Electromagnetic Transition Rate Studies in ^{28}Mg

Matthew S. Martin for the TIP/TIGRESS Collaborations

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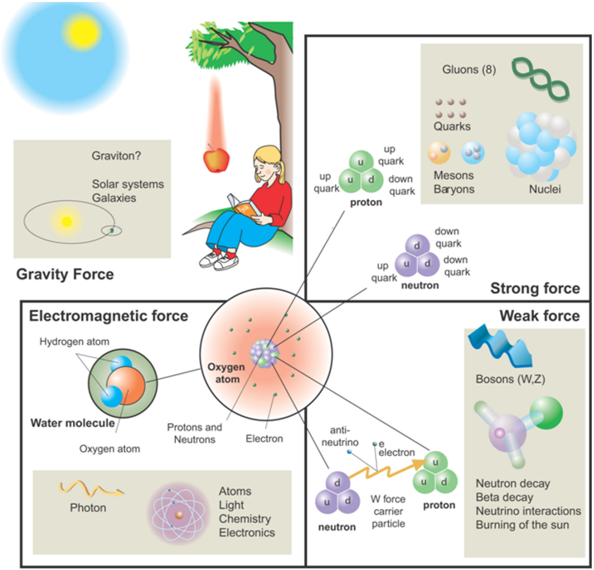
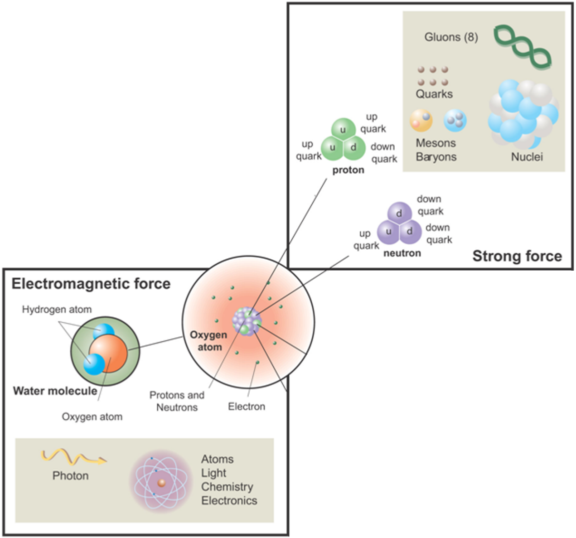
February 15, 2022


Graviton?
Solar systems
Galaxies
Gravity Force
Gluons (8)
Quarks
Mesons
Baryons
Nuclei
up quark
down quark
proton
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
W force carrier particle
Neutron decay
Beta decay
Neutrino interactions
Burning of the sun



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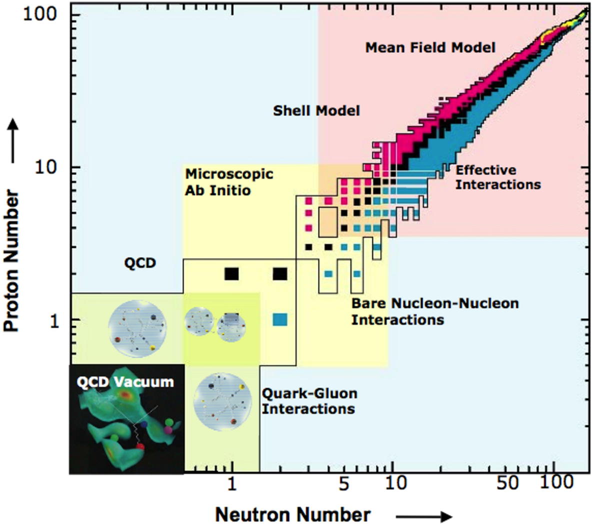
Strong force
Electromagnetic force
Hydrogen atom
Water molecule
Oxygen atom
Oxygen atom
Protons and Neutrons
Electron
Photon
Atoms
Light
Chemistry
Electronics

