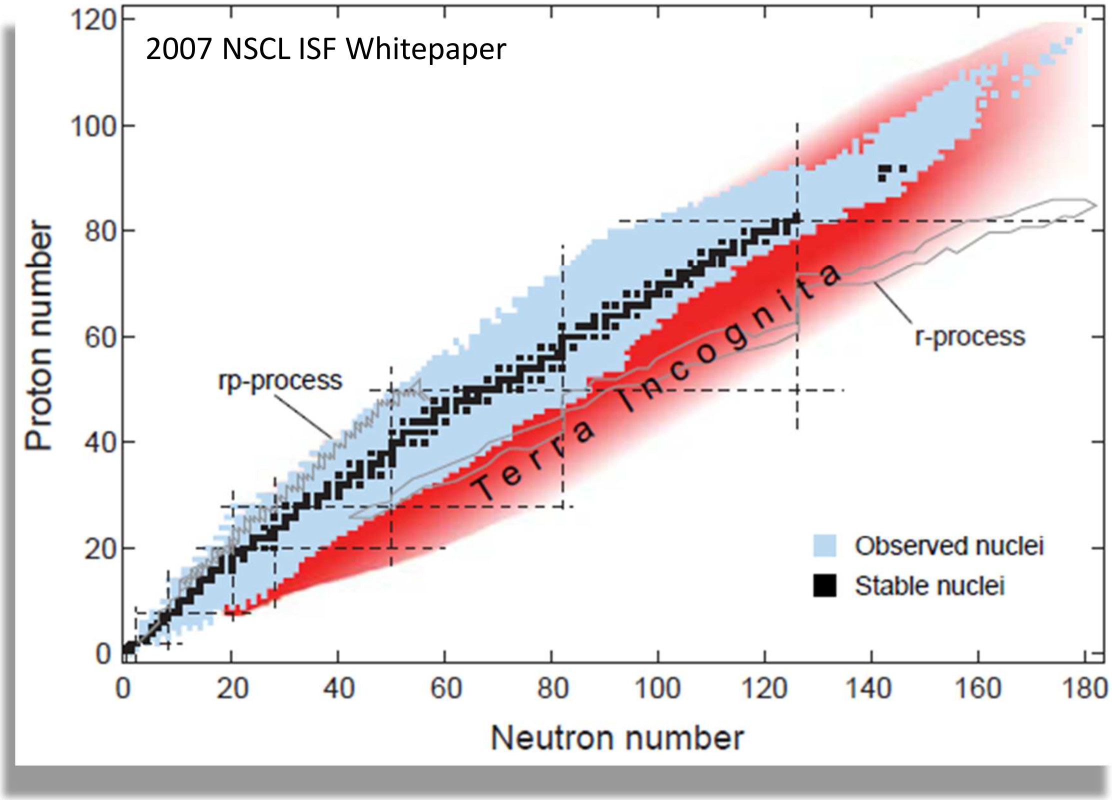
Experimental Update of the TIGRESS HPGe Clover Array

Philip J. Voss
Simon Fraser University

On behalf of the TIGRESS Collaboration
Tuesday, June 17th 2014

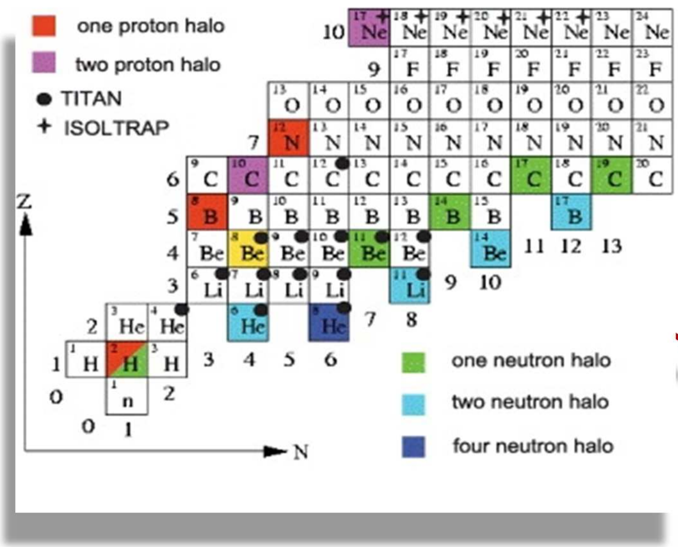
Select Major Questions in Nuclear Physics

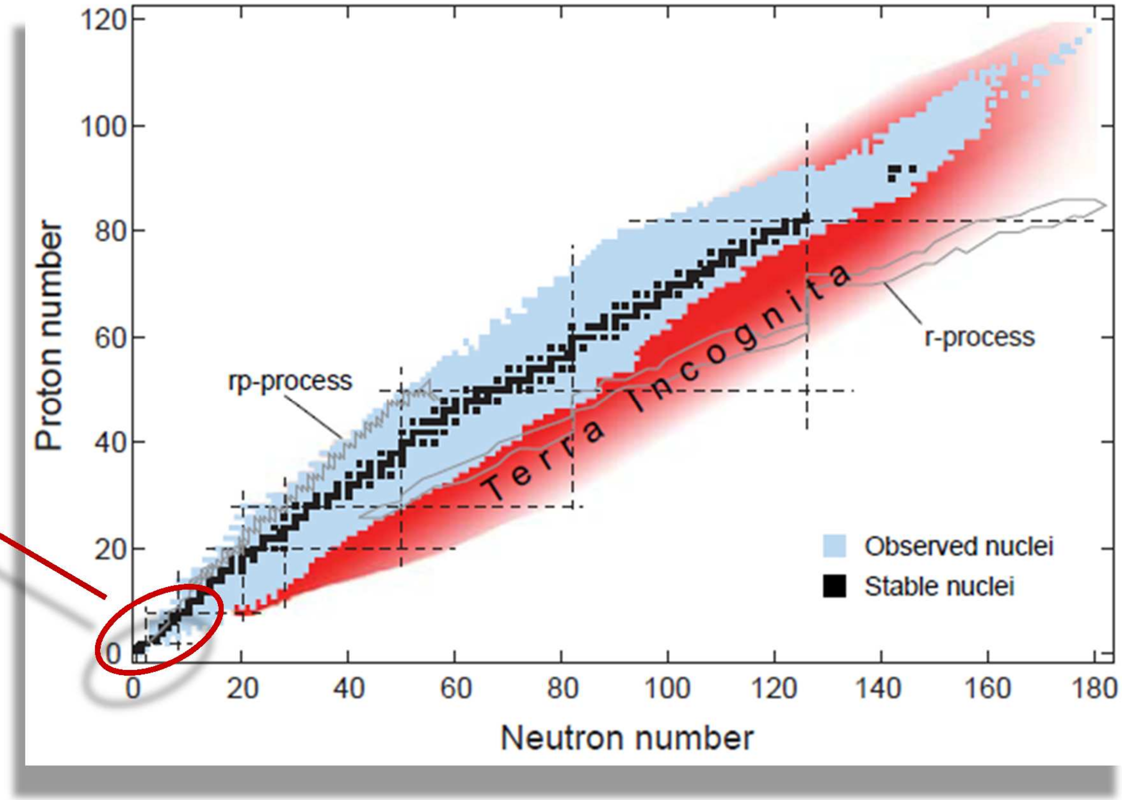


- How does an increasing exotic proton-neutron ratio impact the evolution of nuclear structure?
- What mechanisms underlie the diversity and evolution of nuclear shape deformation?
- What are the most accurate theoretical models for explaining these properties "globally"?

Select Major Questions in Nuclear Physics

K. Blaum et al., 2013 Phys. Scr. **2013** 014017





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  - Spatial decoupling of nucleons from core: **halo nuclei**.

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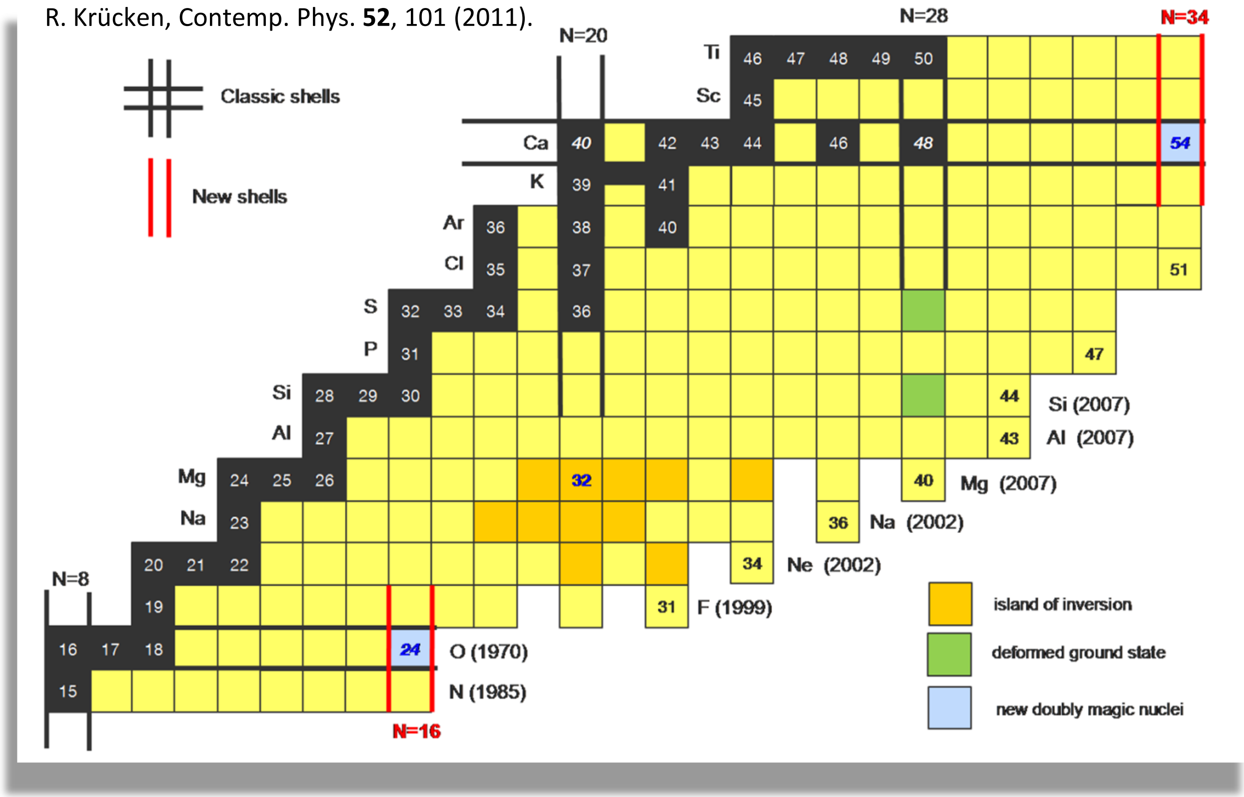
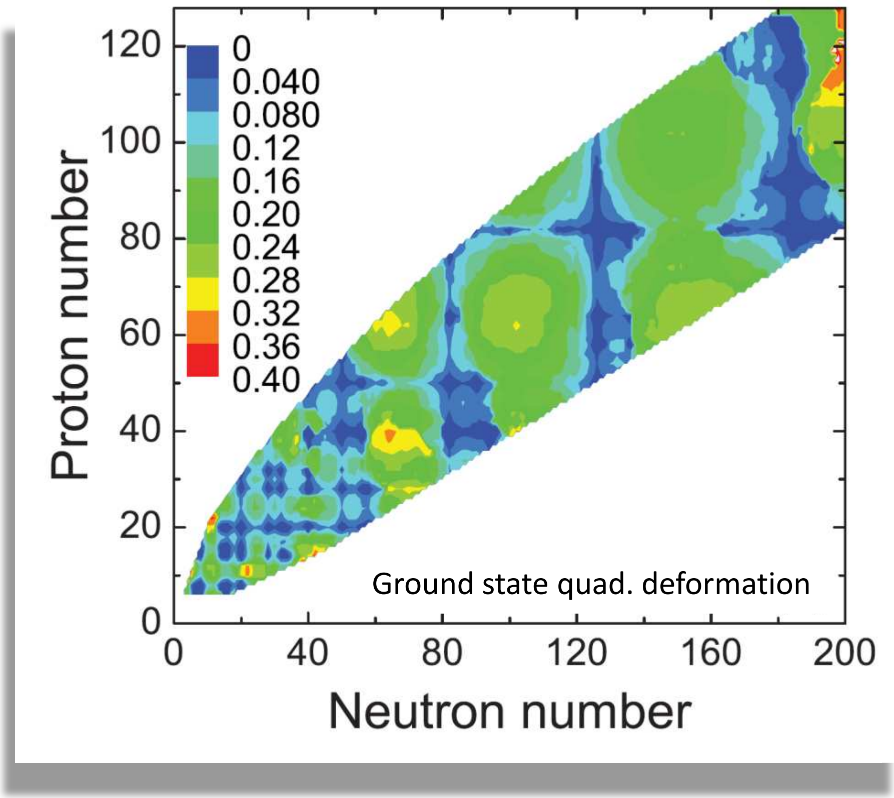


R. Krücken, Contemp. Phys. **52**, 101 (2011).

- How does an increasing exotic proton-neutron ratio impact the evolution of nuclear structure?
  - Spatial decoupling of nucleons from core: **halo nuclei**.
  - **Emergence** of new magic numbers and **disappearance** of traditional ones.

Select Major Questions in Nuclear Physics

N. Wang et al., PRC **82**, 044304 (2010)



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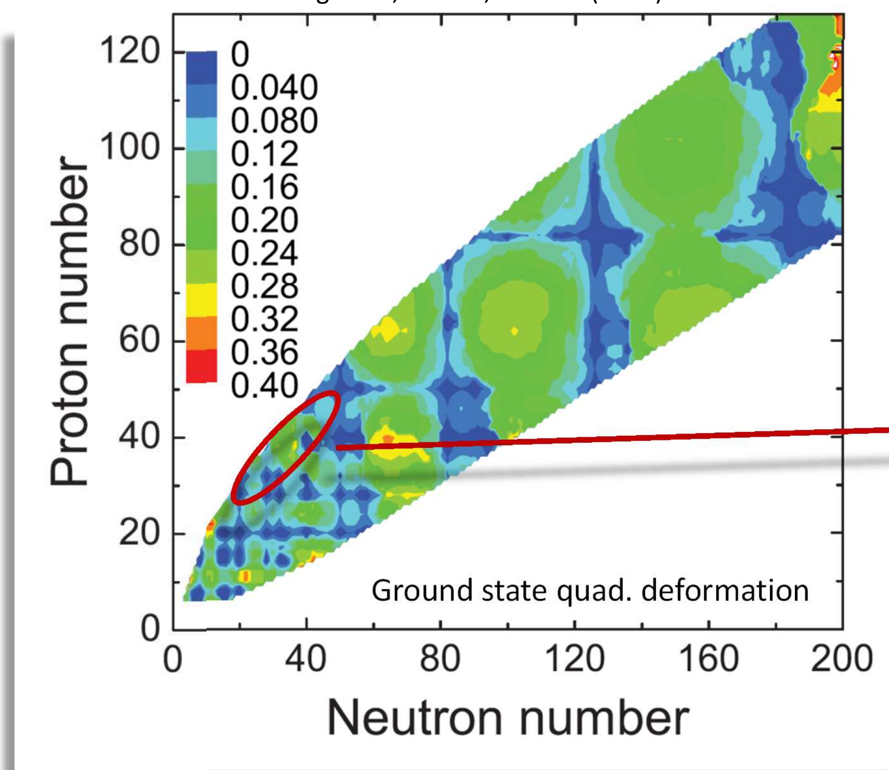
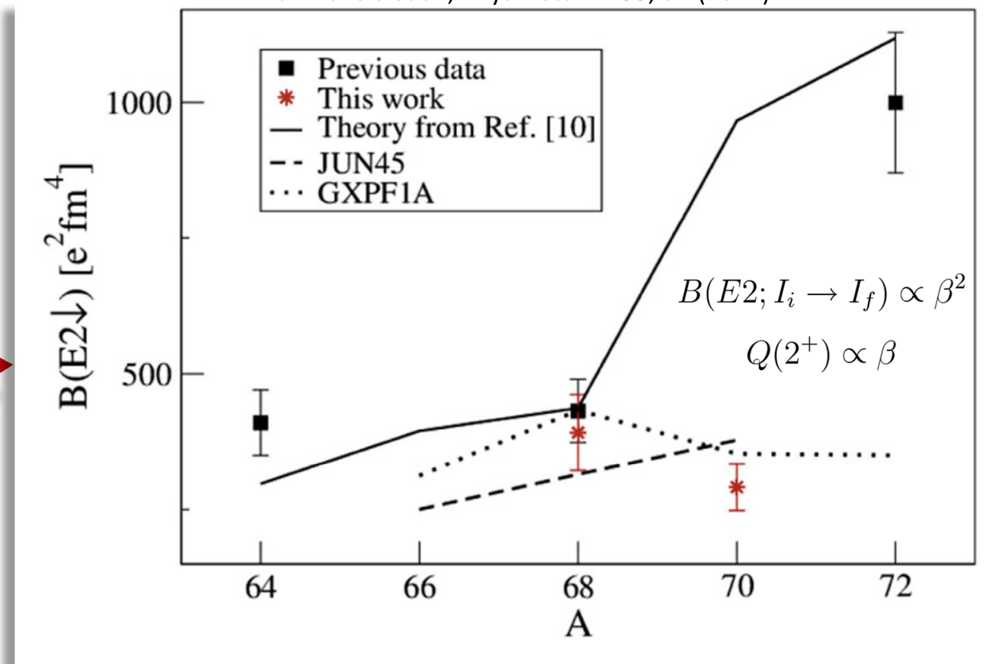


A.J. Nichols et al., Phys. Lett. B **733**, 52 (2014)



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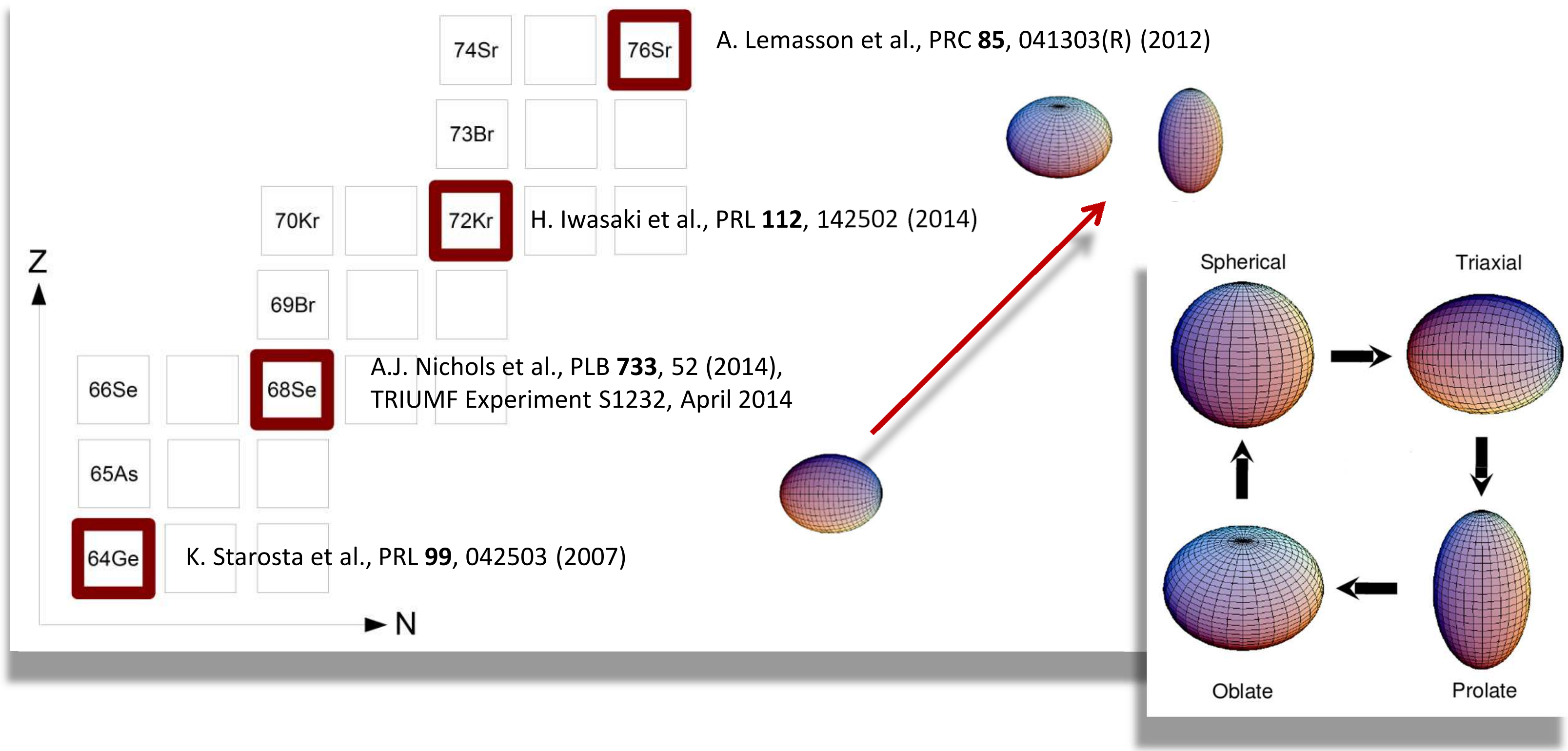
Major Questions: Shape Evolution Along the *N=Z* Line



