Lifetime measurements in inverse kinematics

K. Starosta for TIGRESS/TIP collaboration

Department of Chemistry
Simon Fraser University

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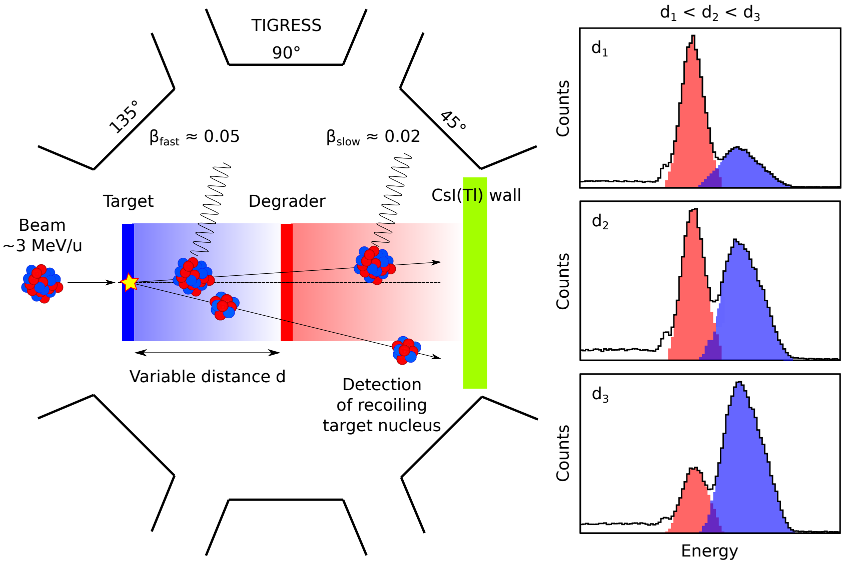
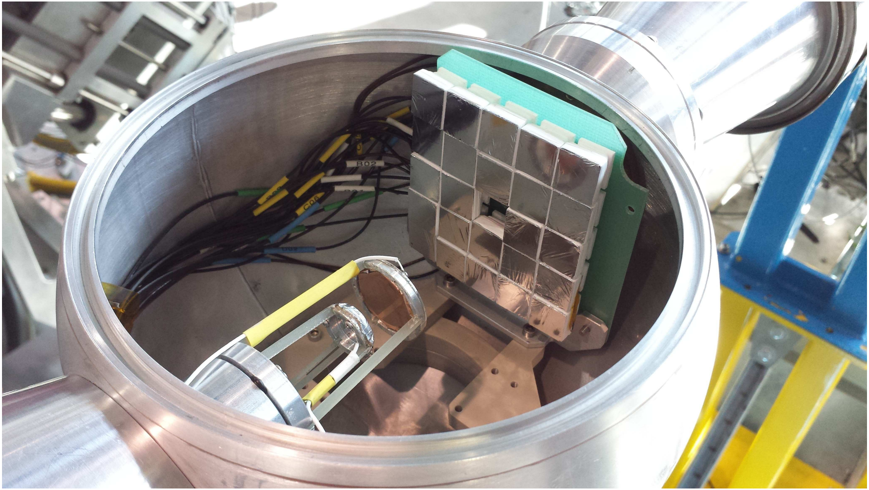
Doppler-shift lifetime measurements in inverse-kinematics

- Doppler-shift lifetime measurements do not depend on the reaction mechanism since the decays are measured instead of excitations.
- The analysis is dependent on the reaction kinematics only, can be reliably simulated yielding model-independent results.
- Forward focusing of reaction products facilitates detection using charged-particle arrays with limited angular coverage.
- Large speed of the projectile in inverse kinematics result in substantial Doppler shifts facilitating the decay curve measurement.
- Reactions of various mechanism can be separated during the analysis for charged-particle detectors which can identified reaction products.
- The same hardware can be easily applied in experiments with stable and radioactive beams.