- 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}

The Nuclear Landscape



- 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

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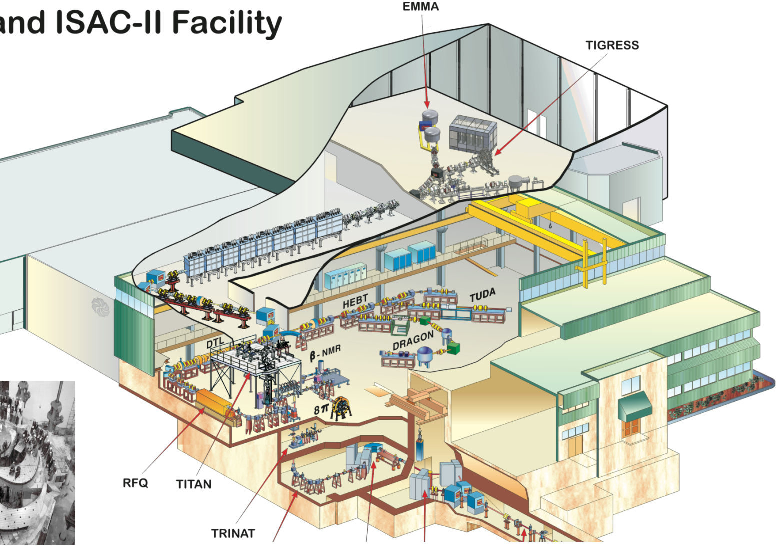
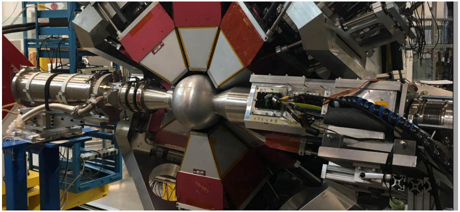
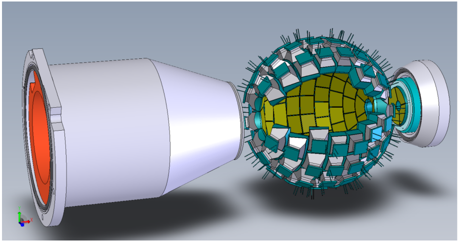

ISAC-I and ISAC-II Facility
EMMA
TIGRESS
HEBT
TUDA
DRAGON
DTL
β - NMR
8π
RFQ
TITAN
TRINAT

Detectors

SFU

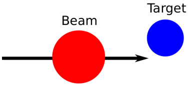




- Gamma ray detection with TIGRESS HPGe clovers
- Charged particle detection with CsI Ball
- Particle-Gamma coincidences allows for selective trigger and offline analysis
  - Essential for isolating low cross-section reactions
  - i.e. $\sim 1/1000$ reactions results in ^{28}Mg

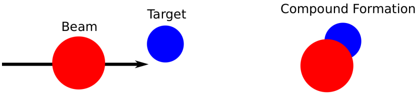
J. Williams. PhD Thesis. Simon Fraser University (2019).

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



- Beam impinges on target with energy above Coulomb barrier

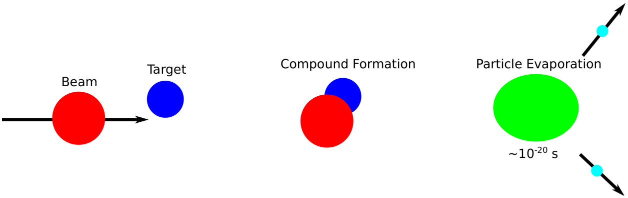
$$^{18}\mathrm{O}\left(^{12}\mathrm{C}, 2\mathrm{p}\right)^{28}\mathrm{Mg}$$