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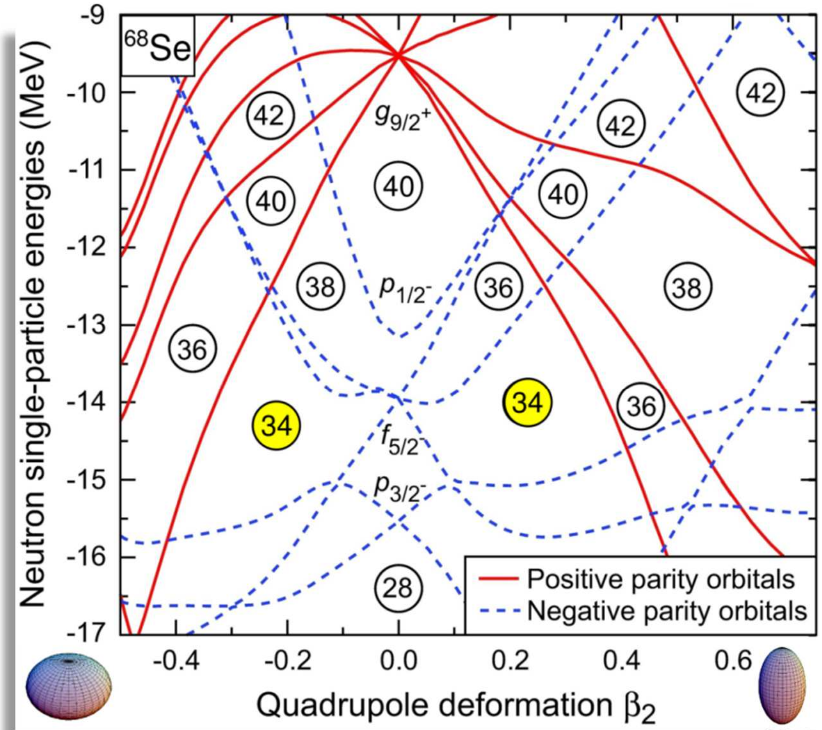
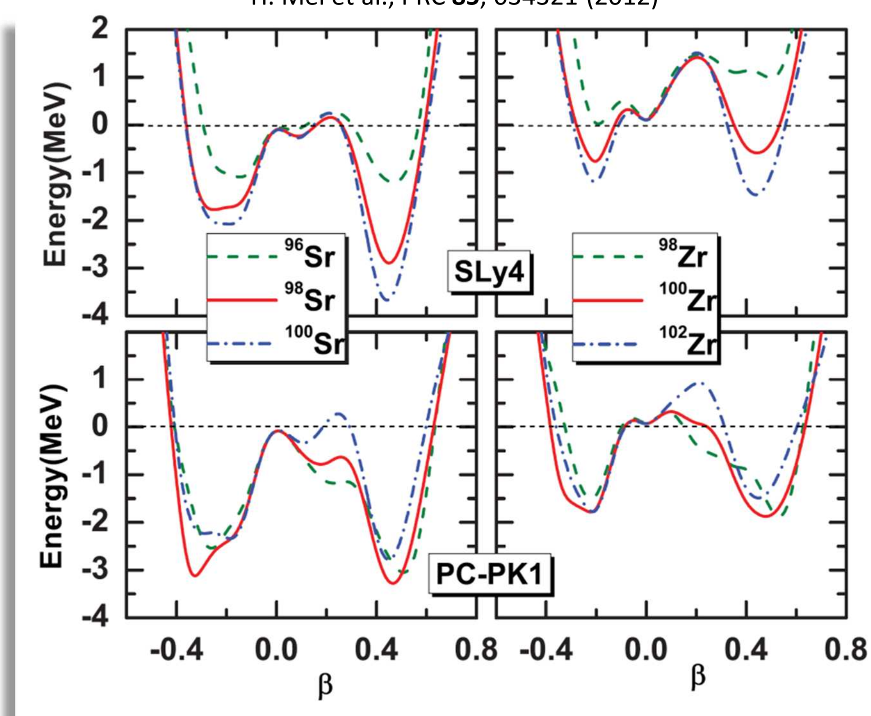
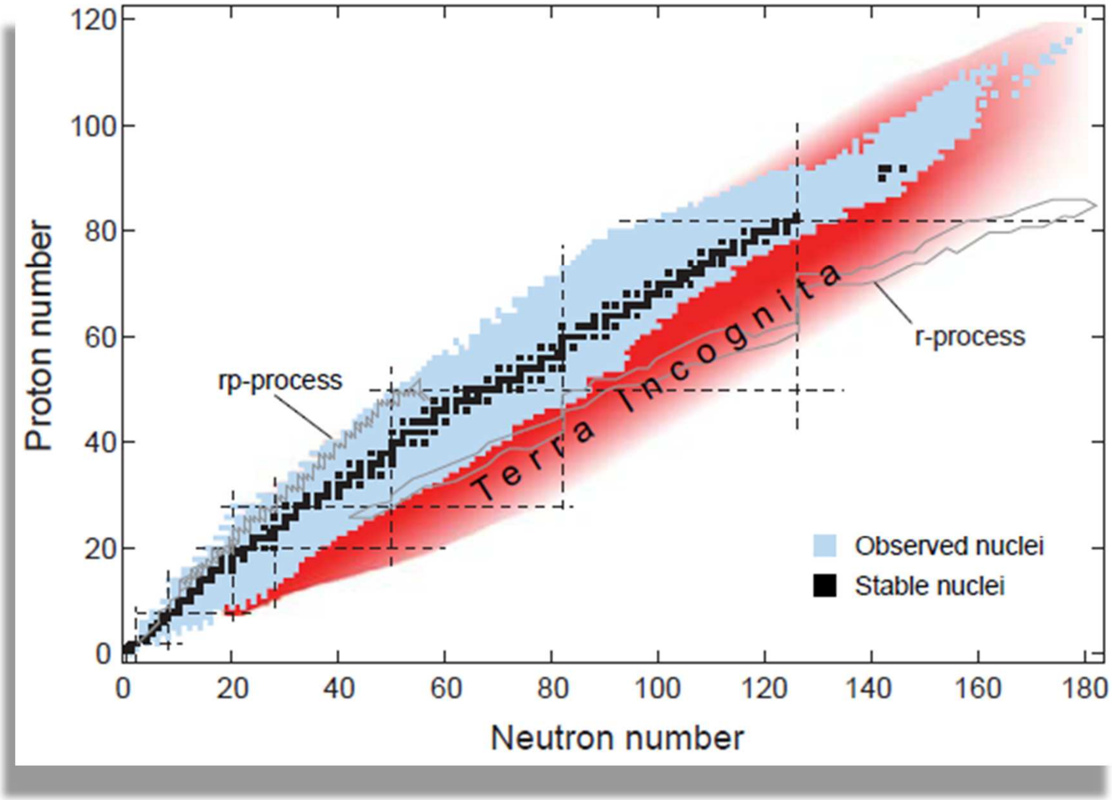
Major Questions: Shape Coexistence Along the *N=Z* Line





- How does an increasing exotic proton-neutron ratio impact the evolution of nuclear structure?
- What mechanisms underlie the diversity and evolution of nuclear shape deformation?
  - Cooperative effects along *N=Z* line from simultaneous filling of orbitals: **shape evolution.**
  - Nearly degenerate shell gaps for positive and negative deformation: **shape coexistence.**

Select Major Questions in Nuclear Physics



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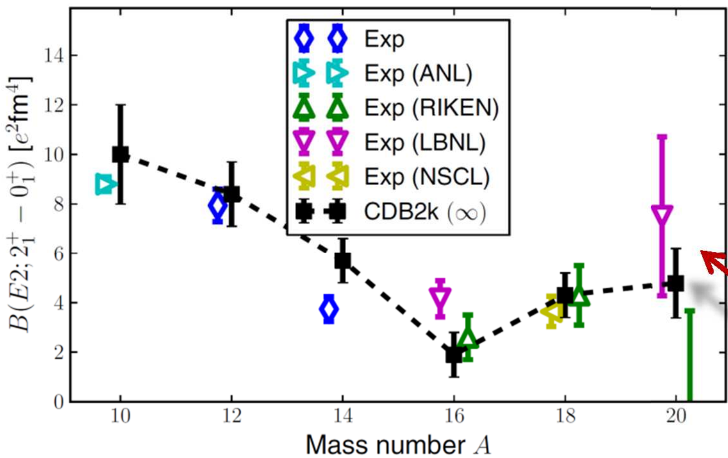
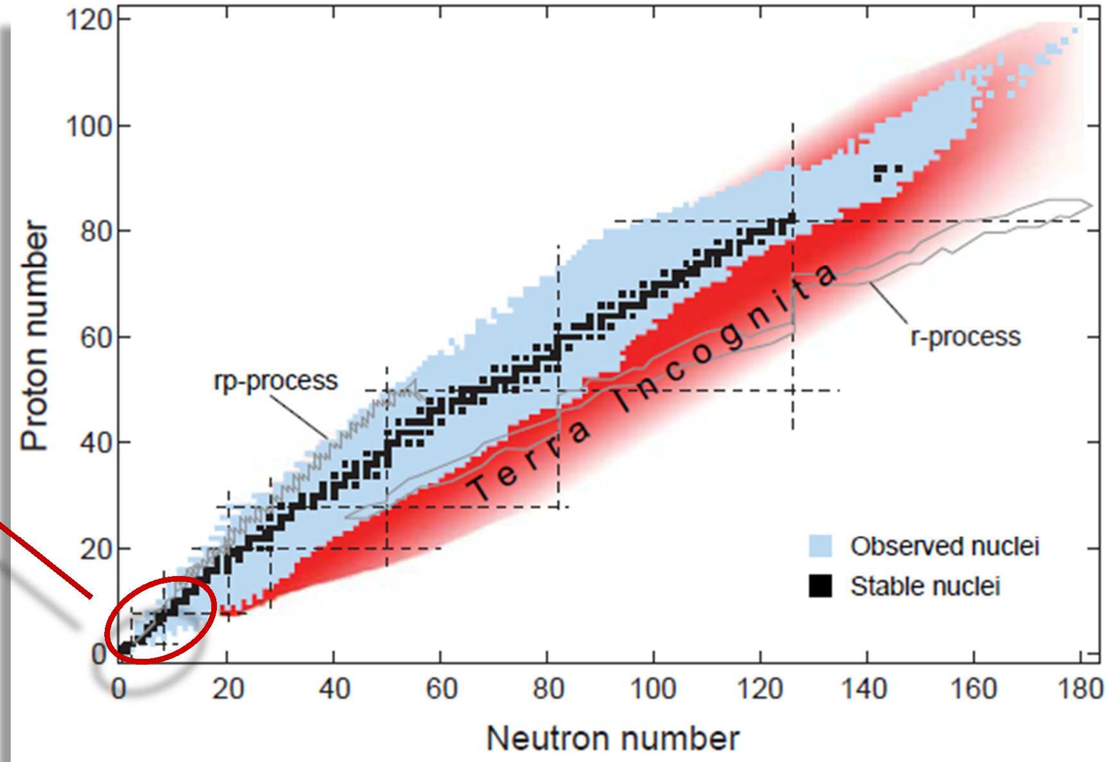
Select Major Questions in Nuclear Physics

C. Forssen et al., JPG:Nucl. Part. Phys. **40**, 055105 (2013)





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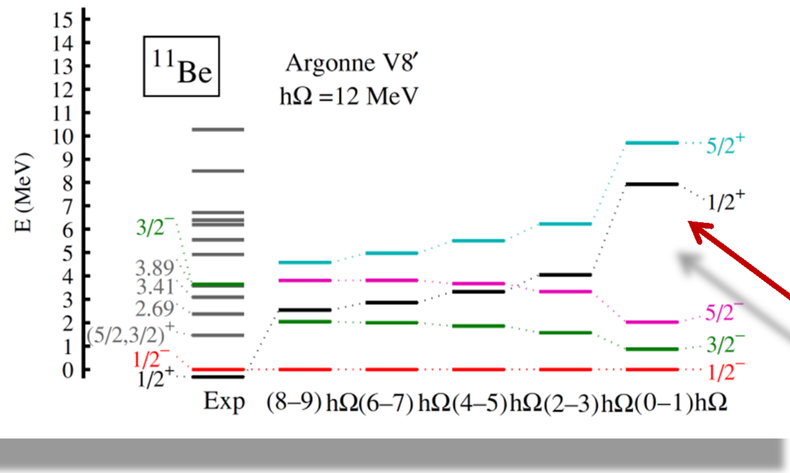
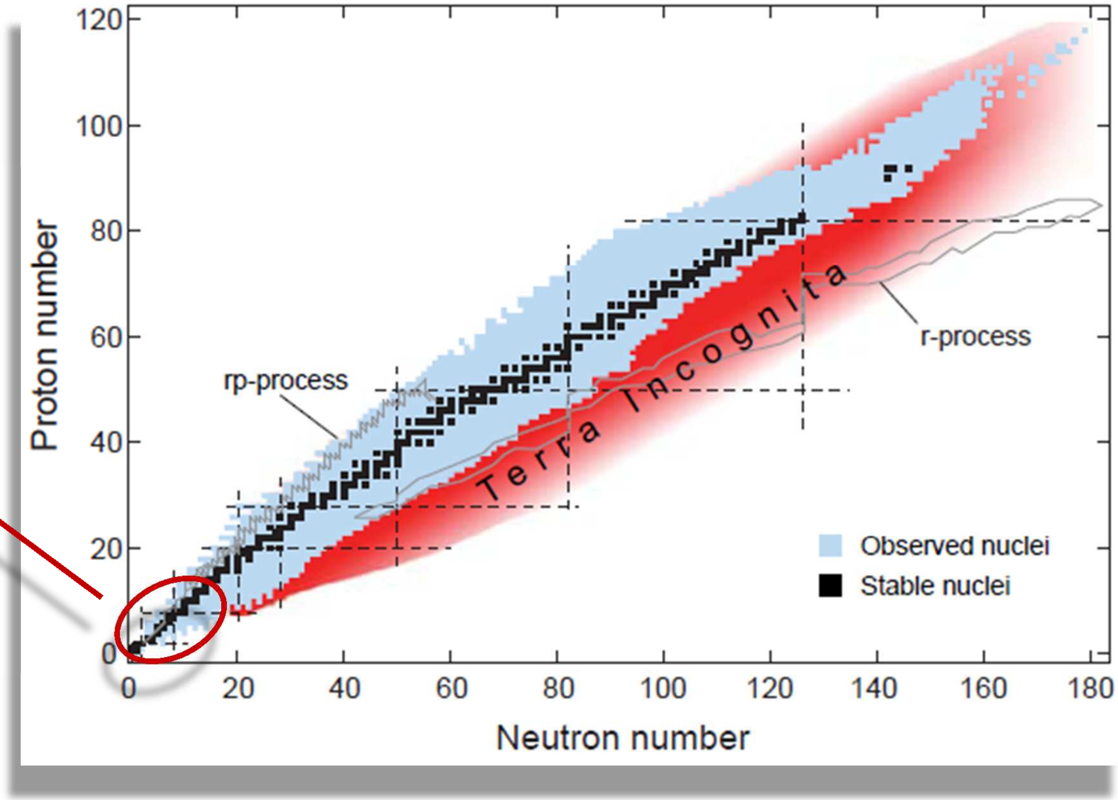
  - No-core Shell Model *ab initio* approaches: **light atomic nuclei (A<20).**

Select Major Questions in Nuclear Physics

C. Forssen et al., PRC **71**, 044312 (2005)





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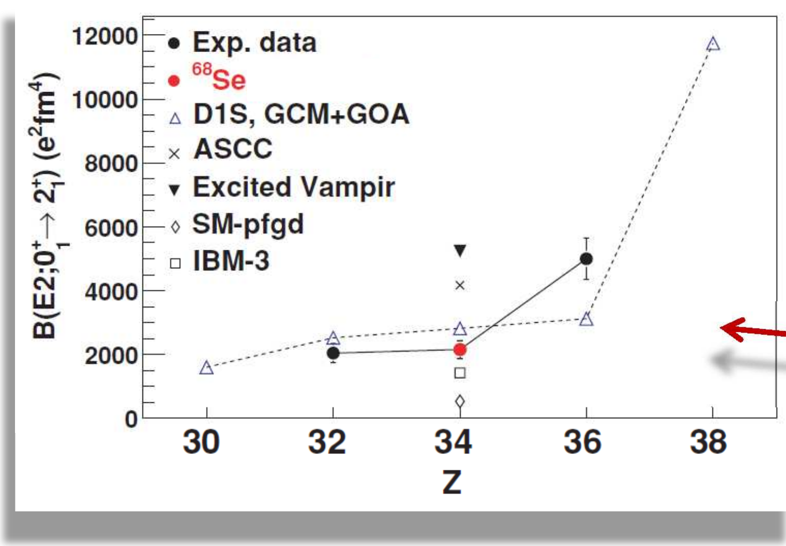
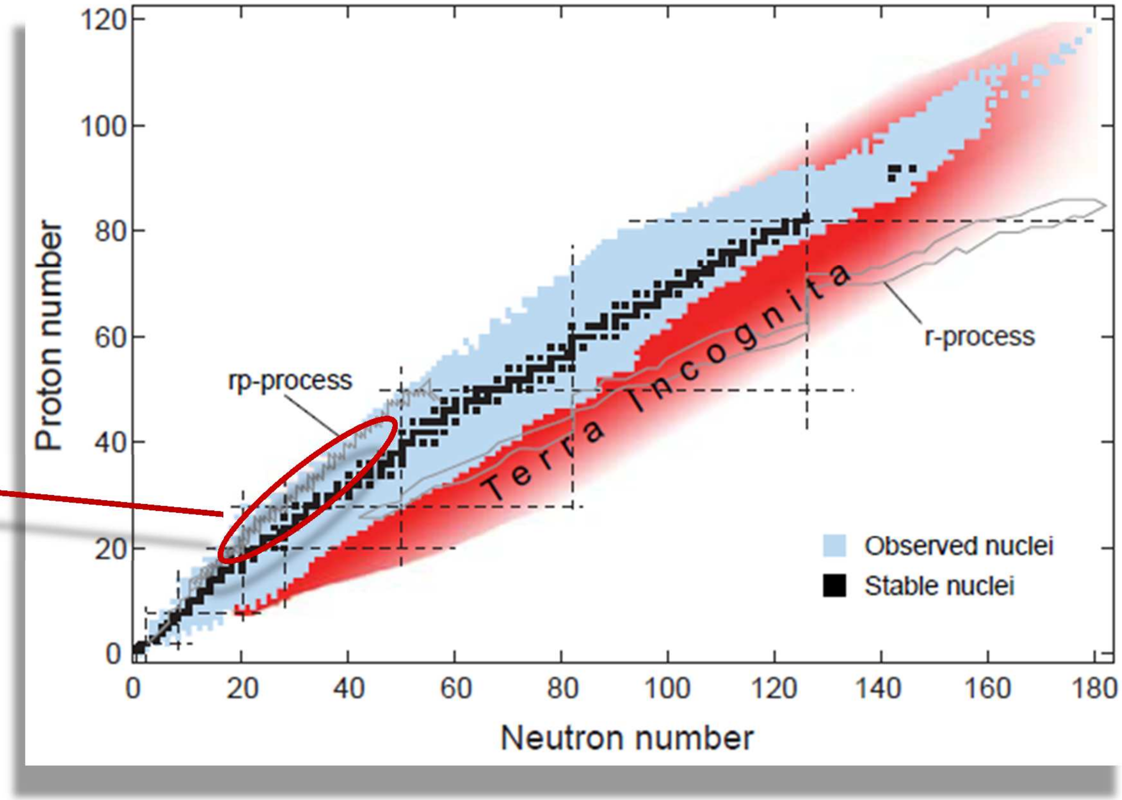
- What mechanisms underlie the diversity and evolution of nuclear shape deformation?
- What are the most accurate theoretical models for explaining these properties "globally"?
    - No-core Shell Model *ab initio* + Continuum (?) approaches: **light atomic nuclei (A<20).**

Select Major Questions in Nuclear Physics

A. Obertelli et al., PRC **80**, 031304(R) (2009)





- How does an increasing exotic proton-neutron ratio impact the evolution of nuclear structure?
- What mechanisms underlie the diversity and evolution of nuclear shape deformation?
- What are the most accurate theoretical models for explaining these properties “globally”?
    - Model space truncations and approximations in HFB/SM: **medium mass nuclei.**

SFU

The Importance of Gamma-Ray Spectroscopy

Studies at the extreme limits of nuclear existence require radioactive beam facilities capable of delivering intense and pure beams of nuclear species.