The Recoil Distance Method (RDM) in inverse kinematics



TIGRESS Integrated Plunger with the CsI(Tl) wall



RDM using inverse-kinematics unsafe Coulex of ^{84}Kr

- Measurement of the $2_1^+ \rightarrow 0_1^+$ lifetime in ^{84}Kr.
- Previous safe Coulex experiment of Ref. [1] reports $\tau = 5.84 \pm 0.18$ ps.
- 11 TIGRESS detectors in a 3/5/3 configuration with 24-element CsI(TI) wall for particle identification and the TIGRESS Integrated Plunger.
- Excited state populated via unsafe Coulex reaction to increase the excitation cross section and rate.
- A total of 13 target/degrader separation distances from 20–400 μm were analyzed.
- Data analysis via a comparison to Geant4-simulated lineshapes developed for low-statistics experiment analysis.

[1] T. J. Mertzimekis et al. Phys. Rev. C 64 (2001) 024314.

RDM using inverse-kinematics unsafe Coulex of ^{84}Kr

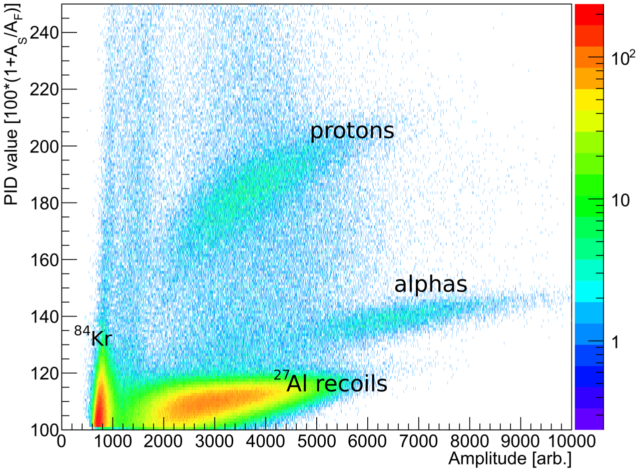
^{84}Kr properties	
E_γ	881.615 keV
$\tau_{\text{lit.}}$	5.84 ± 0.18 ps

Plunger setup.

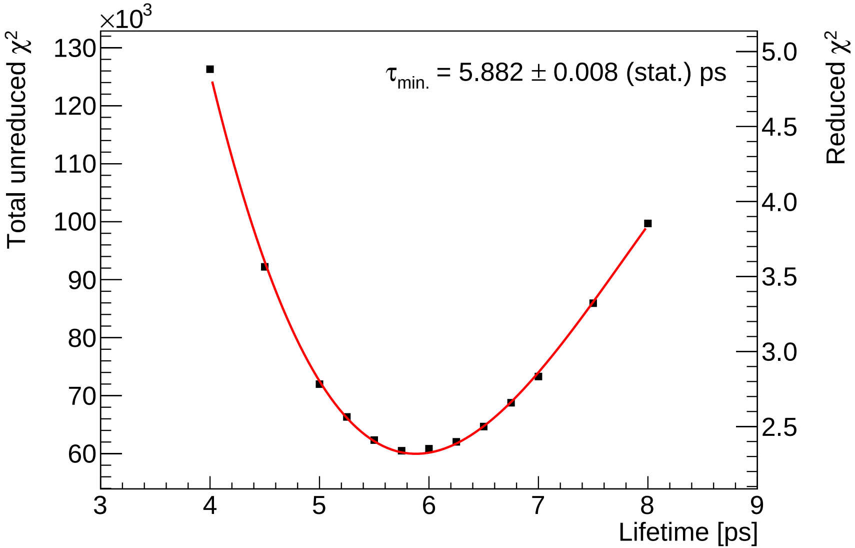
	Material	Thickness [mg/cm^2]	Thickness [μm]
Target	Al	1.07 ± 0.04	3.96 ± 0.16
Degrader	Cu	3.90 ± 0.16	4.35 ± 0.18

Beam properties	
Beam energy	250 MeV
Safe Coulex	200 MeV
Rate	$\sim 2 \times 10^8$ pps