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

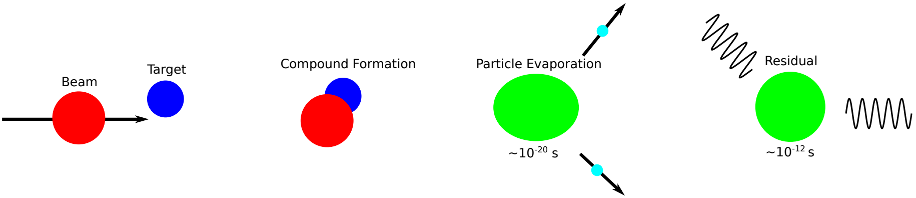
Fusion Evaporation

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

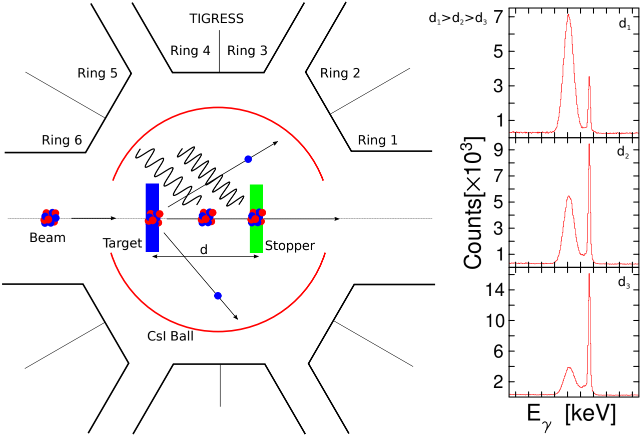


- Beam impinges on target with energy above Coulomb barrier
- Fusion occurs, forming compound nucleus
- On order of $\sim 10^{-20}$ s, particles evaporate
  - Result is excited state of residual nucleus

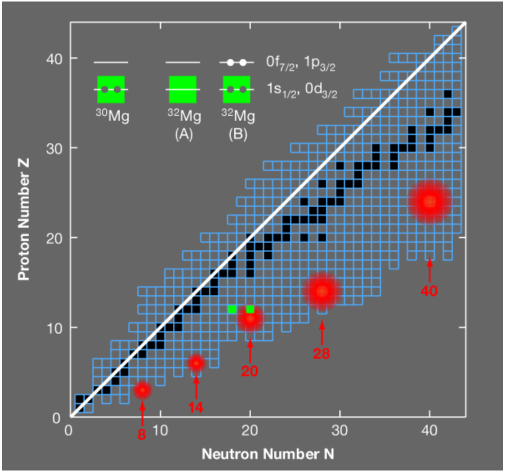
$^{18}\text{O}\left(^{12}\text{C}, 2\text{p}\right)^{28}\text{Mg}$



- 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
- Residual nucleus de-excites by emission of gamma ray



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



- 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).

Previous Measurement of ^{28}Mg

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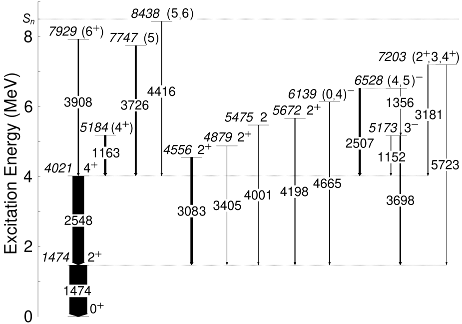
PHYSICAL REVIEW C **100**, 014322 (2019)

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

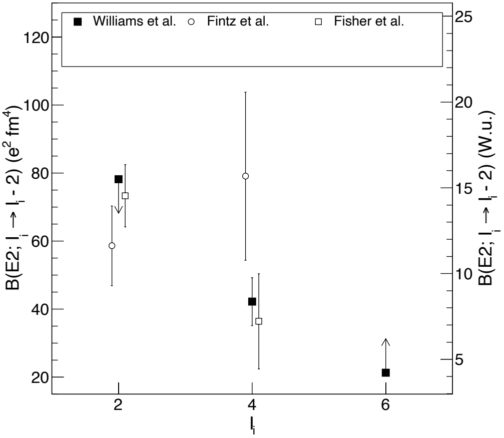
J. Williams,[1,*] G. C. Ball,[2] A. Chester,[1] T. Domingo,[1] A. B. Garnsworthy,[2] G. Hackman,[2] J. Henderson,[2] R. Henderson,[2] R. Krücken,[2,3] Anil Kumar,[4] K. D. Launey,[5] J. Measures,[2,6] O. Paetkau,[2] J. Park,[2,3] G. H. Sargsyan,[5] J. Smallcombe,[2] P. C. Srivastava,[4] K. Starosta,[1,†]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

- Measurement resolved discrepancy in $4^+ \rightarrow 2^+$ 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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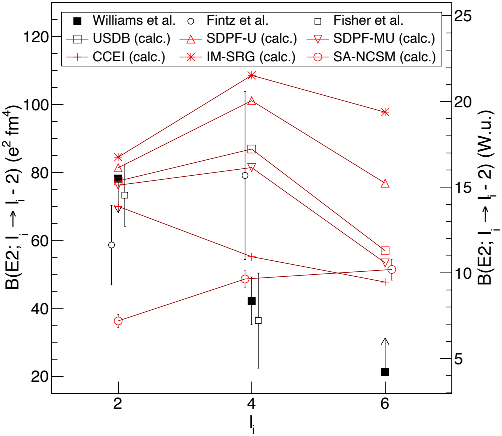