- Reactions require high energy beams (~0.1c) → Doppler reconstruction requires photon detector **segmentation** and **charged particle detection**.
- Inherent low intensities → Need high photon detection **efficiency** and **reaction channel selectivity** to improve the signal of weak channels.
- Ideal detection system → Suppressed HP segmented germanium clover array + ancillary particle detection.

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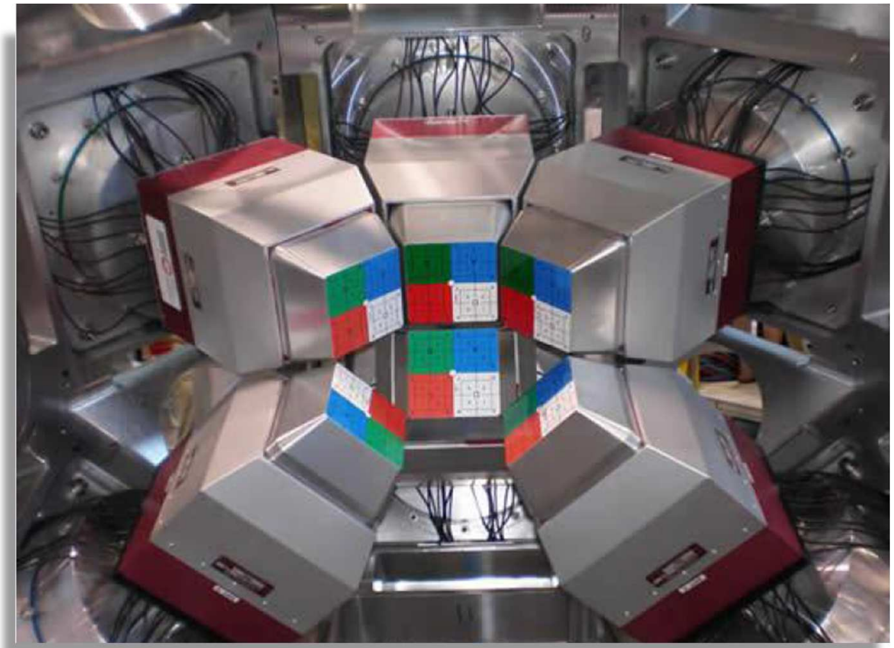
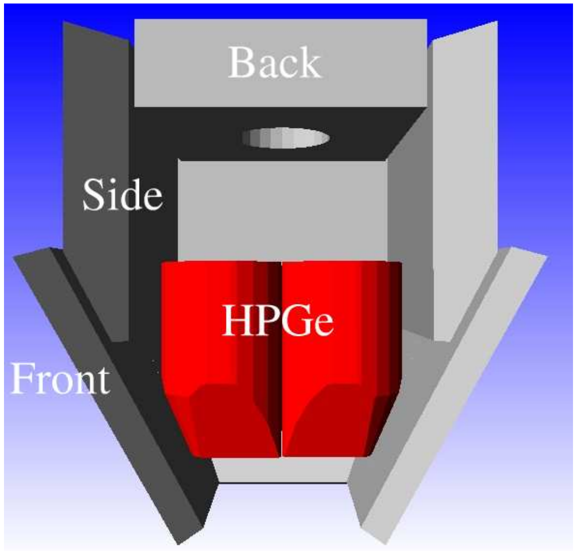
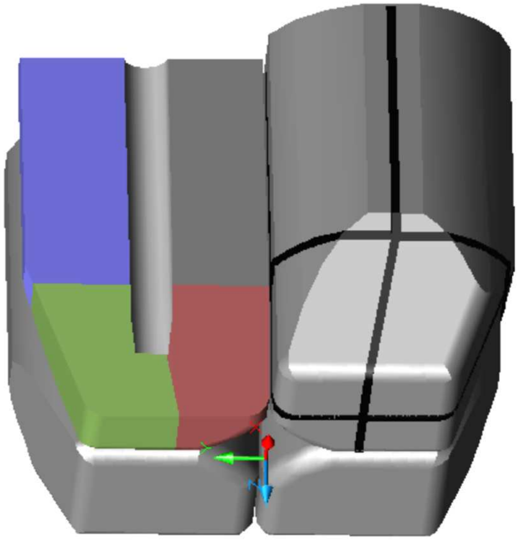
TRIUMF ISAC Gamma-Ray Escape Suppressed Spectrometer





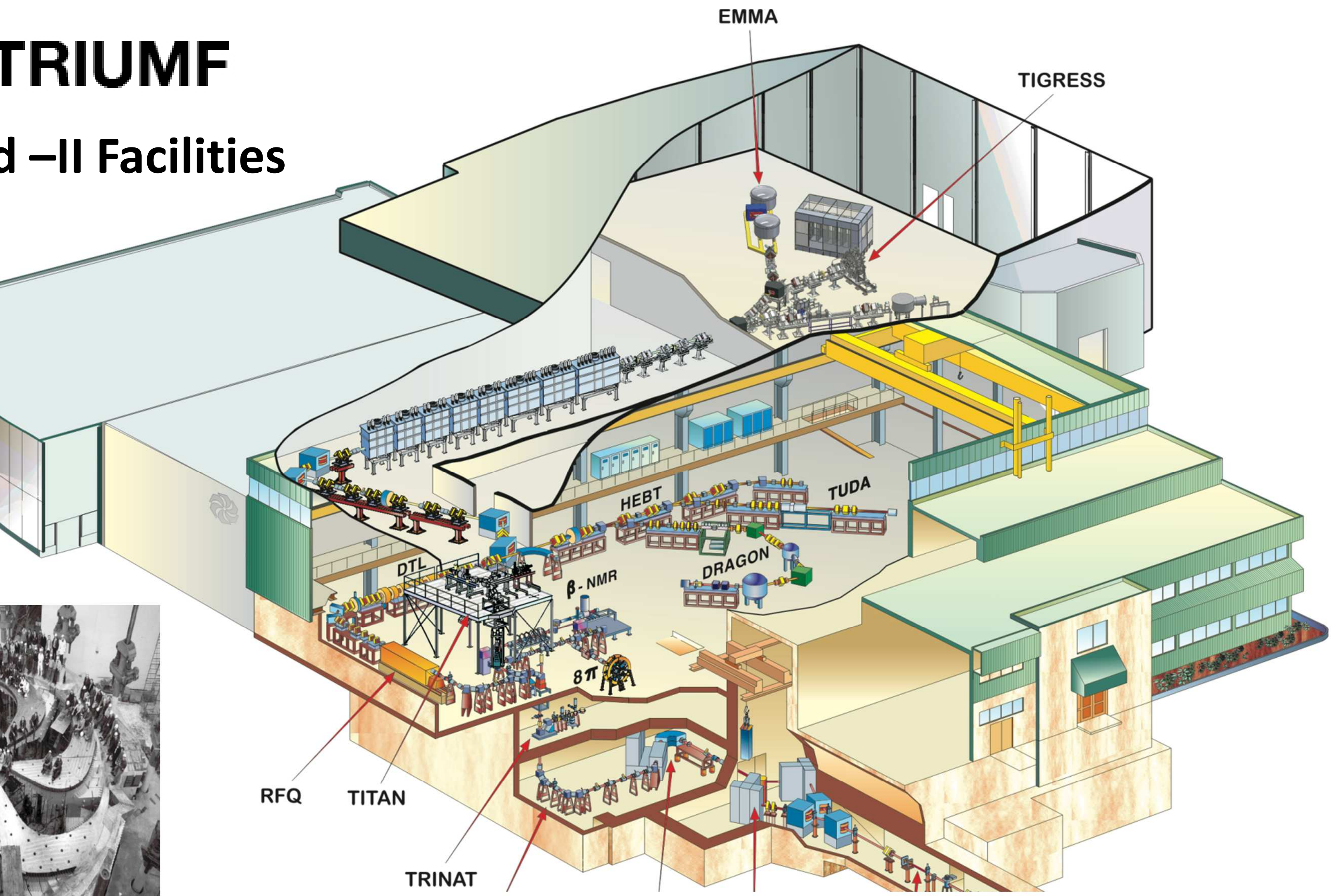


- TIGRESS is an array of 16 high-purity germanium clover detectors with 32-fold segmentation per clover for enhanced position resolution.
- The array is fully instrumented with fast digital electronics and reconfigurable BGO suppressors to meet a variety of experimental needs.

TRIUMF: Canada’s National Nuc. and Part. Physics Laboratory

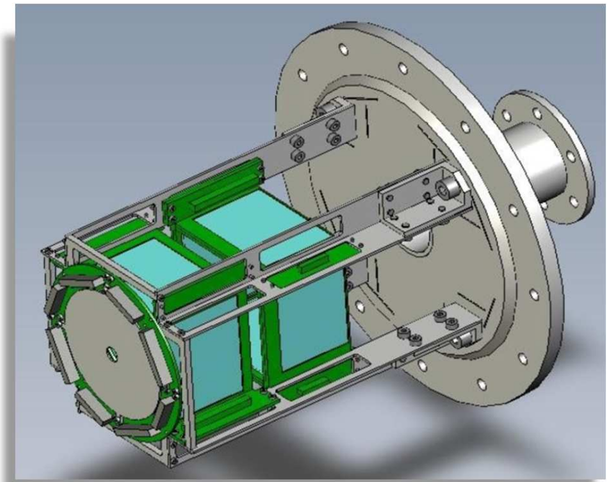
TRIUMF

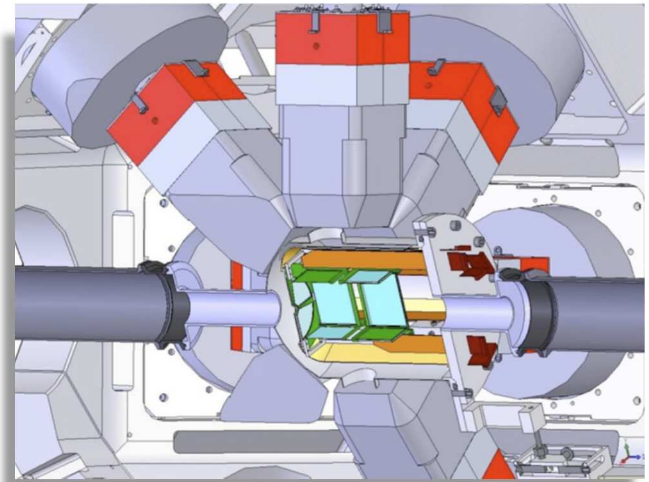
ISAC-I and –II Facilities

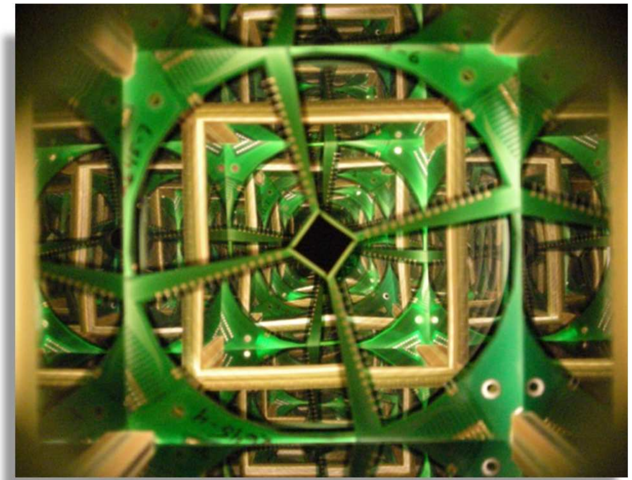


SHARC: Silicon Highly-Segmented Array for Reactions & Coulex

All SHARC figures and plots without credit courtesy of Peter Bender and Steffen Cruz, UBC and TRIUMF

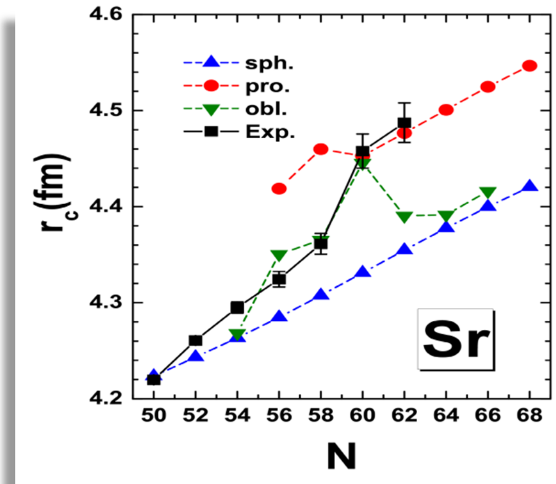






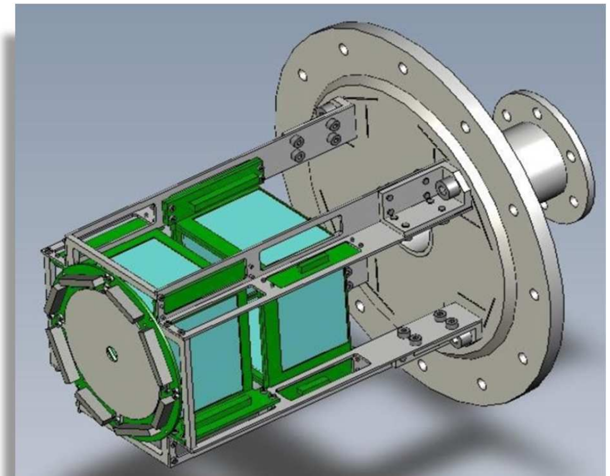
- SHARC is a high-resolution silicon barrel array well-suited for **transfer reaction studies** with TIGRESS to probe the evolution of single particle structure.
- Recently used for low-lying excited state occupation studies in ^{95}Sr. Part of campaign to study *Z=40, N=60* shape-transition region (around Zr, Sr, Mo radioisotopes).
- Sudden change in radius due to competing deformations?

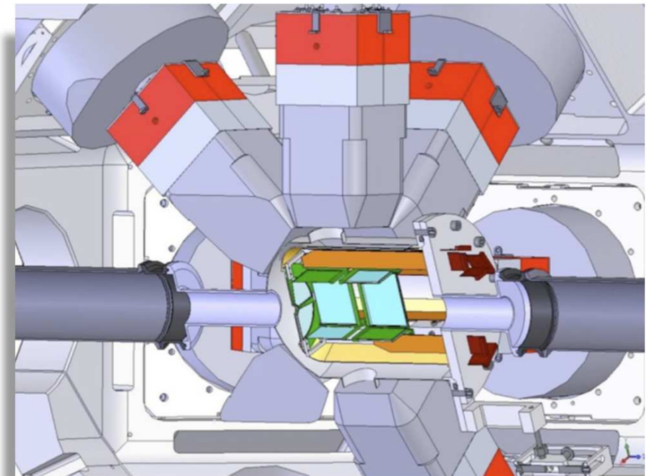
J. Xiang, Nucl. Phys. **A873**, 1 (2012).

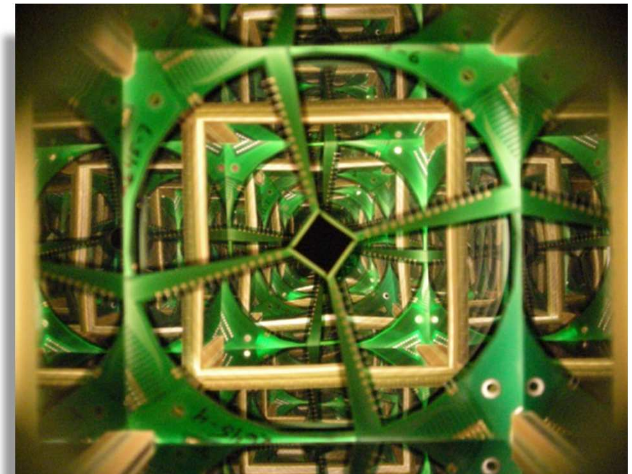


Philip J. Voss
2014 CAP

SHARC Transfer Reactions for Structure Studies: d(^{94}Sr,p)^{95}Sr







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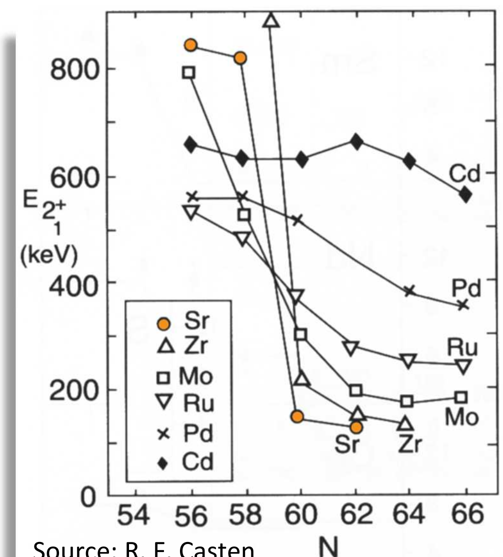
- Dramatic change in *E(2⁺)* is indicative of shape change.



Source: R. F. Casten

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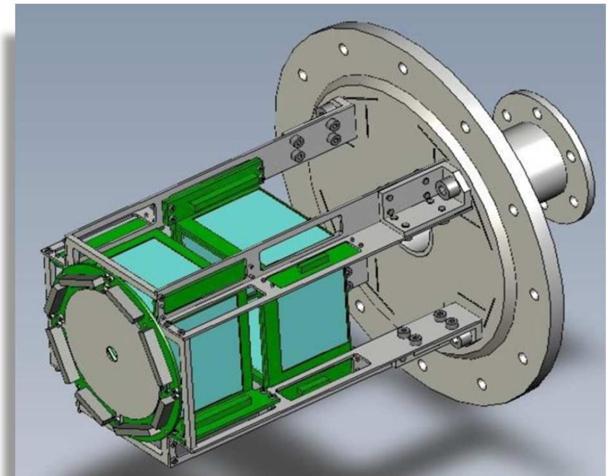

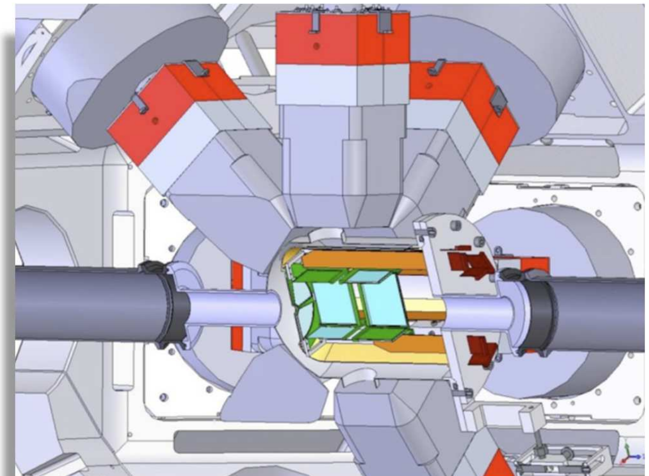

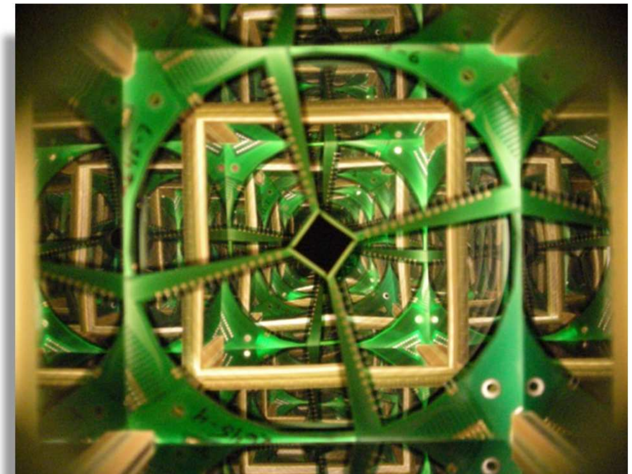

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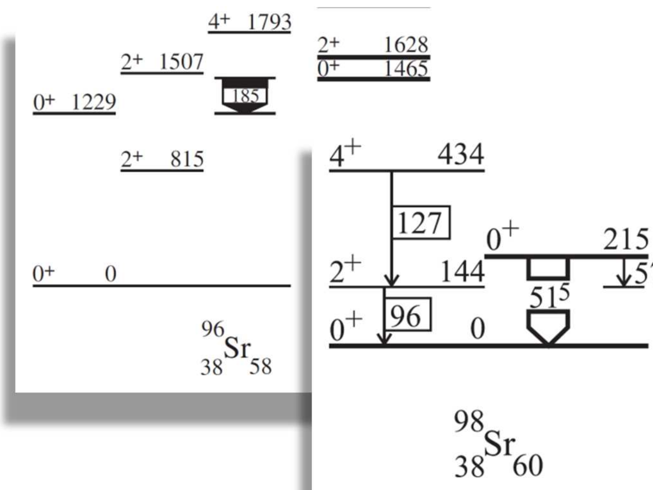
K. Heyde, J.L. Wood, Rev. Mod. Phys. **83**, 1467 (2011).