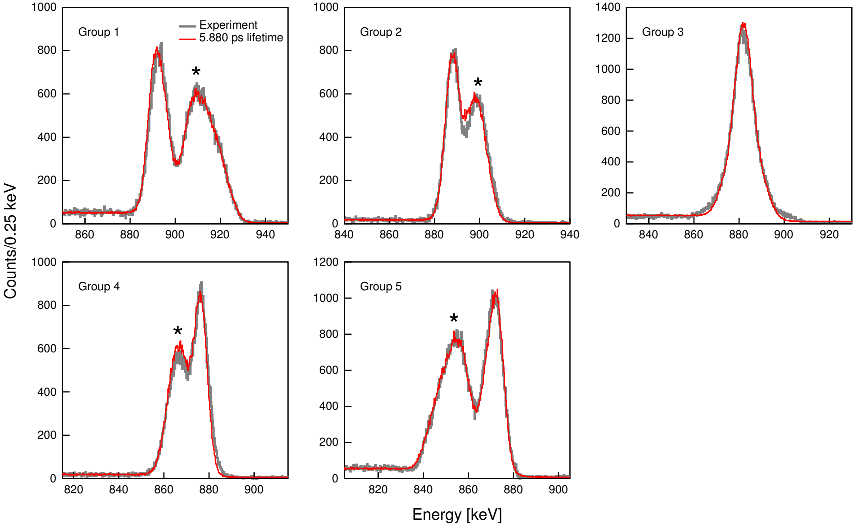
Identifying ^{84}Kr Coulex recoils



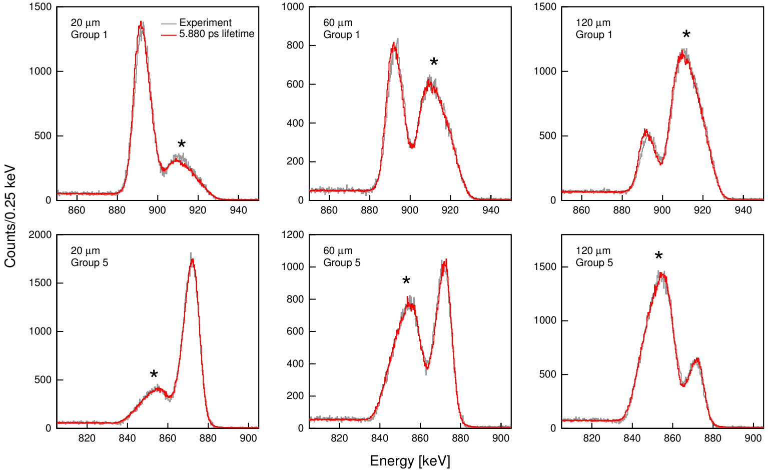
Best fit lifetime from χ^2 analysis at 60 μm



Simulated best fit lineshapes at 60 μm



Simulated lineshapes: groups 1 and 5 at selected distances



Best fit lifetime: 5.880 ± 0.013 (stat.) ± 0.070 (sys.) ps

Literature value: 5.84 ± 0.18 ps [Mertzimekis 2001]

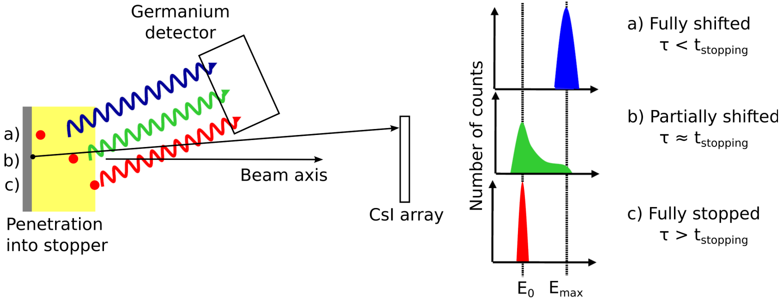
^{84}Kr experiment summary

- Systematic uncertainties from the following 3 sources were identified:
  1. Transitions from higher-lying (feeding) states,
  2. Misalignment of the target and degrader foils,
  3. Choice of fit range for the χ^2 analysis.
- No deorientation effect observed in the data.
- Final reported lifetime: $\tau = 5.880 \pm 0.008$ (stat.) ± 0.070 (sys.) ps.
- Excellent agreement with literature value of 5.84 ± 0.18 ps with factor of $\sim$2 reduction in uncertainty.
- A robust and flexible framework has been developed for the planning and analysis of RDM experiments using TIP.
- Published in A. Chester *et. al.* Nucl. Inst. Meth. A882 (2018) 69.

