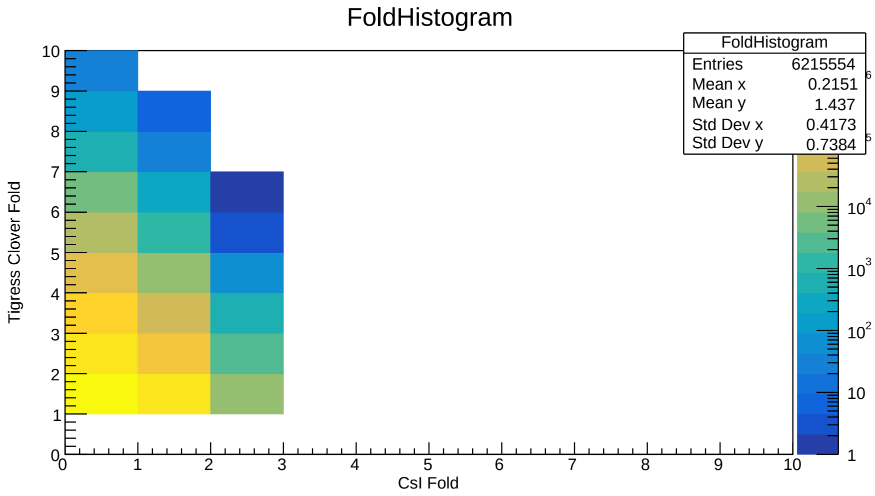


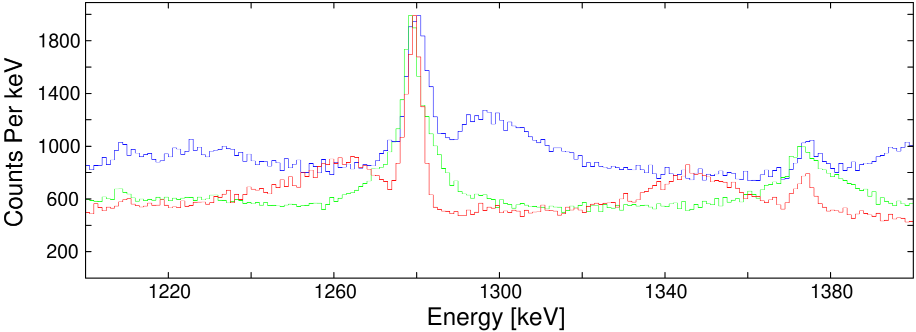
- CsI hits arrive before TIGRESS hits
- Two peaks at $\sim$ 1000 ns; separated by $\sim$420 ns
  - Cause unknown, currently under investigation
- Gate needs to be set to include all coincident events but not overlapping events

Reconstructed Events



- Events reconstructed from individual fragments
- Currently, very few 2-particle events - under investigation

^{22}Ne: 1274 keV Gamma-Ray



- Run 54409: RDM with d=31 μm
- RDM structure present for ^{22}Ne: $2^+ \rightarrow 0^+$ ~1274 keV gamma ray
  - 2α channel, but no gating performed yet
  - Blue: Downstream, Green: Corona, Red: Upstream
- Same "zero offset" issue found as online. Work ongoing

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]

[1] Department of Physics, Simon Fraser University
[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

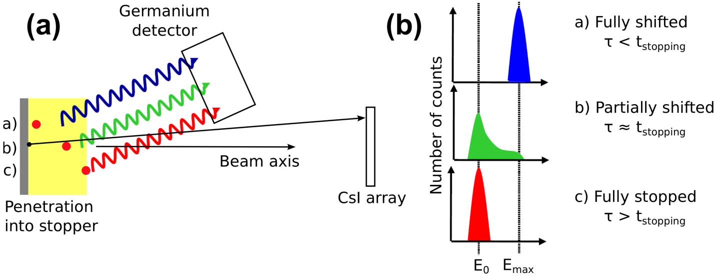
Electromagnetic Transition Rates

- Electromagnetic operators can be calculated analytically
- Transition rates are can be experimentally measured
- Comparison of rates leads to information about nuclear wavefunctions

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

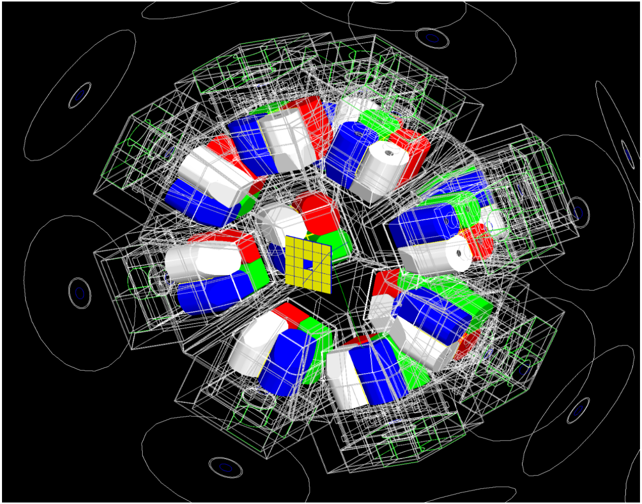
$$B(\sigma L; I_i \to I_f) = \frac{\left|\langle I_f \,\|\, \mathfrak{M}(\sigma L) \,\|\, I_i \rangle\right|^2}{2I_i + 1} \tag{2}$$

- L is the angular momentum of the photon
- E is energy of the photon
- $B(\sigma L; I_i \to I_f)$ is the reduced transition probability
- $\mathfrak{M}(\sigma L)$ is an electric or magnetic multipole operator



- 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

GEANT4 Simulations



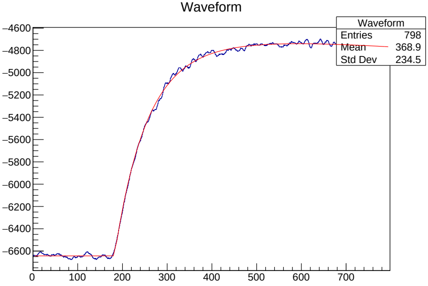
- Monte Carlo simulation framework
- Simulate reactions and geometries
- TIGRESS and CsI ball constructed
- Simulate and optimize experimental parameters
- Data analysis

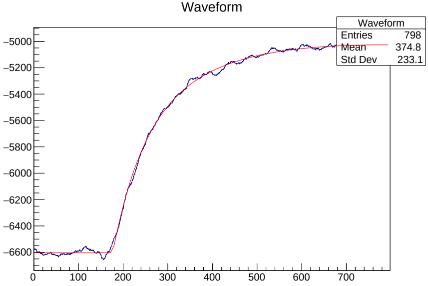
J. Williams. PhD Thesis. Simon Fraser University (2019).

Waveform Analysis

SFU

- 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