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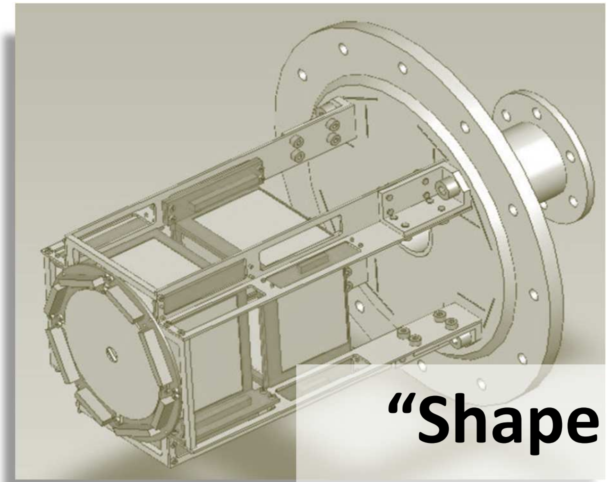

"Shape coexistence in exotic Sr isotopes"

Steffen Cruz, UBC and TRIUMF

10am Tuesday, June 17

C-114

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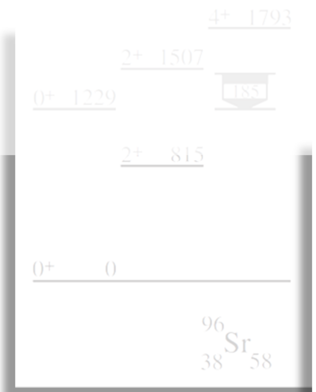

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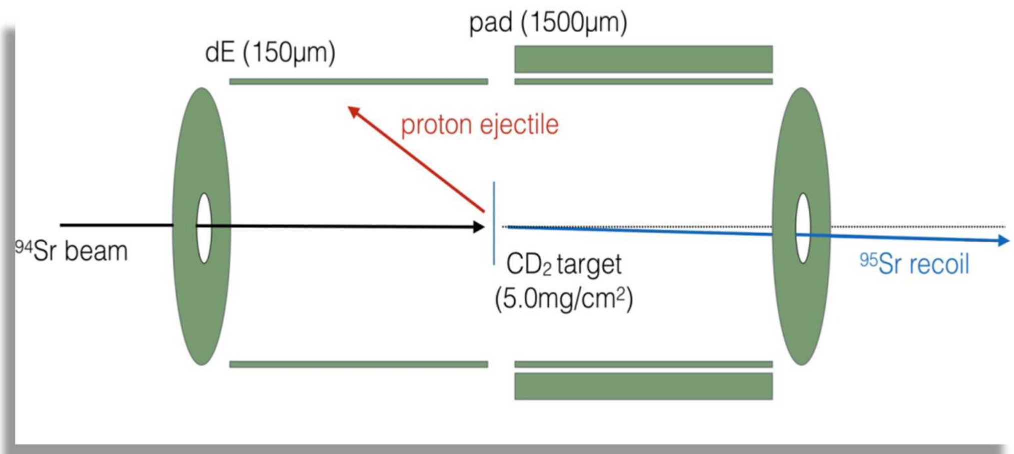
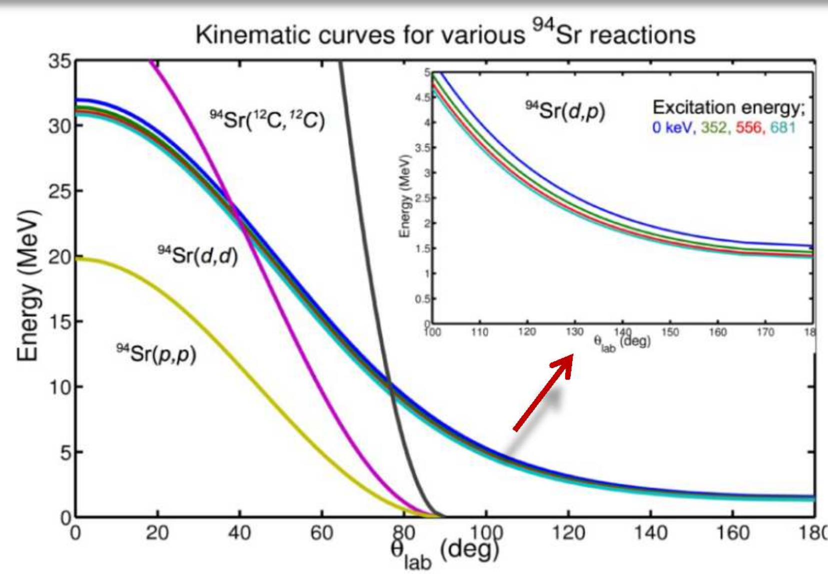
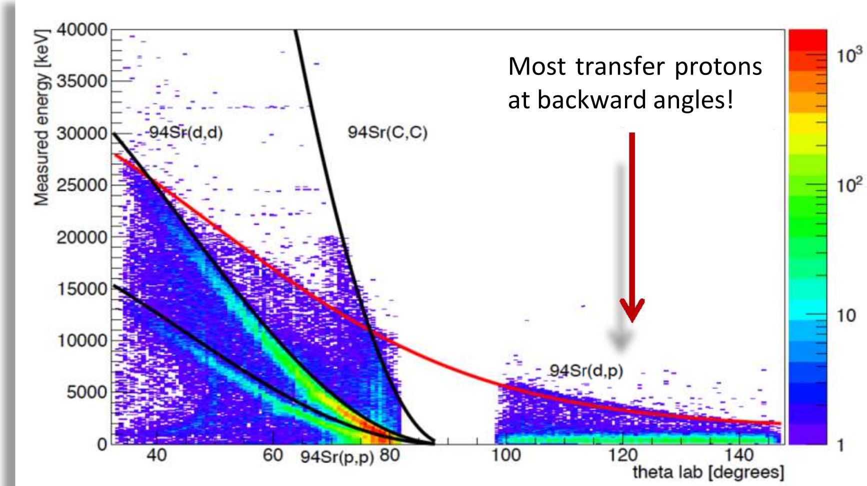
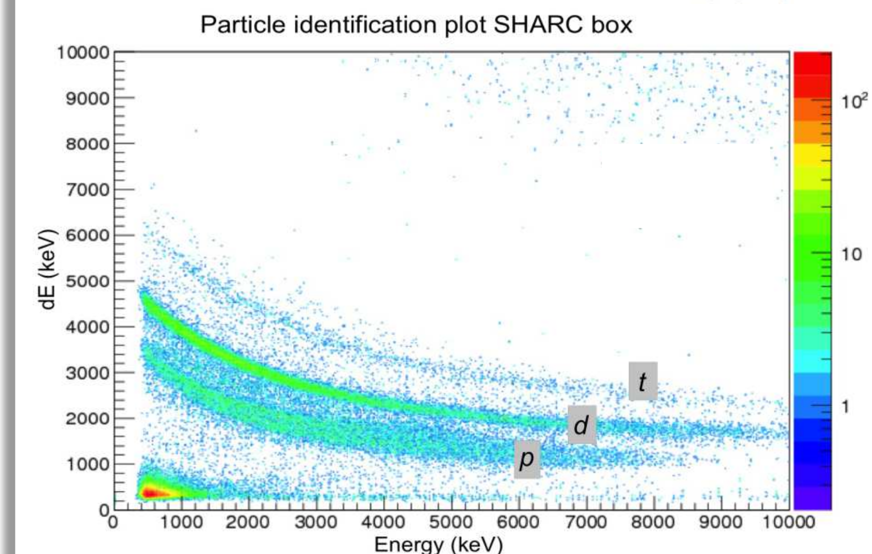
SHARC Transfer Reactions for Structure Studies: $d(^{94}Sr,p)^{95}Sr$





Cannot resolve excited states by proton spectroscopy alone!





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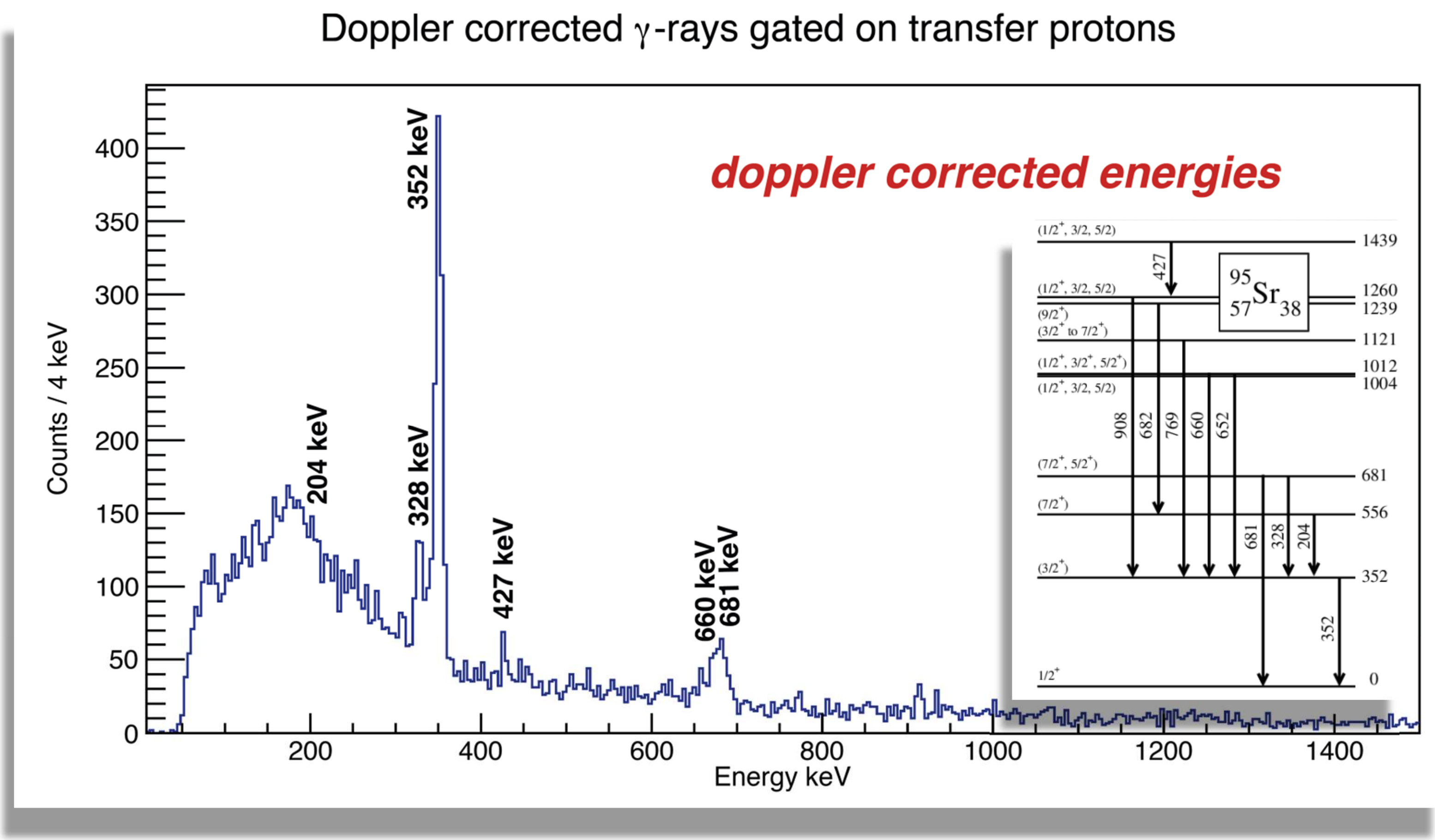
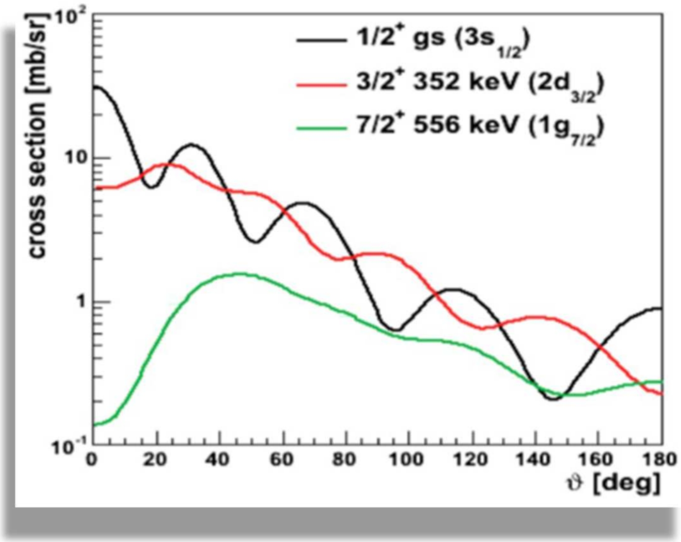
2014 CAP

SHARC Transfer Reactions for Structure Studies: d(^{94}Sr,p)^{95}Sr



TIGRESS summed gamma-ray spectrum. Doppler-corrected and gated on transfer protons. Evidence for the direct population of at least five excited states in ^{95}Sr.

SHARC Transfer Reactions for Structure Studies: d(^{94}Sr,p)^{95}Sr



- The analysis is in progress; cross sections, angular distributions, and level occupancies will be extracted.
- Continuation of the program with ^{95}Sr(d,p)^{96}Sr measurement this month.

The SHARC Collaboration: Shape Coexistence in Sr Isotopes

R. Krücken, K. Wimmer, P. C. Bender, F. Ames, C. Andreoiu, G. C. Ball, C. S. Bancroft, R. Braid, T. Bruhn, W. Catford, D. S. Cross,C. A. Diget, T. Drake, A. Knapton, K. Kuhn, A. B. Garnsworthy, G. Hackman, J. Lassen, R. Laxdal, M. Marchetto, A. Matta, D. Miller, M. Moukaddam, N. Orr, A. Sanetullaev, C. E. Svensson, C. Unsworth, P. Voss

SPICE: Spectrometer for Internal Conversion Electrons

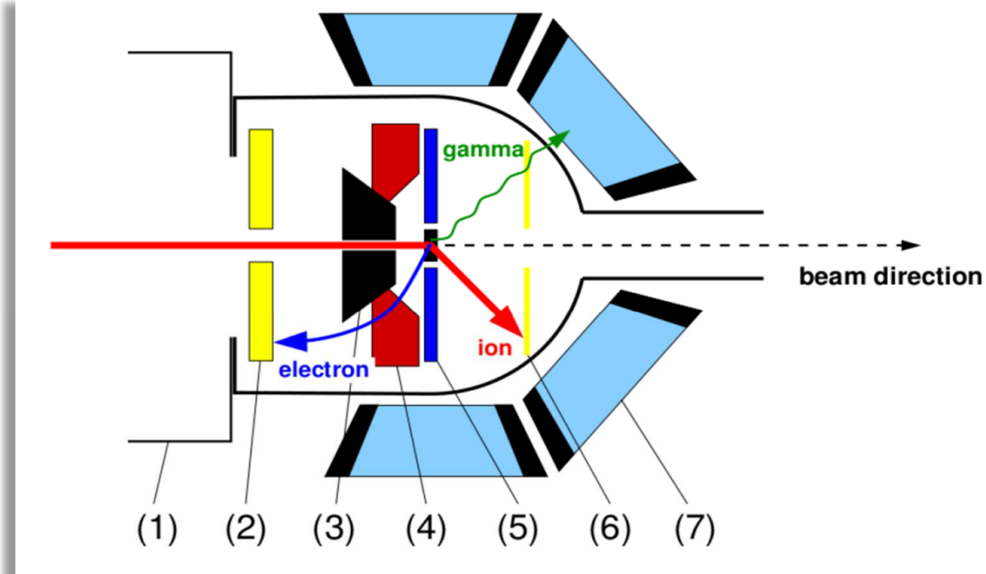
- SPICE provides a means for *E0* transition rate studies via **internal conversion electron spectroscopy** in coincidence with gamma-rays and scattered projectiles.
- *E0* transition rates provide additional information on nuclear structure, in particular **shape coexistence** and **mixing** of nearly-degenerate 0^+ excited states.

$$\rho = \frac{\langle \phi_i | M(E0) | \phi_f \rangle}{eR^2} \simeq \frac{\alpha\beta\Delta\langle r^2 \rangle}{eR^2}$$

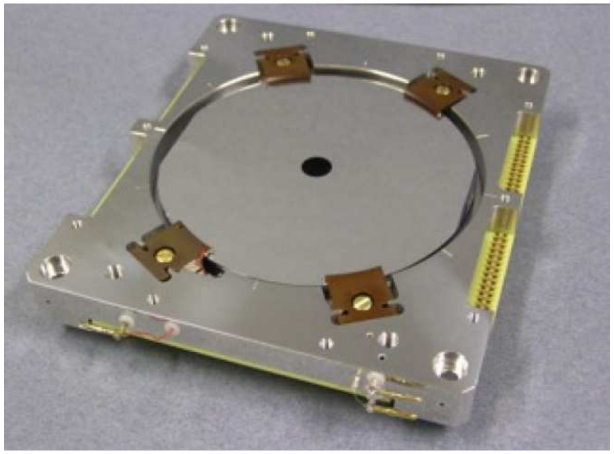
- Measuring the transition rate gives access to the mixing amplitudes α and β between the initial and final states, given knowledge of their deformation ($\Delta\langle r^2\rangle$).