T. J. Mertzimekis et al. Phys. Rev. C 64 (2001) 024314.

Doppler Shift Attenuation Method (DSAM)

$$E_\gamma = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta cos\theta} \approx E_0(1+\beta cos\theta)$$



- Recoil slows and stops in a thick target backing.
- Observe lineshape depending on the speed distribution of the residual at time of gamma-ray emission.

DSAM using inverse-kinematics unsafe Coulex of ^{86}Kr

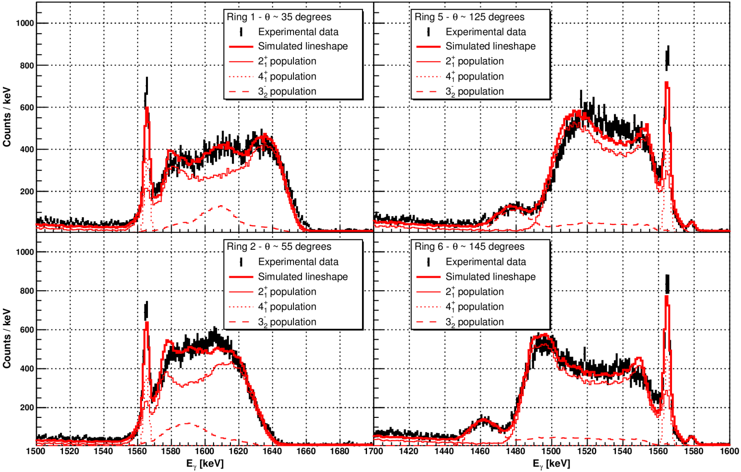
^{86}Kr properties	
E_γ	1565 keV
$\tau_{\text{lit.}}$	0.263 ± 0.009 ps

Plunger setup.

	Material	Thickness [mg/cm^2]	Thickness [µm]
Target	C	0.50 ± 0.01	2.17 ± 0.05
Stopper	Au	28.8 ± 0.2	14.9 ± 0.1

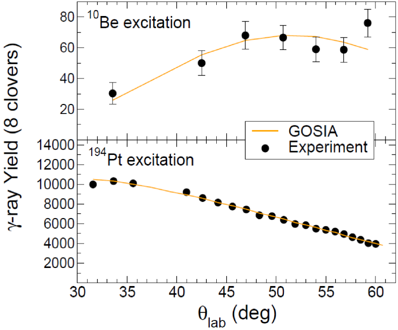
Beam properties	
Beam energy	256.7 MeV
Safe Coulex	180.9 MeV
Rate	$\sim 6 \times 10^8$ pps

Simulated best fit lineshapes for $2_1^+ \rightarrow 0_1^+$ in ^{86}Kr



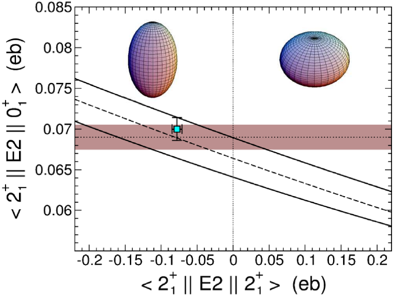
J. Henderson et al. Phys. Rev. C 97 (2018) 044311.

Coulex and DSAM lifetime combined result analysis



Figures courtesy of Nico Orce

Gamma-ray yields were calculated with GOSIA, a semi-classical Coulomb excitation code.



$$\langle 2_1^+||E2||0_1^+\rangle = 0.0690(15)\ \text{eb}$$

E.A. McCutchan et al., PRL 103, 192501 (2009).

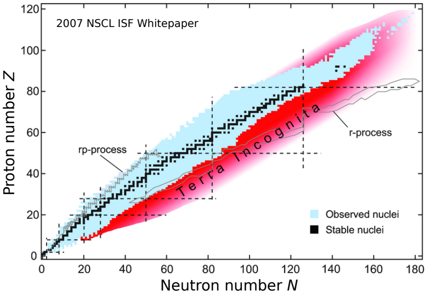
N. Orce et al. Phys. Rev. C86 (2012) 041303.