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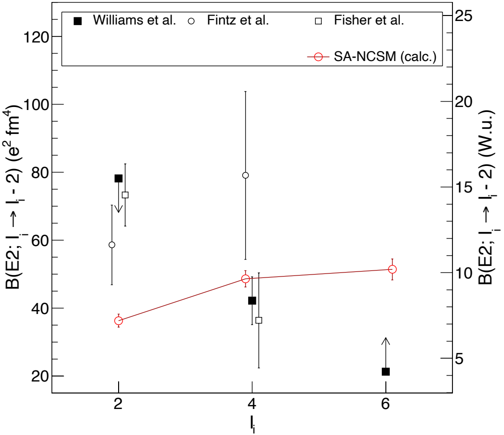
- NCSM agrees with $B(E2; 4^+ \rightarrow 2^+)$ measurement
- Disagrees with previous measurements of $2^+ \rightarrow 0^+$ transition



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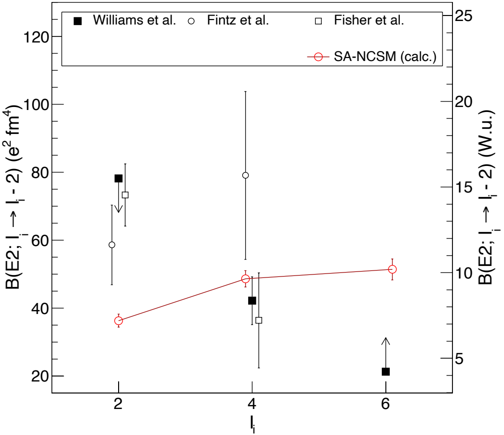
- NCSM agrees with $B(E2; 4^+ \rightarrow 2^+)$ measurement
- Disagrees with previous measurements of $2^+ \rightarrow 0^+$ transition
- Provide different conclusions on nuclear properties



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Experiment Run May-June 2021

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- RUN 1: Calibration of CsI Ball (May 26 → May 29)

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- RUN 2: DAQ Shakedown (May 31 $\rightarrow$ June 3)
  - New free-flowing DAQ with no global trigger
  - Requires reconstruction of events from individual fragments

Experiment Run May-June 2021

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- RUN 1: Calibration of CsI Ball (May 26 $\rightarrow$ May 29)
- RUN 2: DAQ Shakedown (May 31 $\rightarrow$ June 3)
  - New free-flowing DAQ with no global trigger
  - Requires reconstruction of events from individual fragments
- RUN 3: Production Run (June 12 $\rightarrow$ June 22)
  - 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

Time Coincidence Method

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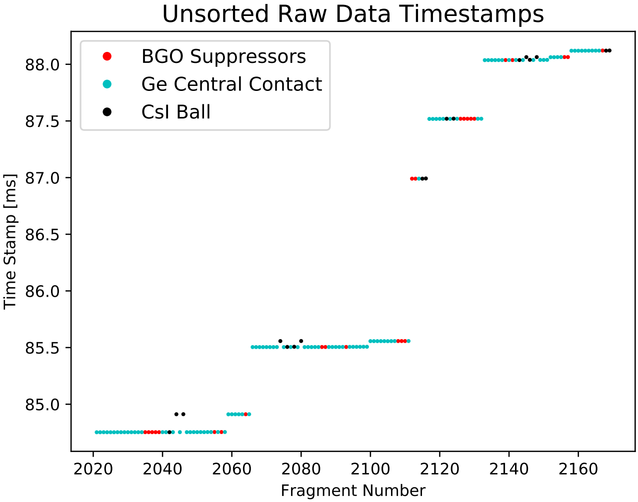
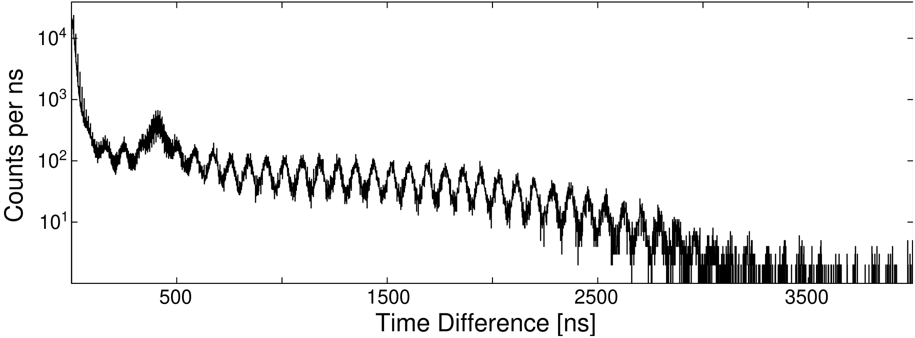