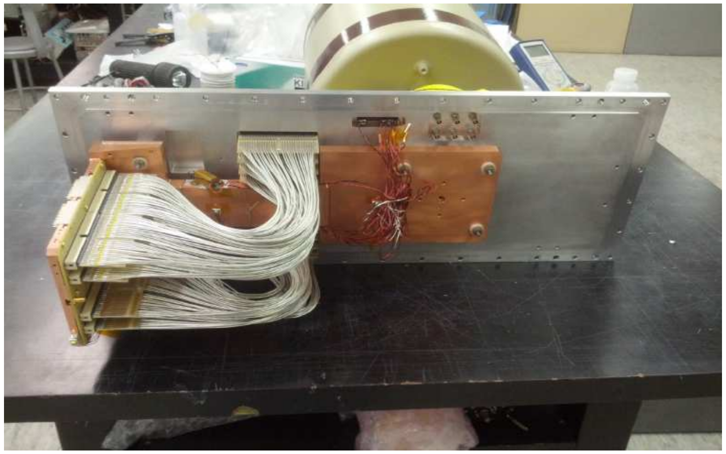
SPICE: Spectrometer for Internal Conversion Electrons

1) Vacuum Vessel
2) Silicon (Li Drifted) Detector
3) Tantalum Photon Shield
4) NdFeB Magnetic Lens
5) 7 Position Target Wheel
6) Silicon DSSD
7) TIGRESS Clover (12 Total)



Figures courtesy of Mohamad Moukaddam, TRIUMF





SFU

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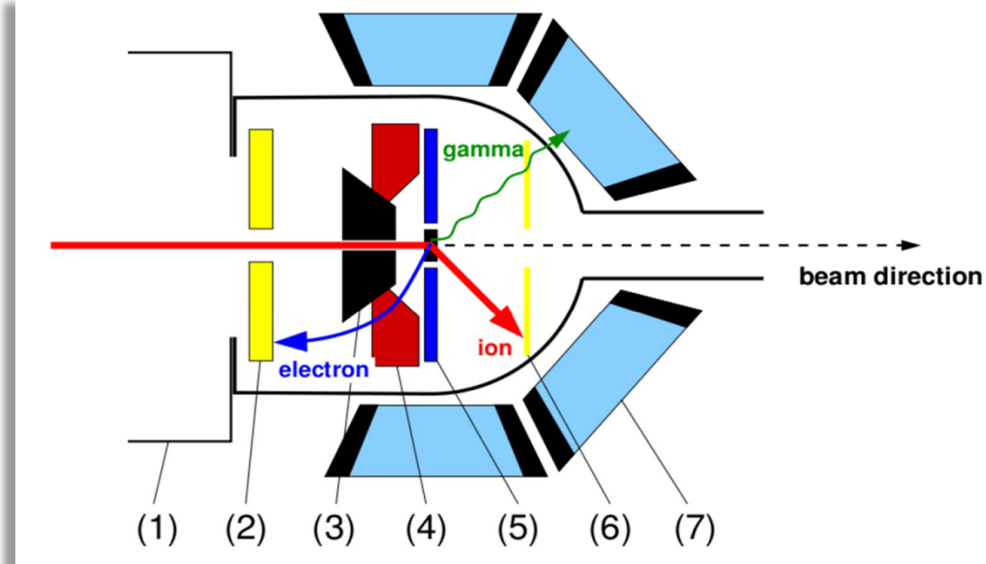

Figures courtesy of Mohamad Moukaddam, TRIUMF

The SPICE Collaboration:

L.J.Evitts, A.B.Garnsworthy, S.Ketelhut, C.Bolton, J.Witmer, G.C.Ball, R.Churchman, M.Constable, G.Hackman, R.Henderson, L.Kurchaninov, P.C.Bender, A.Knapton, W.Korten, R.Krücken, D.Miller, W.J.Mills, M.M.Rajabali, C.Unsworth, C.E.Svensson, E.T.Rand, R.Dunlop, V.Bildstein, G.A.Demand, G.Deng, M.Dunlop, A.Finlay, P.E.Garrett, B.Hadinia, B.Jigmeddorj, A.T.Laffoley, A.Diaz Varela, J.Wong, C. Andreoiu, P. Voss

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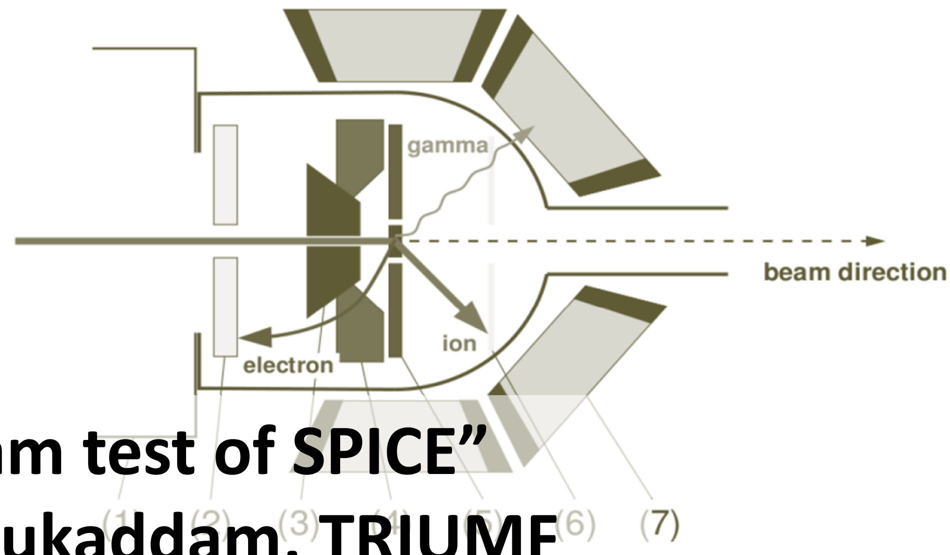


Figures courtesy of Mohamad Moukaddam, TRIUMF

"First in-beam test of SPICE"
Mohamad Moukaddam, TRIUMF
2:30pm Tuesday, June 17
C-203

The SPICE Collaboration:

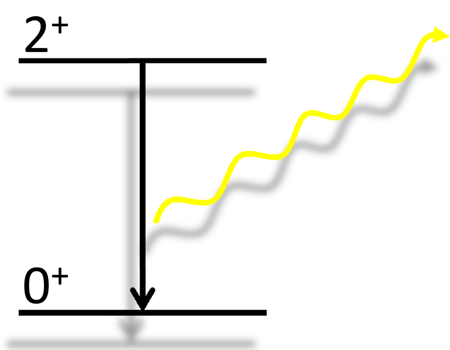
L.J.Evitts, A.B.Garnsworthy, S.Ketelhut, C.Bolton, J.Witmer, G.C.Ball, R.Churchman, M.Constable, G.Hackman, R.Henderson, L.Kurchaninov, P.C.Bender, A.Knapton, W.Korten, R.Krücken, D.Miller, W.J.Mills, M.M.Rajabali, C.Unsworth, C.E.Svensson, E.T.Rand, R.Dunlop, V.Bildstein, G.A.Demand, G.Deng, M.Dunlop, A.Finlay, P.E.Garrett, B.Hadinia, B.Jigmeddorj, A.T.Laffoley, A.Diaz Varela, J.Wong, C. Andreoiu, P. Voss

Electromagnetic Transition Rate Measurements

Electromagnetic transition rate measurements provide a probe of nuclear structure:

- Lend **experimental** insight into the evolution of nuclear structure.
- Provide a sensitive benchmark for advanced **theoretical models**.

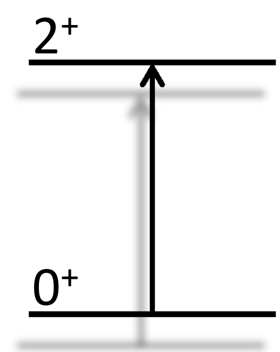
Lifetime Measurements



$$\frac{1}{\tau(E2;2_1^+ \rightarrow 0_{gs}^+)} \propto E(2_1^+)^5 B(E2;2_1^+ \rightarrow 0_{gs}^+)$$

$$B(E2;I_i \rightarrow I_f) = \frac{1}{2J_i+1}\langle I_f||E2||I_i\rangle^2 \propto \beta^2$$

Coulomb Excitation

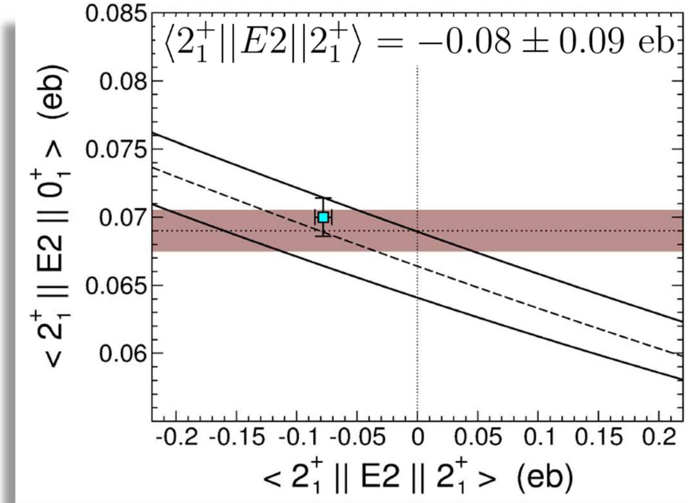


$$P_{0_1^+\rightarrow 2_1^+} \propto B(E2;0_1^+ \rightarrow 2_2^+)[1+\alpha Q(2_1^+)]$$

$$Q(2^+) \propto \left\langle 2^+||E2||2^+\right\rangle \propto \beta$$

Electromagnetic Transition Rate Measurements

J. N. Orce et al. PRC **86,** 041303(R) (2012).



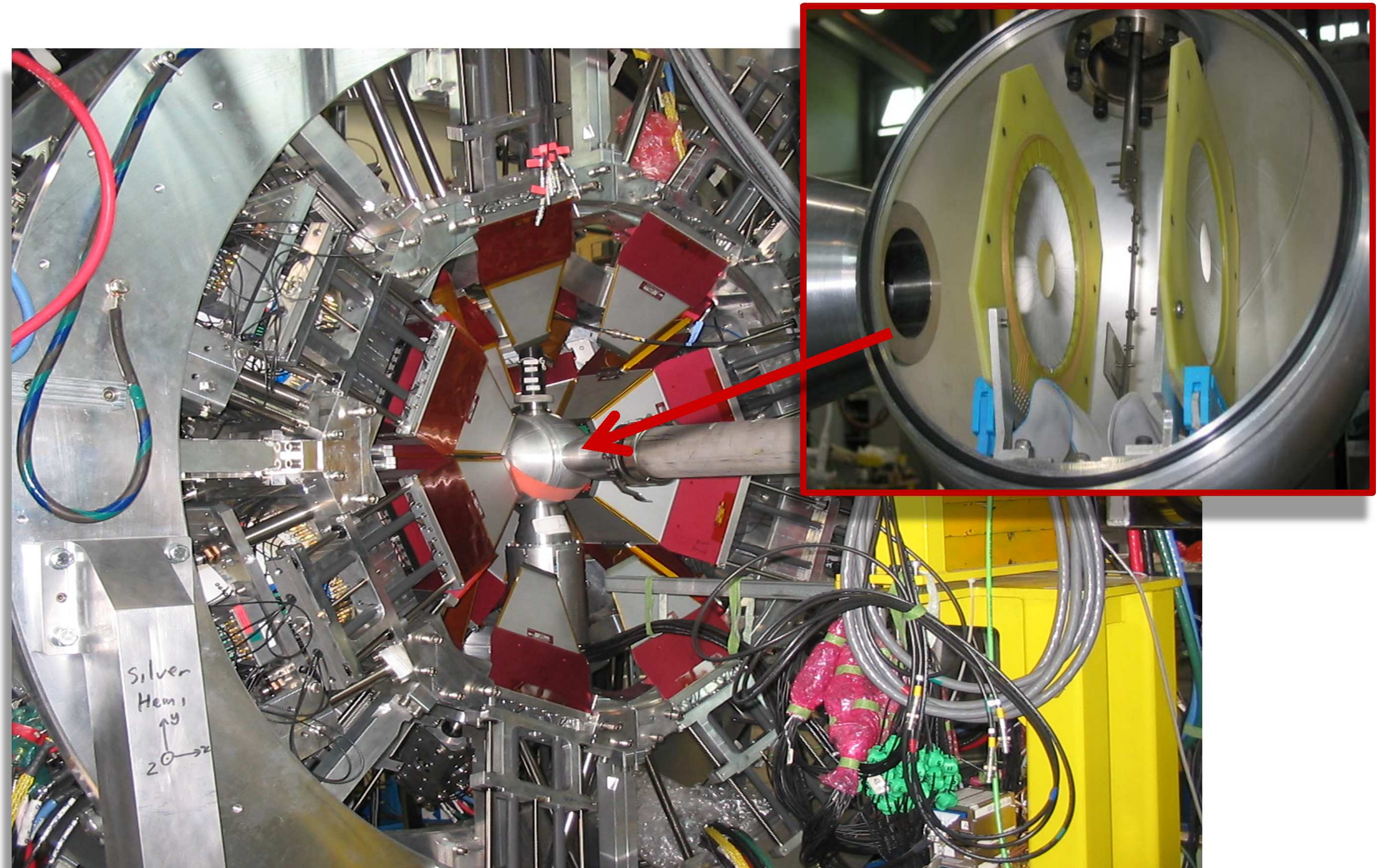
A powerful technique: Simultaneous measurement of lifetimes and excitation probabilities to probe quadrupole deformation with the same setup to minimize systematic uncertainties!

$$P_{0_1^+\rightarrow 2_1^+} \propto B(E2; 0_1^+ \rightarrow 2_2^+)[1 + \alpha Q(2_1^+)]$$

Lifetime Measurements

Coulomb Excitation

Bambino for Coulomb Excitation: ^{196}Pt(^{11}Be, ^{11}Be*) ^{196}Pt*



Precision *B(E1)* Transition Strength Measurements in ^{11}Be

Neutron-rich ^{11}Be provides a complex testing ground for *ab initio* theoretical models:

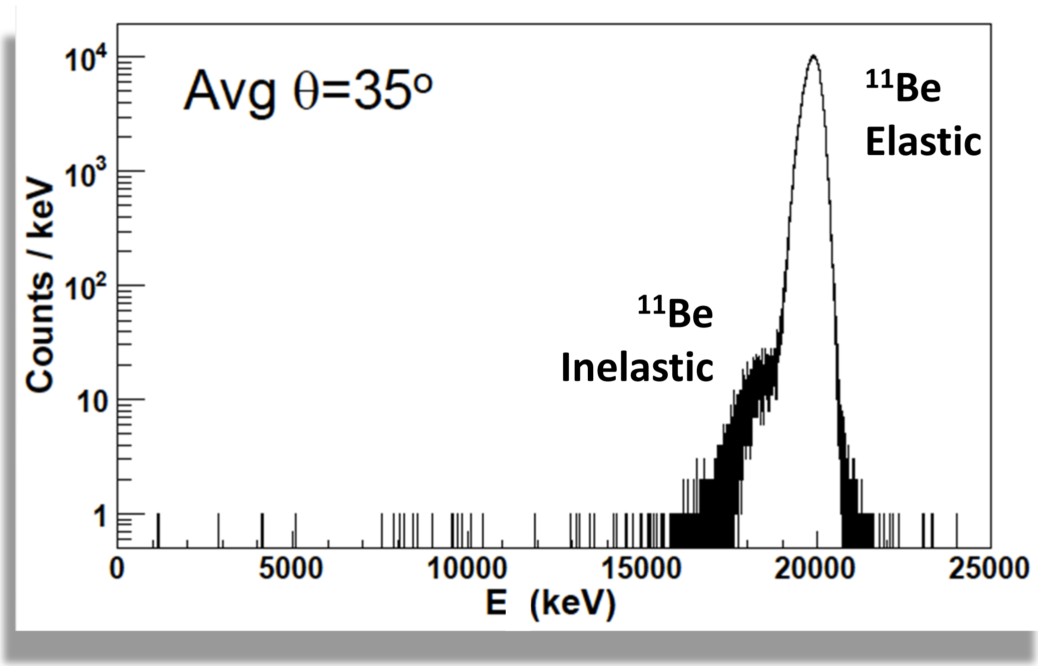
- Has **largest *E1* transition strength** (~3 W.U.) between bound states of nuclear chart.
- Decoupling phenomena (^{10}Be + n) → **one-neutron halo** nucleus.
- Ground state has **inverted parity** (½$^+$) → unpaired neutron should fill the $1p_{1/2}$ orbital.
- Is **weakly bound** with only one excited state.

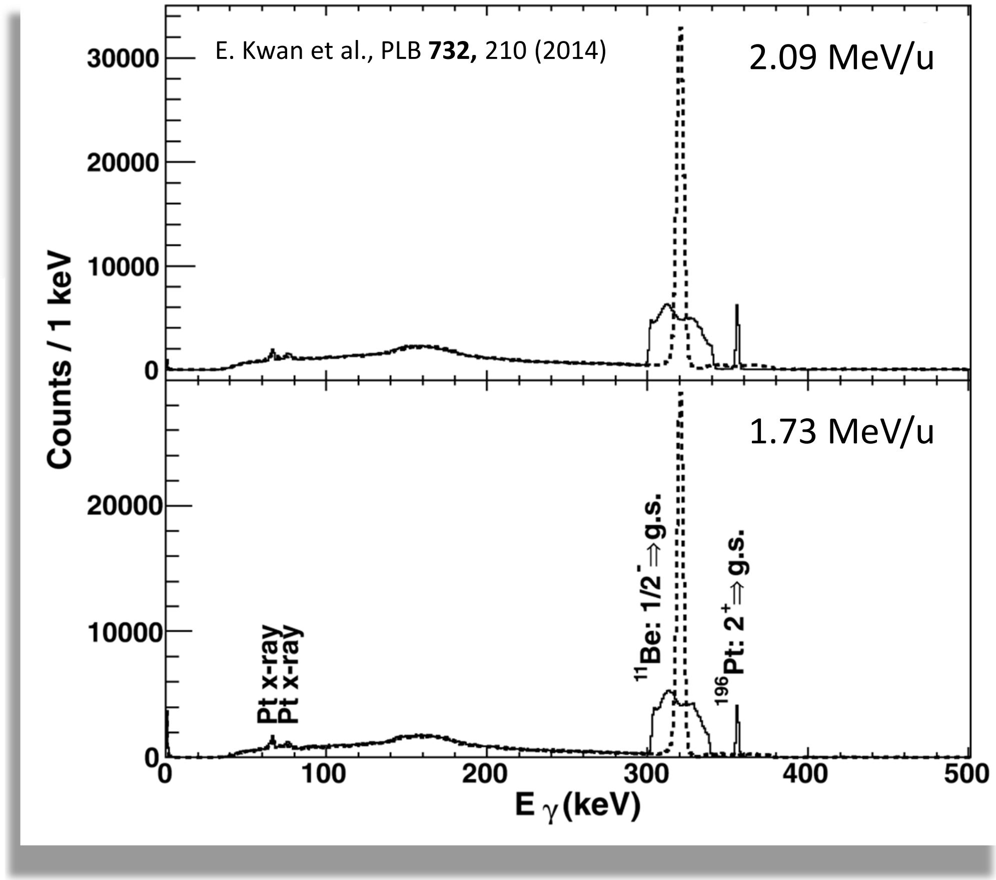
Table courtesy of Greg Hackman, TRIUMF

B(E1)	Source	Ref.
0.116(12)	DSAM lifetime measurement	PRC 28, 497 (1983)
0.094(11) 0.079(8) 0.099(11) 0.105(12)	Intermediate-energy Coulomb excitation	PRC 56,R1 (1997) Ibid PLB 394, 11 (1997) PLB 650, 124 (2007)
0.15	Phenomenological cluster	NPA 596, 171 (1986)
0.006	Ab Initio NCSM (wrong g.s.)	PRC 71, 044312 (2005)
0.018	NCSM with resonating groups	PRL 101, 092501 (2008)

Precision *B(E1)* Transition Strength Measurements in ^{11}Be

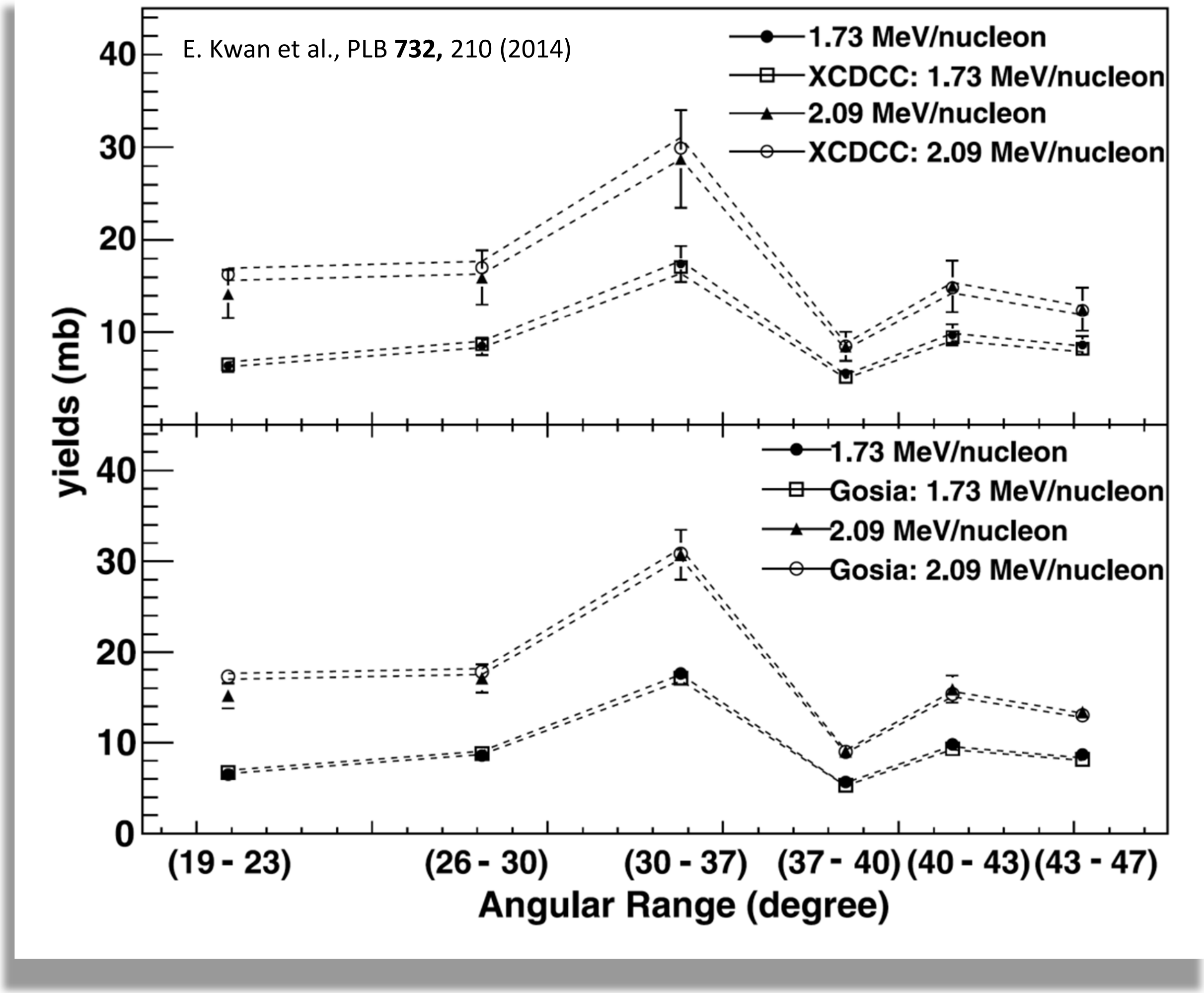
- First low-energy Coulomb excitation study of ^{11}Be at TRIUMF.
- Used both semi-classical and quantum mechanical reaction codes to analyze data.