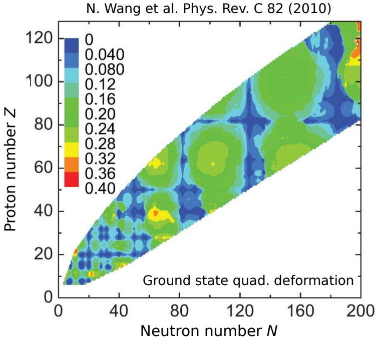
Conclusions

- Be first or be right.
- It is difficult to be first when using stable beams.
- It is still possible to be right when using stable beams.
- New cyclotron $\Rightarrow$ large range of beam selection $\Rightarrow$ access to unsafe Coulex energies $\Rightarrow$ opportunities for the heaviest ions for which the number of measurements is limited.
- New cyclotron $\Rightarrow$ large beam currents $\Rightarrow$ access to isotopes of small abundance $\Rightarrow$ opportunities for the rare ions for which the number of measurements is limited.
- New cyclotron $\Rightarrow$ large beam currents $\Rightarrow$ opportunities for reactions of low cross-section $\Rightarrow$ access to nuclei far from stability.
- Accurate and precise transition rate measurements provide valid constrains for theories and models.

Backup slides

Selected goals of nuclear science research



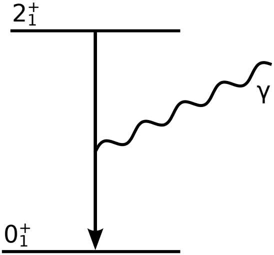


- Understand the mechanisms of shell and shape evolution in medium-mass and heavy nuclei as a function of isospin.
- Develop a theoretical framework that is able to make accurate predictions of nuclear properties.

TRIUMF 5 Year Plan 2015–2020.

Studying nuclear structure using the electromagnetic force

- The electromagnetic force provides a convenient non-intrusive probe of nuclear systems bound by the strong force.
- Lifetime measurements using gamma-ray spectroscopy provide:
  - An observable sensitive to nuclear structure.
  - A useful benchmark for nuclear model calculations.

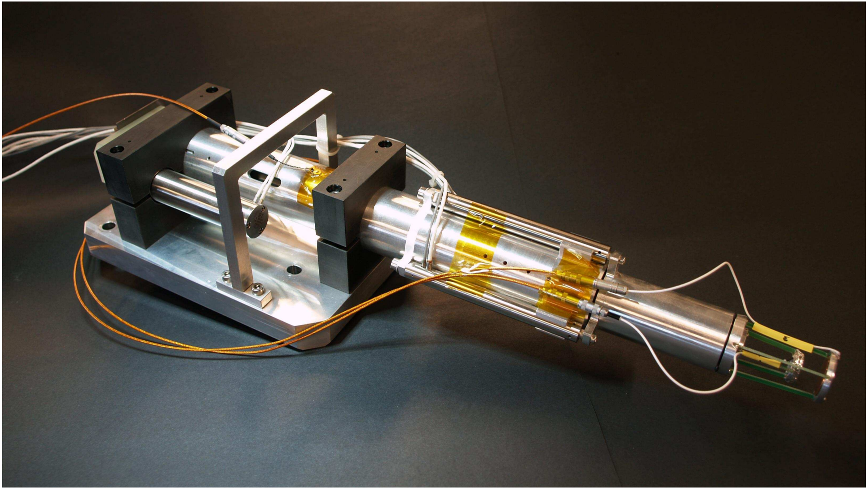


$$\tau(E2; 2_1^+ \to 0_1^+) = \lambda(E2; 2_1^+ \to 0_1^+)^{-1}$$

$$\lambda(E2; 2_1^+ \to 0_1^+) \propto E(2_1^+)^5 \times B(E2; 2_1^+ \to 0_1^+)$$