TIGRESS-TIGRESS Timing



- Coincidence peak ends $\lesssim$ 150 ns
- Second peak at $\sim$ 450 ns
- Resolution allows observation of beam bunches

TIP-TIGRESS Timing

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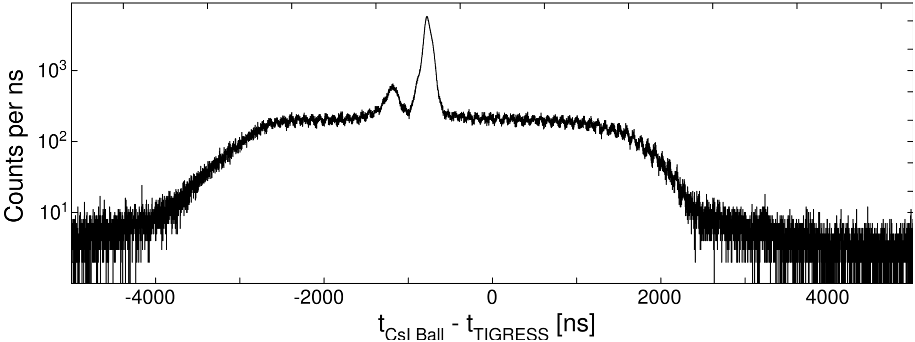
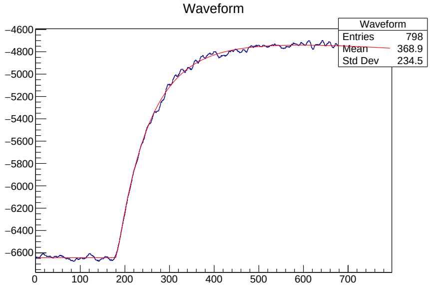


- CsI hits arrive before TIGRESS hits
- Two peaks at $\sim$ 1000 ns
  - Belived to be protons vs. alphas, currently under investigation
- Gate needs to be set to include all coincident events but not overlapping events