Scattered ^{11}Be energy spectrum in Bambino in coincidence with gamma-ray energy spectra in TIGRESS in the laboratory (solid) and projectile (dashed) frames.

Precision *B(E1)* Transition Strength Measurements in ^{11}Be



Comparison of experimental (closed) to calculated yields (open) in six different angular regions.

B(E1) = 0.102(2) e^2fm^2 (Gosia) and 0.098(4) e^2fm^2 (FRESCO); results in uncertainties < 5 %!

		^{10}Be	^{11}Be($\frac{1}{2}^-$)		^{11}Be($\frac{1}{2}^+$)	
	N_{max}	$E_{g.s.}$	E	E_{th}	E	E_{th}
NCSM [14,15]	8/9	−57.06	−56.95	0.11	−54.26	2.80
NCSM [14,15],[a]	6/7	−57.17	−57.51	−0.34	−54.39	2.78
NCSM/RGM[a]			−57.59	−0.42	−57.85	−0.68
Expt.		−64.98	−65.16	−0.18	−65.48	−0.50

S. Quaglioni et al., PRL **101**, 092501 (2008).

With TIGRESS coupled to Bambino, precision transition rate studies provide extremely sensitive tests of state-of-the-art theoretical models like **NCSM+Continuum+NNN**.

Precision *B(E1)* Transition Strength Measurements in ^{11}Be

Physics Letters B 732 (2014) 210–213

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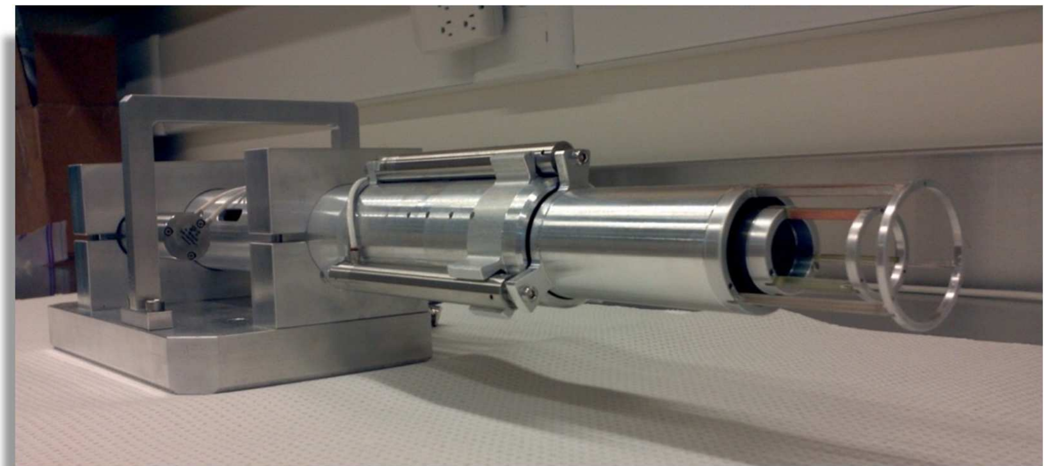
Precision measurement of the electromagnetic dipole strengths in ^{11}Be

CrossMark

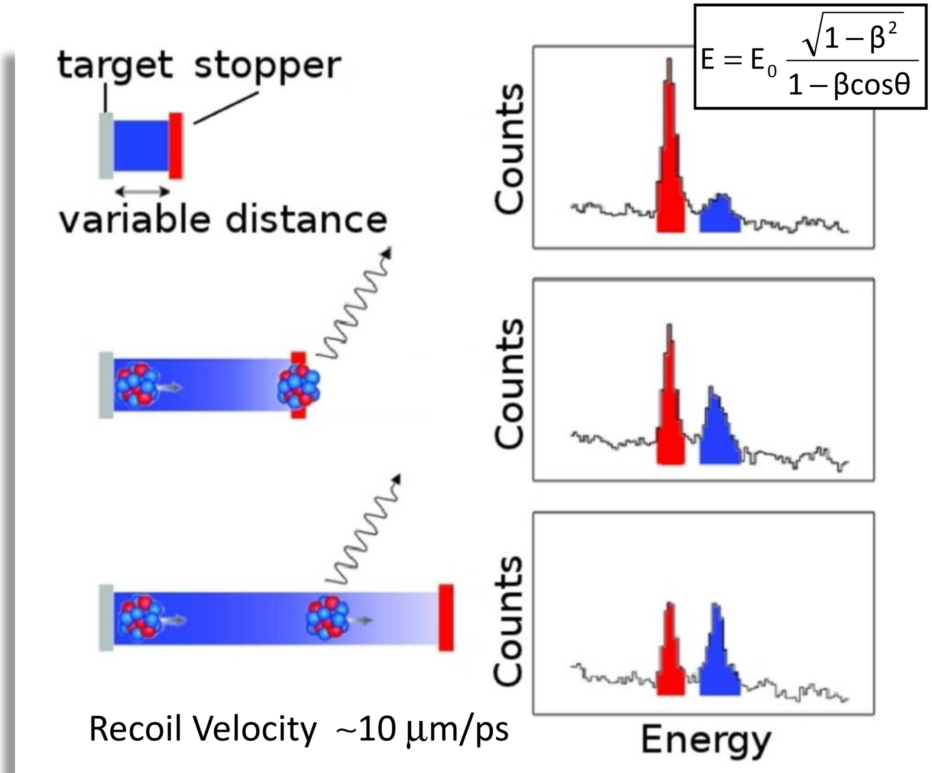
E. Kwan[a,*,1], C.Y. Wu[a,*], N.C. Summers[a], G. Hackman[b], T.E. Drake[c], C. Andreoiu[d], R. Ashley[d], G.C. Ball[b], P.C. Bender[b], A.J. Boston[e], H.C. Boston[e], A. Chester[d], A. Close[b], D. Cline[f], D.S. Cross[d], R. Dunlop[g], A. Finlay[g], A.B. Garnsworthy[b], A.B. Hayes[f], A.T. Laffoley[g], T. Nano[h], P. Navrátil[b], C.J. Pearson[b], J. Pore[d], S. Quaglioni[a], C.E. Svensson[g], K. Starosta[d], I.J. Thompson[a], P. Voss[d], S.J. Williams[b,1], Z.M. Wang[d,b]

[a] *Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA 94550, USA*
[b] *TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, V6T 2A3, Canada*
[c] *Department of Physics, University of Toronto, Toronto, Ontario, M5S 1A7, Canada*
[d] *Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, V5A 1S6, Canada*
[e] *Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[f] *Department of Physics & Astronomy, University of Rochester, Rochester, NY, 14627, USA*
[g] *Department of Physics, University of Guelph, Guelph, Ontario, N1G 2W1, Canada*
[h] *University of Windsor, Windsor Ontario, N9B 3P4, Canada*

The TIGRESS Integrated Plunger (TIP)

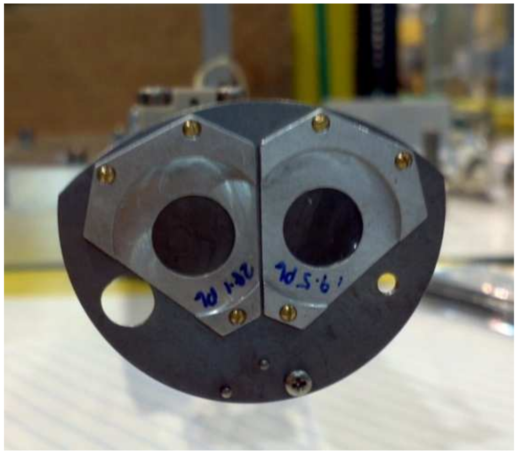


TIP is a new TRIUMF experimental program for Recoil Distance Method lifetime studies.



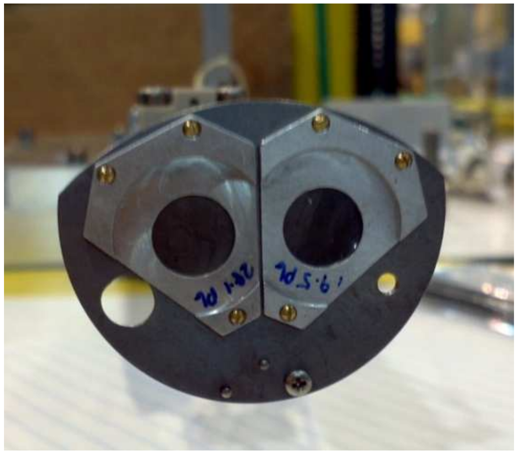
TIP offers great flexibility for nuclear structure studies via **Doppler-shift lifetime** and **Coulomb excitation** measurements utilizing a diverse set of ancillary charged-particle detectors and a variety of reaction mechanisms.

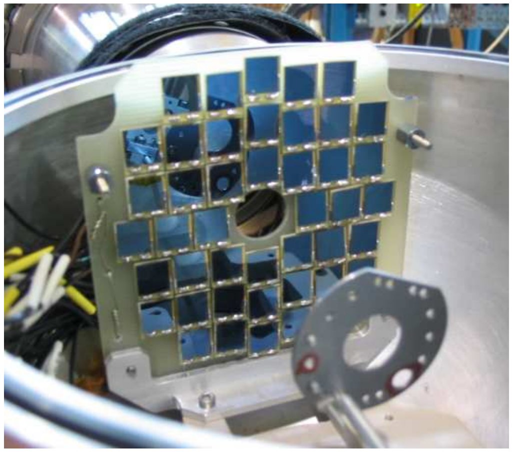
TIP Target Wheel and Ancillary Detectors



- Rotating G10 target wheel accommodates two targets and beam-tuning apertures.
- Ancillary charged-particle detector systems for the TIP scattering chamber.
  - Modular, 44-element silicon PIN diode array for target recoil tagging enabling **Doppler-shift lifetime measurements**.
  - Annular silicon S3 for high-resolution kinematic reconstruction of inelastic scattering partners from **Coulomb excitation measurements**.
  - 24-element CsI(Tl) scintillator wall for particle identification via pulse shape analysis following **fusion-evaporation reactions**.

TIP Target Wheel and Ancillary Detectors





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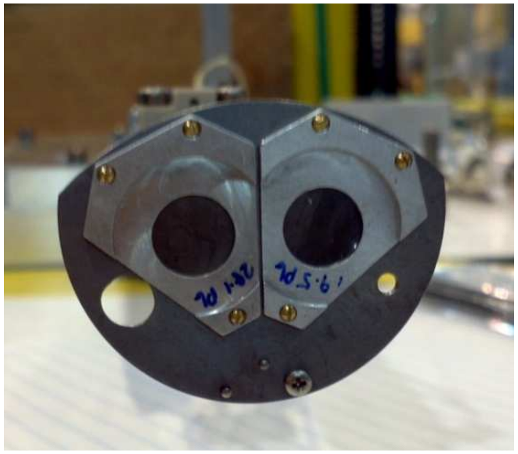
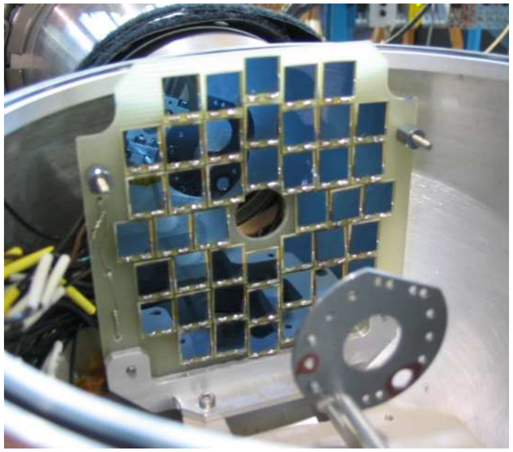


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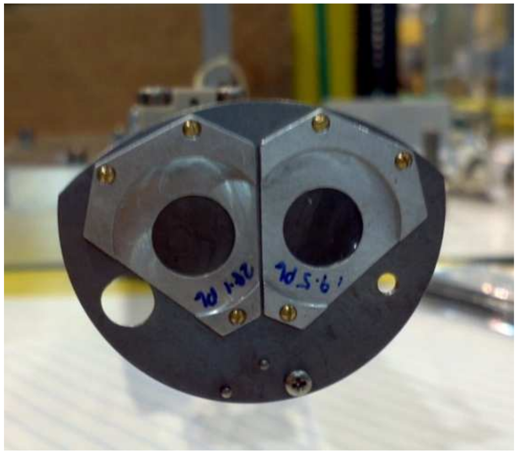
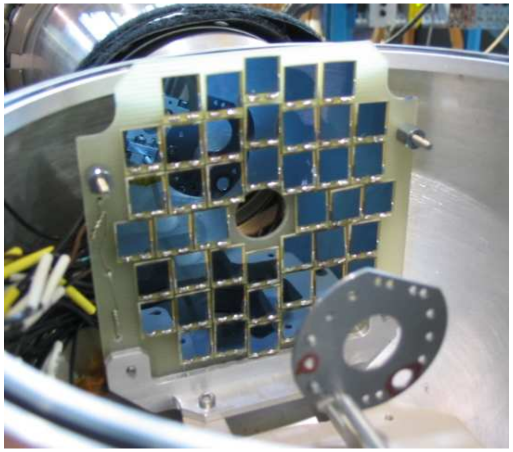

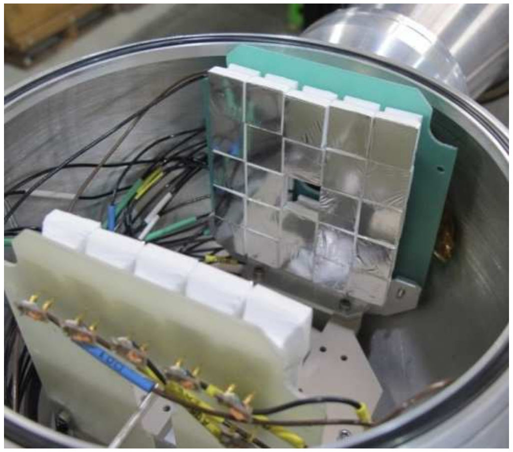

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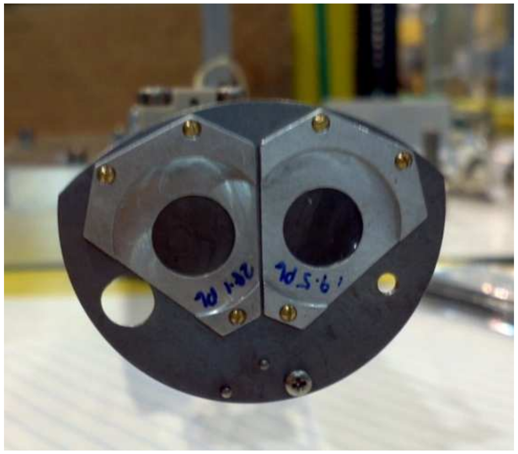
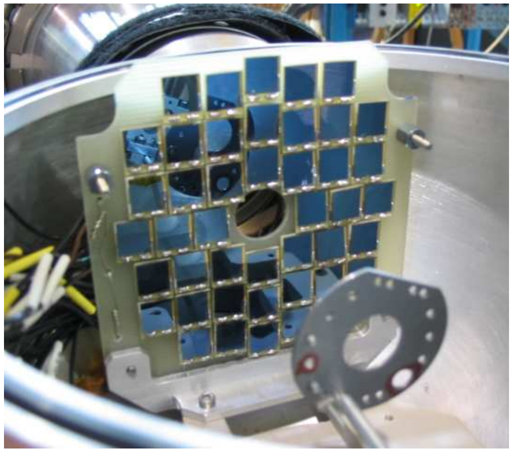

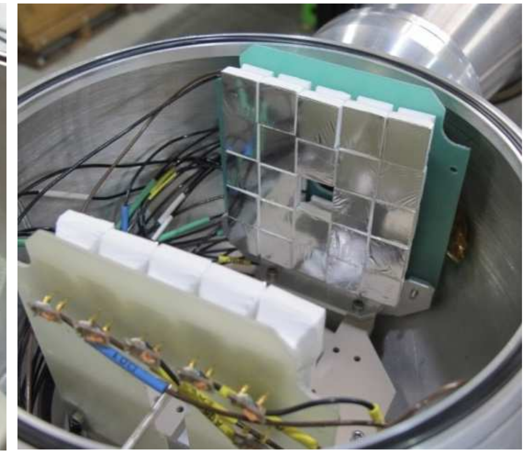

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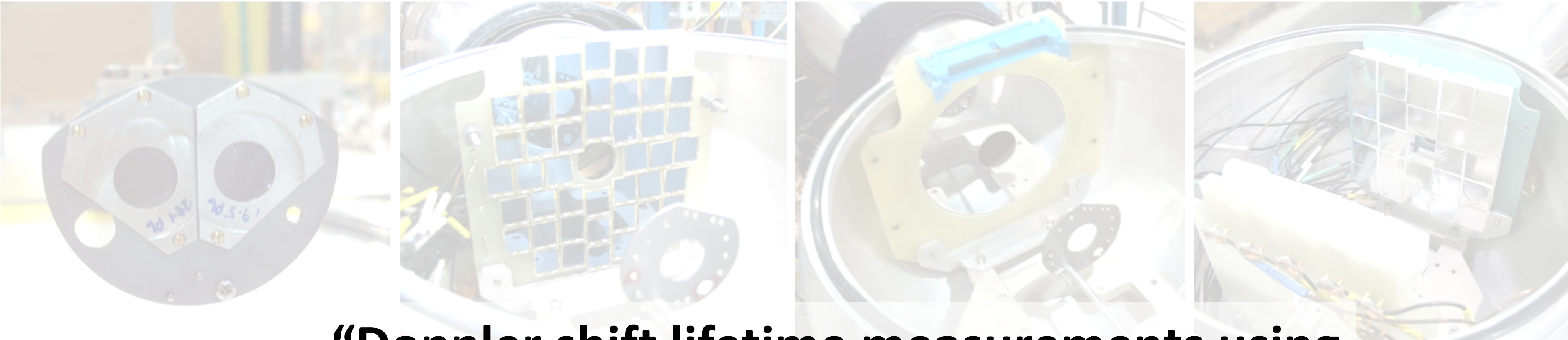

"Doppler shift lifetime measurements using the TIGRESS Integrated Plunger device"