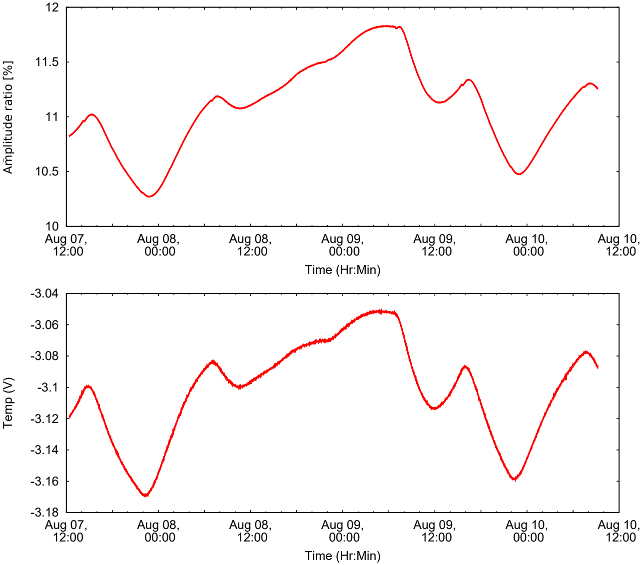
$$B(E2; 2_1^+ \to 0_1^+) = \frac{1}{5} \langle 2_1^+ | |E2| |0_1^+ \rangle^2 \propto \beta^2$$

The TIGRESS Integrated Plunger (TIP) device

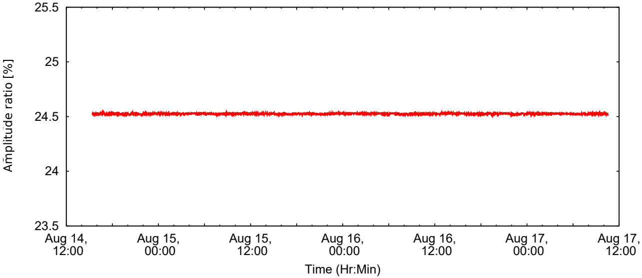


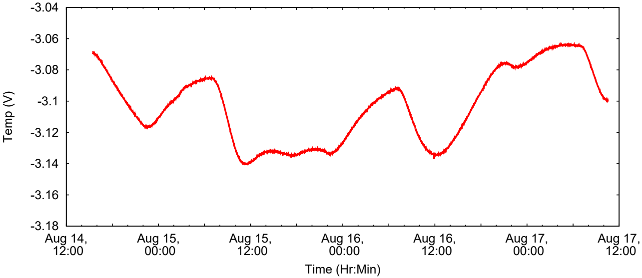
P. Voss et al. Nucl. Inst. and Meth. A 746 (2014) 87, P. Voss et al. Phys. Proc. 66 (2015) 524.