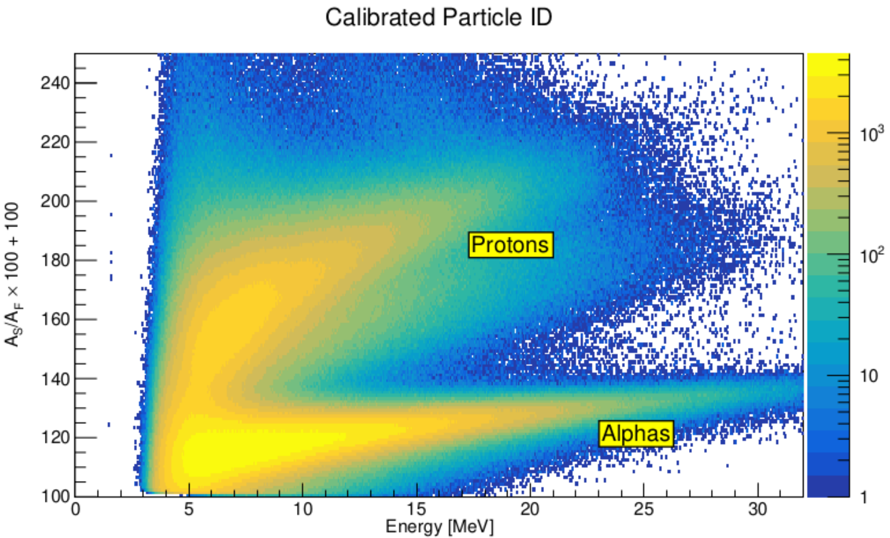


- Can fit waveforms from data

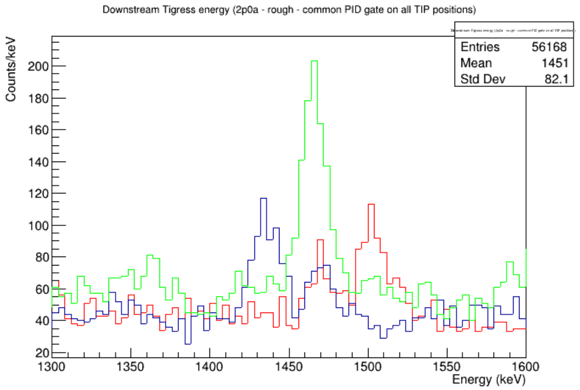
$$W(t) = C + A_F(1 - e^{-(t-t_0)/\tau_F})e^{-(t-t_0)/\tau_{RC}} + A_S(1 - e^{-(t-t_0)/\tau_S})e^{-(t-t_0)/\tau_{RC}}$$

- 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



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

Acknowledgements

Thank you to all those who helped with the experiment

M. S. Martin[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], T. S. H. Schilbach[1], 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

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Electromagnetic Transition Rates

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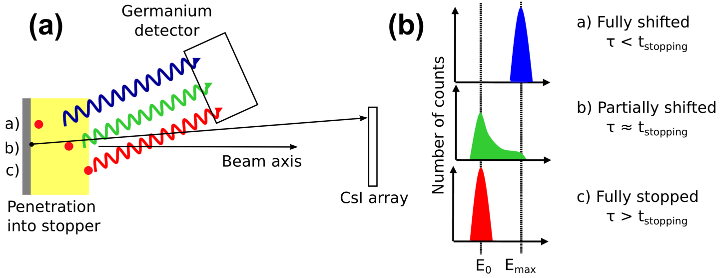
- Electromagnetic operators can be calculated analytically
- Transition rates are can be experimentally measured
- Comparison of rates leads to information about nuclear wavefunctions

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

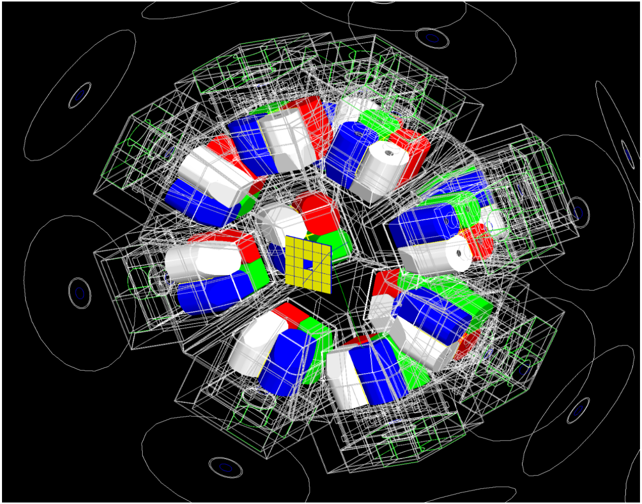
$$B(\sigma L; I_i \to I_f) = \frac{\left|\langle I_f \parallel \mathfrak{M}(\sigma L) \parallel I_i \rangle\right|^2}{2I_i + 1} \tag{2}$$

- 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

Doppler Shift Attenuation Method



- 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



- 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).

Event Reconstruction

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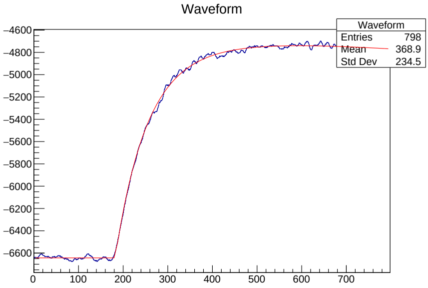
- With newly installed GRIFFIN DAQ at TIGRESS, there is no global trigger number
  - Fragments are written with individual timestamps
  - Events need to be reconstructed from individual fragments
- Fragments come from various detector types
  - CsI Ball
  - TIGRESS
    - Central contacts
    - Individual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

- 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