Aaron Chester, SFU

2:15pm Tuesday, June 17

C-203

- Rotating G10 targ… ng apertures.
- Ancillary charged-particle dete… scattering chamber.
  - Modular, 44-element … t recoil tagging enabling **Doppler-shift lifetime measurements**.
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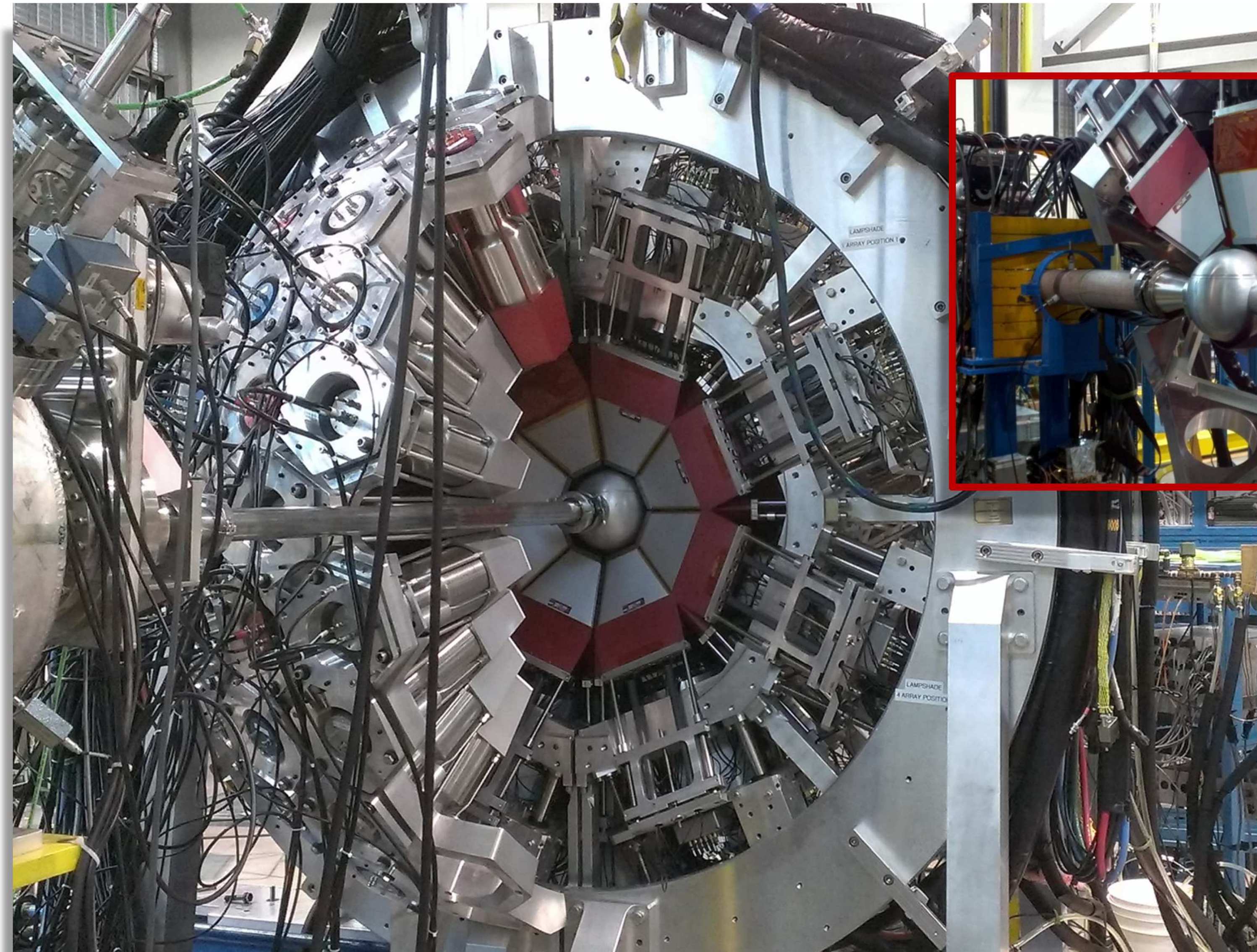
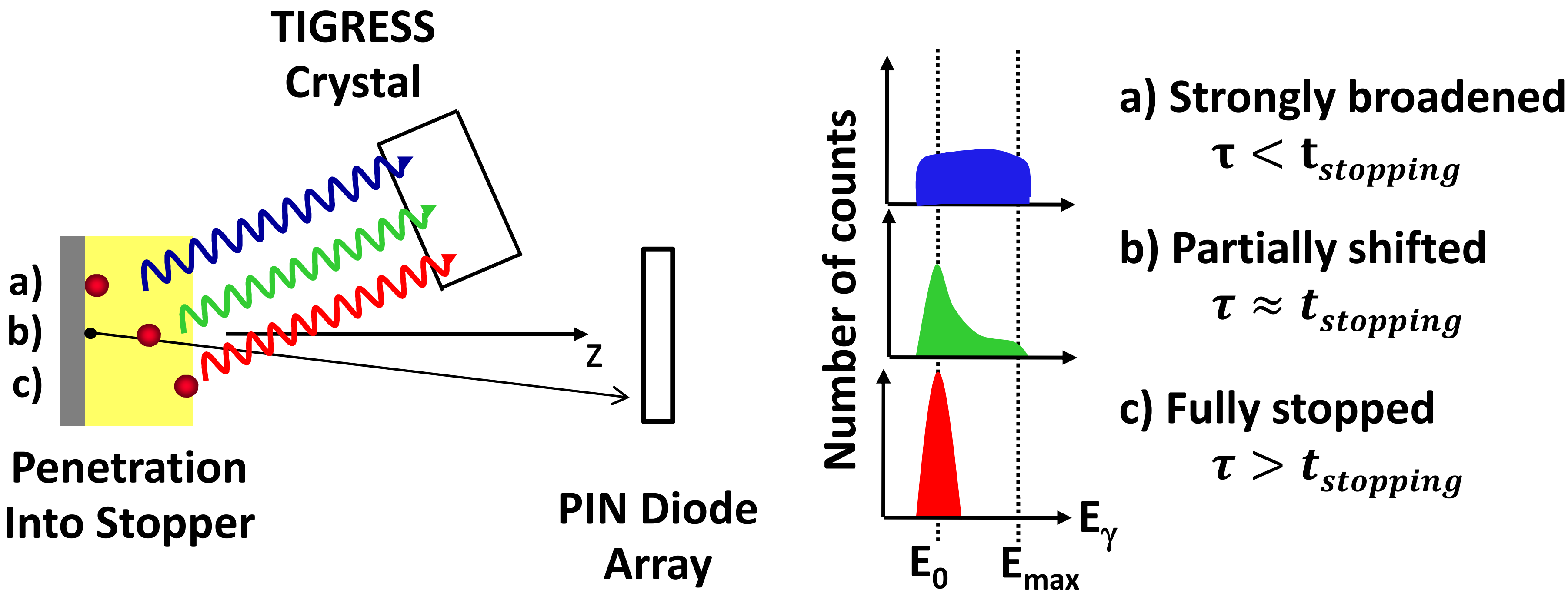
TIP for Doppler Shift Attenuation Measurements

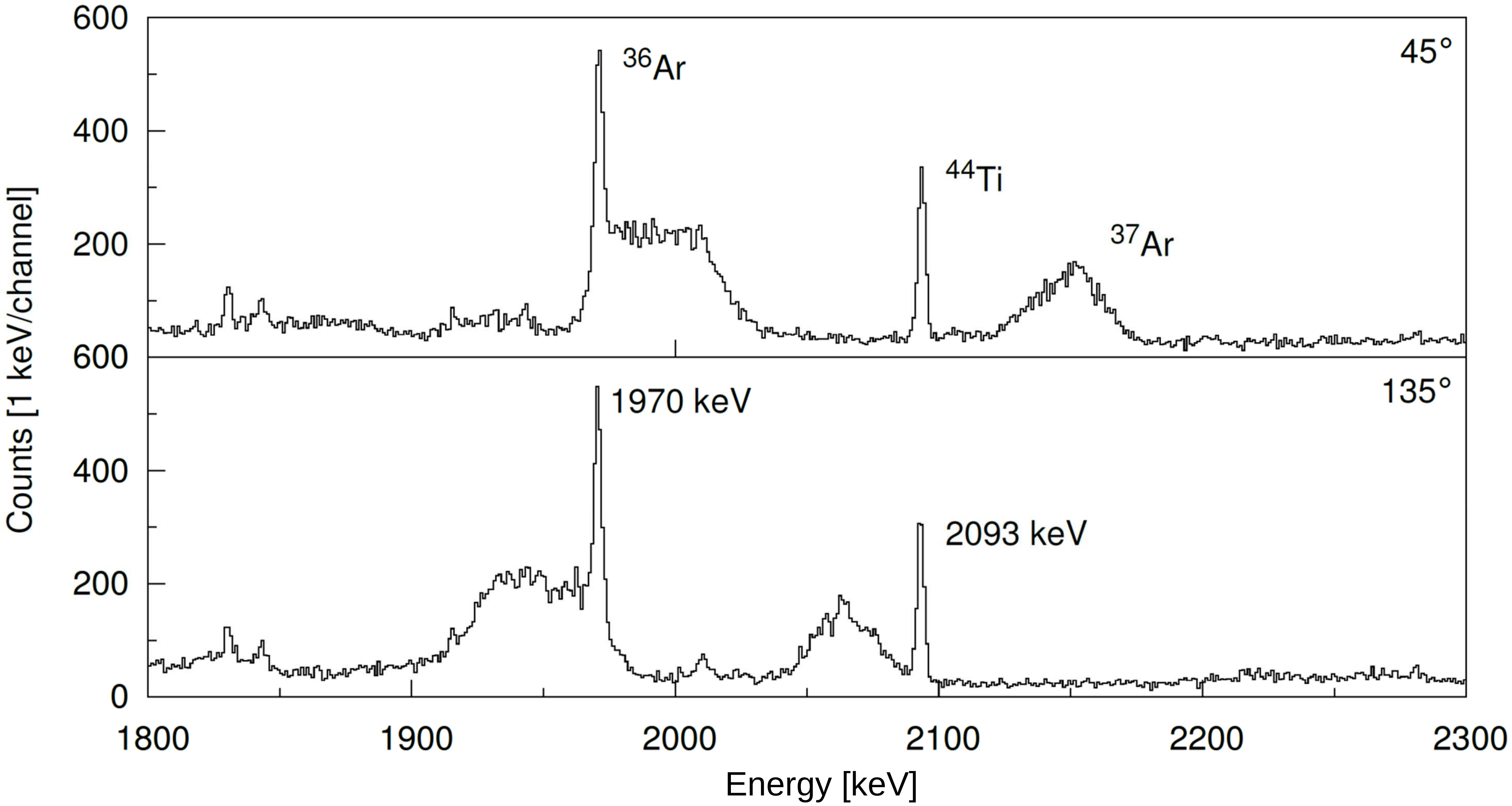


^{36}Ar Doppler Shift Attenuation Measurements



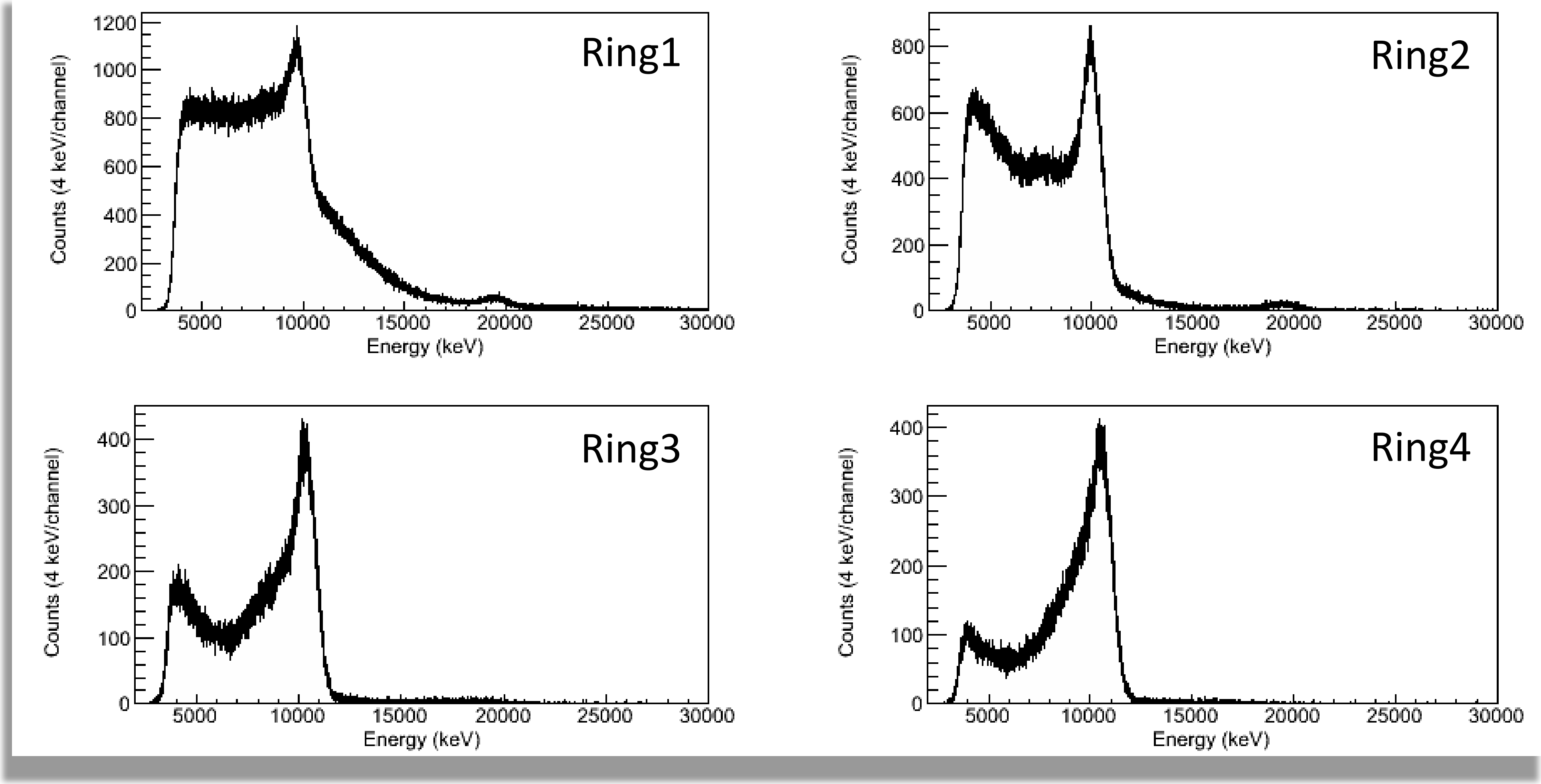
- ^{36}Ar Coulomb excited on carbon layer. Gold backing provided stopping.
- 44-element silicon diode array for particle-gamma coincidence trigger.

Gold Target DSAM Line Shape of ^{36}Ar



SFU

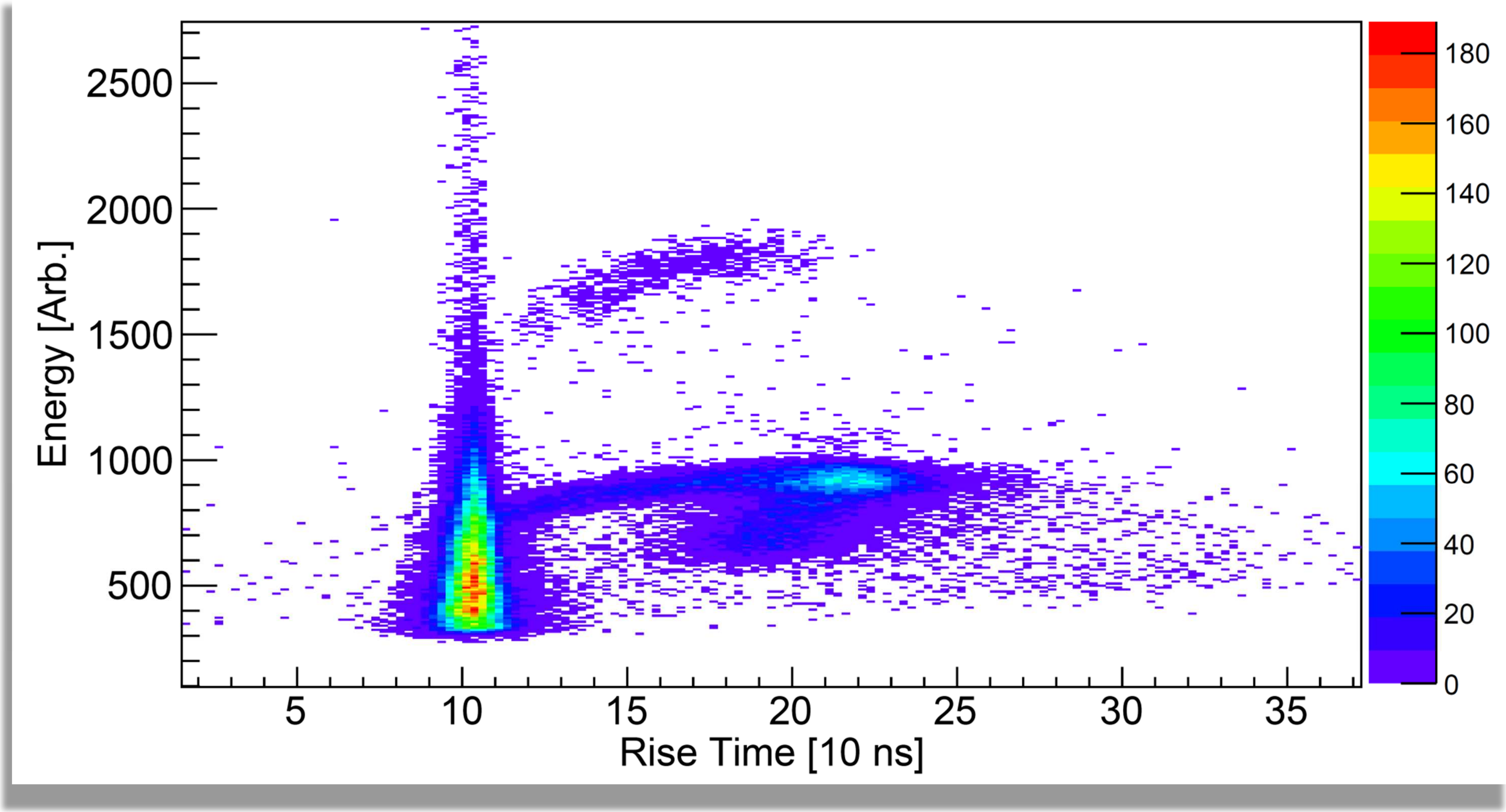
Recoiling Charged Particle Energies



Evidence of two reaction mechanisms producing recoiling charged particles.