TIP plunger capacitance stabilization

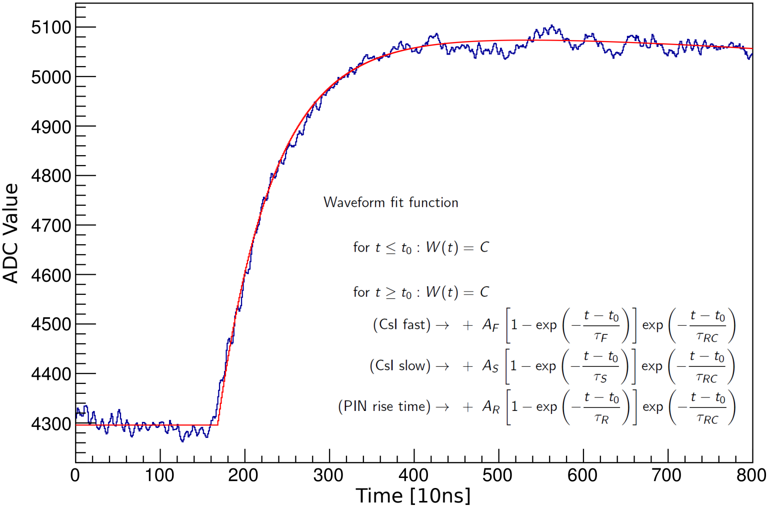


TIP plunger capacitance stabilization



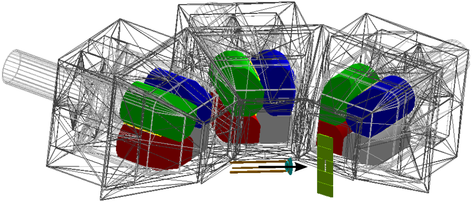


CsI(Tl) detector waveform fits



P. Voss et al. Nucl. Inst. and Meth. A 746 (2014) 87, P. Voss et al. Phys. Proc. 66 (2015) 524.

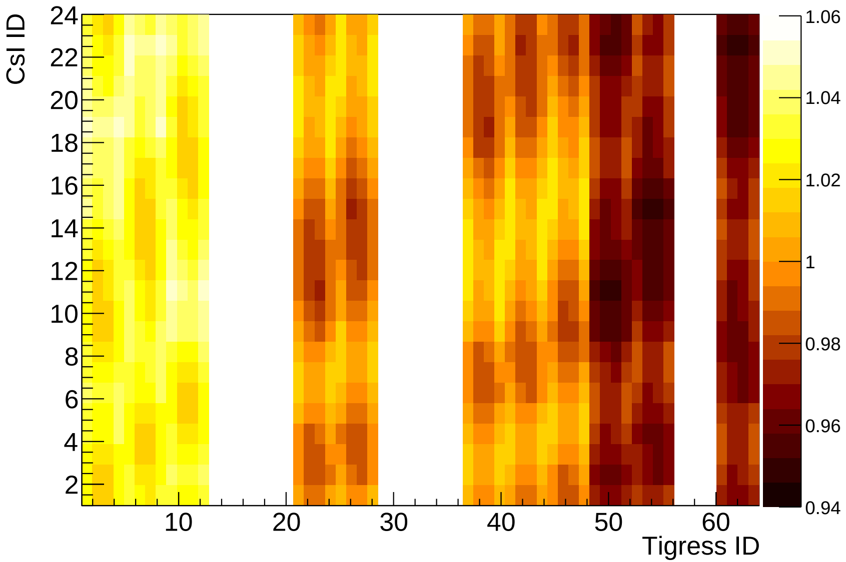
Geant4 simulation framework



- Coulomb excitation followed by gamma-ray decay.
- Analytic solutions for single step $E2$ process (Coulex kinematics, angular distributions, etc.) with track weighting to handle thick target integration.
- Gamma-ray sensitive detectors ported from GRIFFIN/TIGRESS code originating from Guelph.

Adrich et al. Nucl. Inst. and Meth. A 598 (2009) 454, Alder et al. Rev. Mod. Phys. 28 (1956) 432.

Geant4-facilitated data analysis: Doppler-shift factors



Histogram analysis using the likelihood ratio χ^2

- For a Poisson likelihood function, the likelihood ratio χ^2 is given by

$$\chi^2 = 2\sum_{i=1}^{k} y_i - n_i + n_i \ln(n_i/y_i)$$

  where y_i is the model and n_i the observed data.
- Pros:
  - Versatile (goodness of fit, point estimation, error analysis).
  - Control over parent distribution.
  - Minimizing likelihood ratio $\chi^2 \equiv$ maximizing likelihood function.
  - **No variance estimation!**
- Cons:
  - Non-linear.
  - ...

Baker and Cousins. Nucl. Inst. and Meth. A 221 (1984) 437.

Data analysis procedure

- For a given input lifetime τ, simulate gamma-ray spectra grouped by the Doppler-shift factor at all distances.
- Model data using

$$y_i = \alpha_0 s_i + \alpha_1 + \alpha_2 \,\mathrm{erfc}\left(\frac{i-c}{w\sqrt{2}}\right),$$

  where s_i is the simulated data and the α's are free parameters.

- Minimize $\chi^2_{d,g}$ for each distance and group.
- Minimum in total $\chi^2 = \sum_{\text{dist.}} \sum_{\text{gr.}} \chi^2_{d,g}$ corresponds to best fit lifetime $\tau_{\text{min.}}$

$B(E2, 2_1^+ \rightarrow 0_1^+)$ in N=50 isotones at Z=36