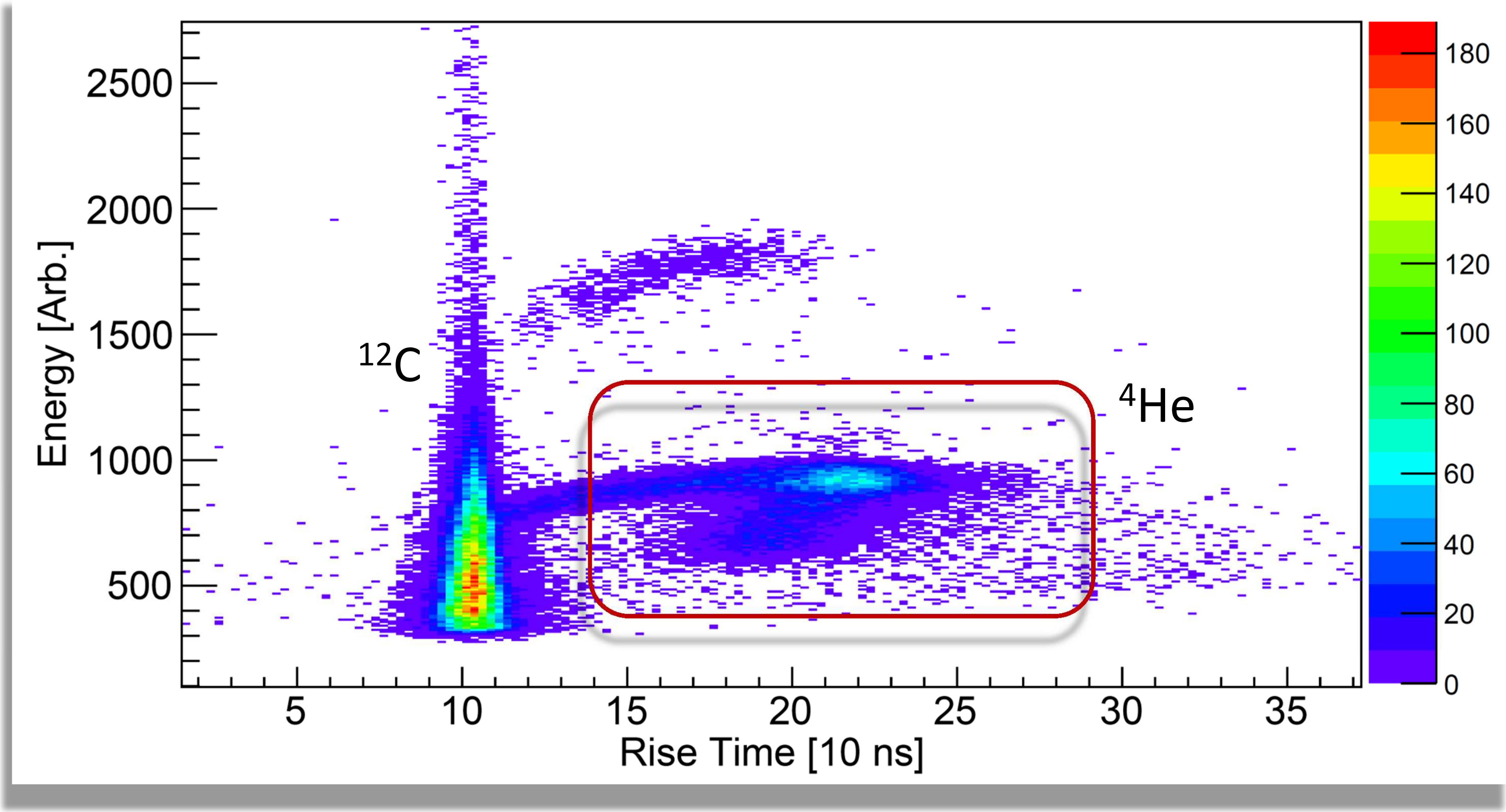
Philip J. Voss
2014 CAP

Recoiling Charged Particle Rise Times



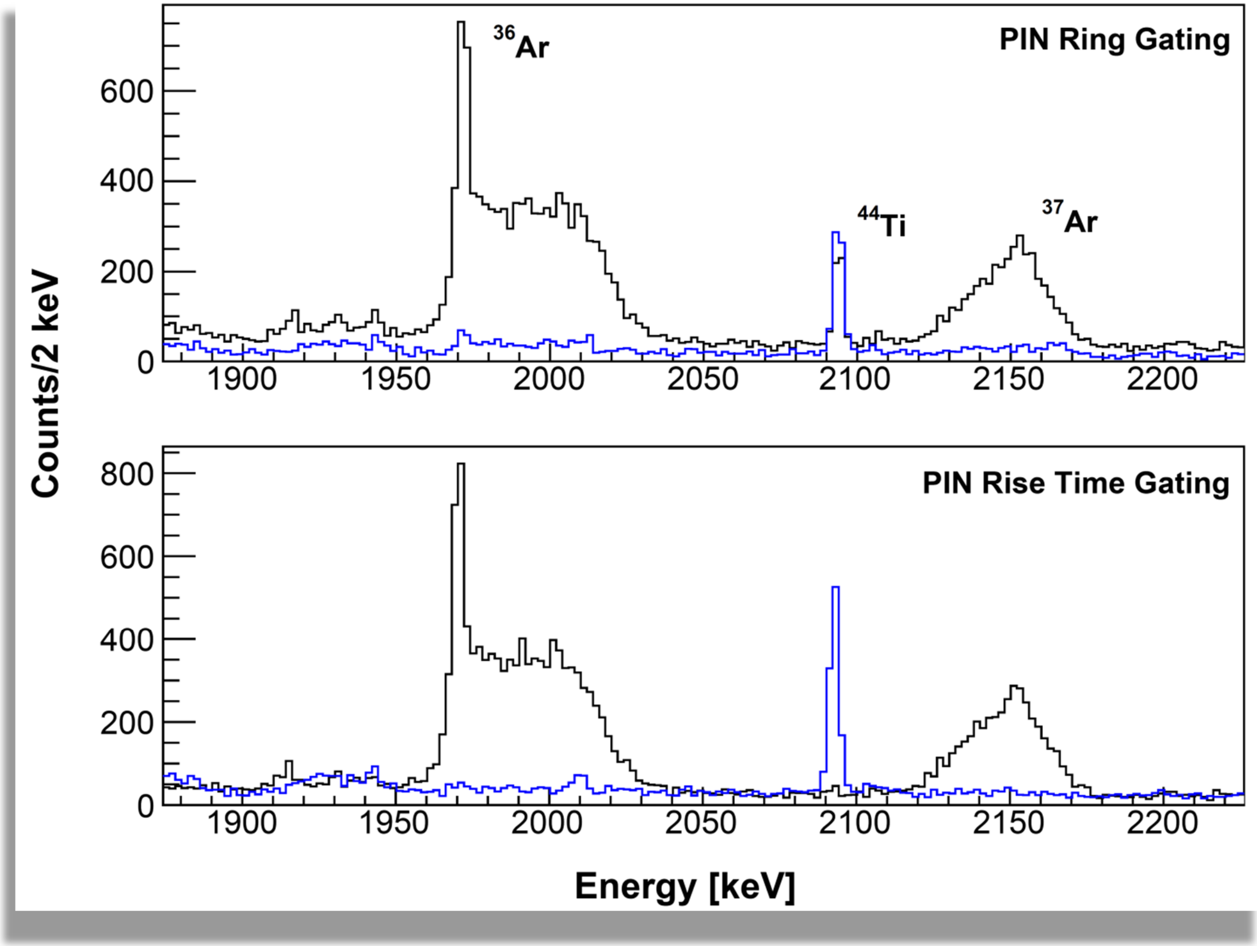
Further evidence from digital pulse shape analysis of signal rise times.

Recoiling Charged Particle Rise Times



Further evidence from digital pulse shape analysis of signal rise times.

Particle-Gamma Coincidences: Enhanced Exp. Sensitivity



Gamma-ray energy spectra in coincidence with particles in the silicon PIN diode wall:

- Top → Recoiling charged particles detected in **Rings 1, 2** and **Rings 3, 4**.
- Bottom → **Carbon** and **alpha-particle** recoils via rise-time separation.

The TIP and TIGRESS Collaborations

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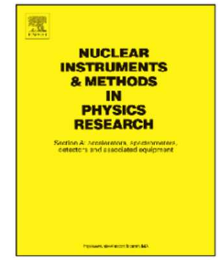


The TIGRESS Integrated Plunger ancillary systems for electromagnetic transition rate studies at TRIUMF

CrossMark

P. Voss [a,*], R. Henderson [b], C. Andreoiu [a], R. Ashley [a], R.A.E. Austin [c], G.C. Ball [b], P.C. Bender [b], A. Bey [b], A. Cheeseman [b], A. Chester [a], D.S. Cross [a], T.E. Drake [d], A.B. Garnsworthy [b], G. Hackman [b], R. Holland [e], S. Ketelhut [b], P. Kowalski [e], R. Krücken [b], A.T. Laffoley [f], K.G. Leach [f], D. Miller [b], W.J. Mills [b], M. Moukaddam [b], C.J. Pearson [b], J. Pore [a], E.T. Rand [f], M.M. Rajabali [b], U. Rizwan [a], J. Shoults [e], K. Starosta [a,**], C.E. Svensson [f], E. Tardiff [b], C. Unsworth [b], K. Van Wieren [e], Z.-M. Wang [a,b], J. Williams [a]

[a] *Department of Chemistry, Simon Fraser University, Burnaby, BC, Canada V5A 1S6*
[b] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3*
[c] *Department of Astronomy and Physics, St. Mary's University, Halifax, NS, Canada B3H 3C3*
[d] *Department of Physics, University of Toronto, Toronto, ON, Canada M5S 1A7*
[e] *Science Technical Center, Simon Fraser University, Burnaby, BC, Canada V5A 1S6*
[f] *Department of Physics, University of Guelph, Guelph, ON, Canada N1G 2W1*

This work is supported in part by NSERC award SAPIN/371656-2010, SAPEQ/390539-2010, and the SFU Vice President, Research.

Summary

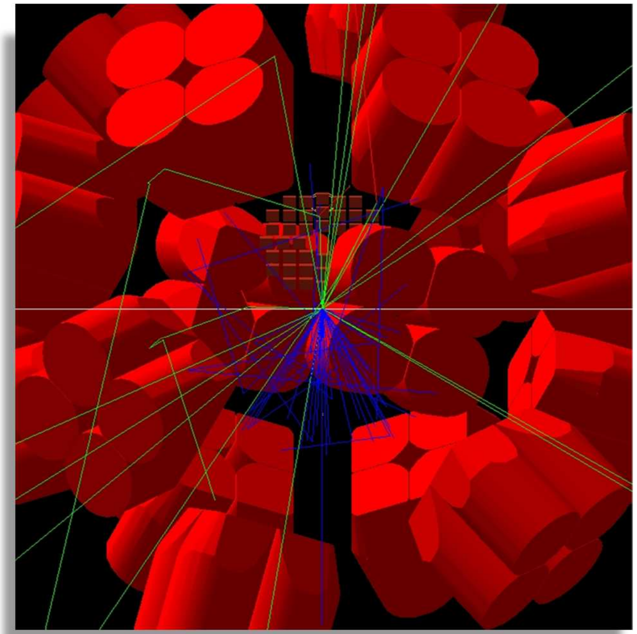
- Gamma-ray spectroscopy plays a major role in quantifying the evolution of nuclear structure for exotic radionuclides.
- TIGRESS is the key driver for such experimental studies using accelerated beams provided by the ISAC-II facility at TRIUMF. A rich set of auxiliary particle detector arrays compliment and enhance these spectroscopy studies.
  - **SHARC** $\longrightarrow$ Transfer reactions for single particle structure evolution.
  - **SPICE** $\longrightarrow$ Internal conversion electron spectroscopy.
  - **BAMBINO** $\longrightarrow$ Low energy Coulomb excitation.
  - **TIP** $\longrightarrow$ Low energy Coulomb excitation and Doppler-shift lifetime.
- Additional coupling schemes with **DESCANT** and **EMMA** have been demonstrated or are anticipated.

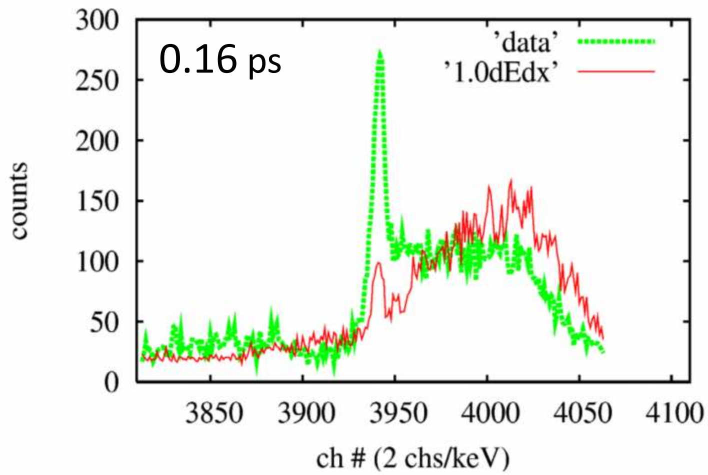
Thank You!

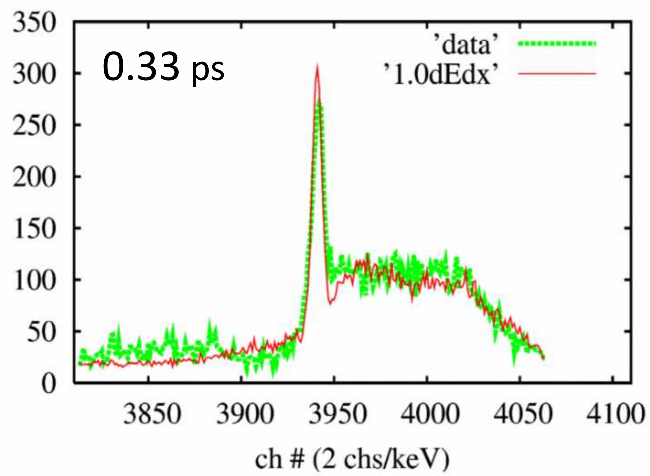
Merci!

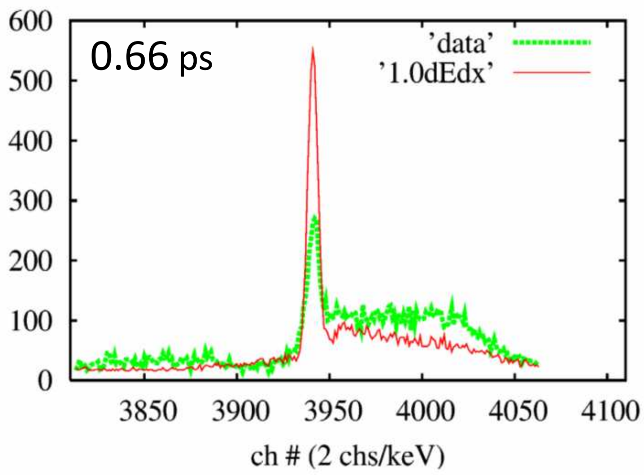
Preliminary Line Shape Simulations

- Gamma-ray line shape analysis presently underway in collaboration with Tom Drake of U. of Toronto.
- Experimental setup modelled within GEANT4.
- Coulomb excitation reaction kinematics employed for ^{36}Ar momentum distribution.
- A chi-square minimization of the fit between data and simulations yields the lifetime.

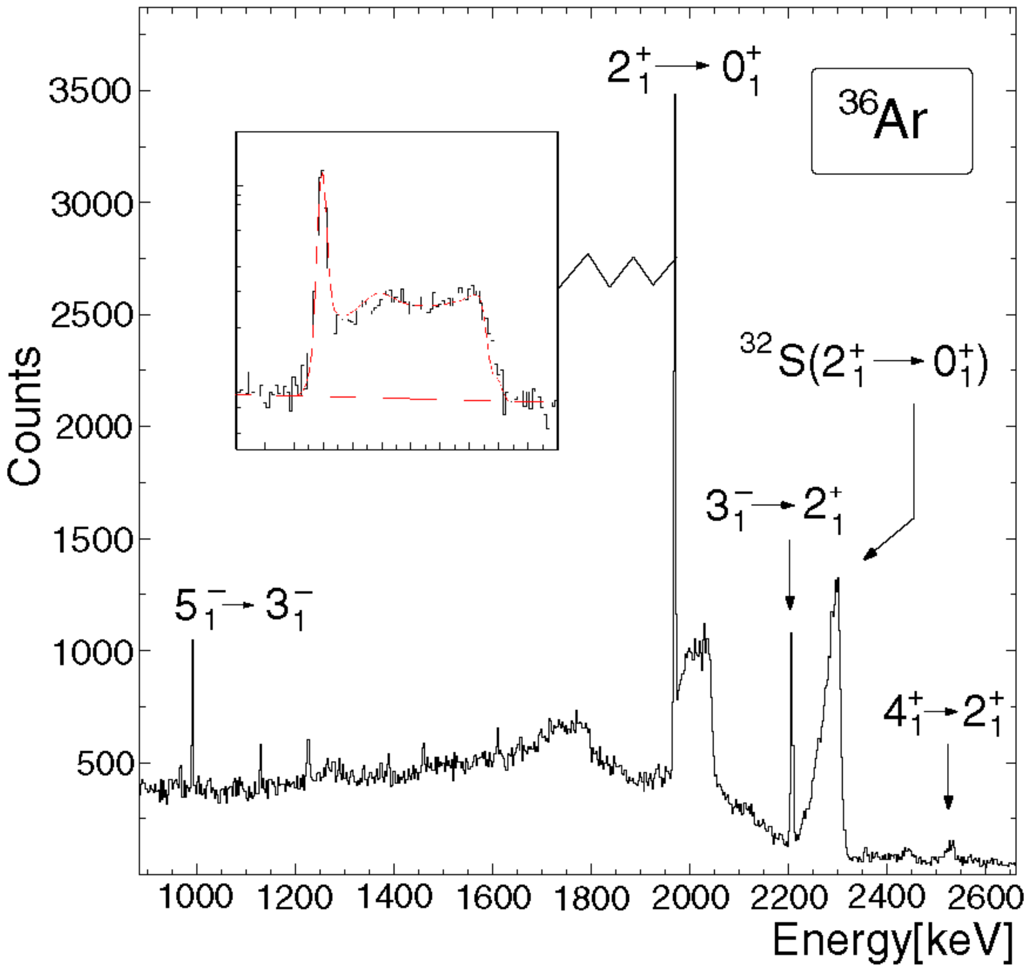




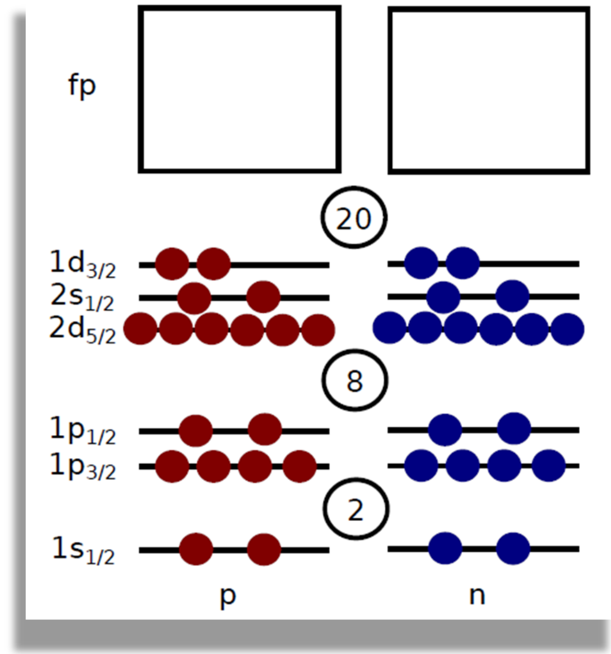




The Case for Self-Conjugate ^{36}Ar



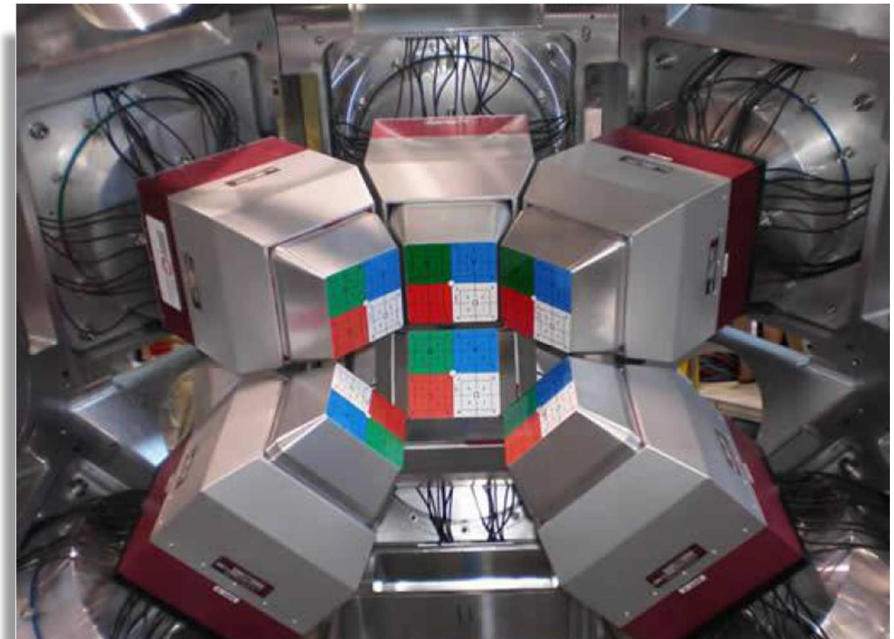
[1] K.-H. Speidel et al., Phys. Lett. B **632,** 207 (2006)
[2] B. V. Pritychenko et al., Phys. Lett. B **461**, 322 (1999)
[3] P. D. Cottle et al., Phys. Rev. C **60**, 031301(R) (1999)

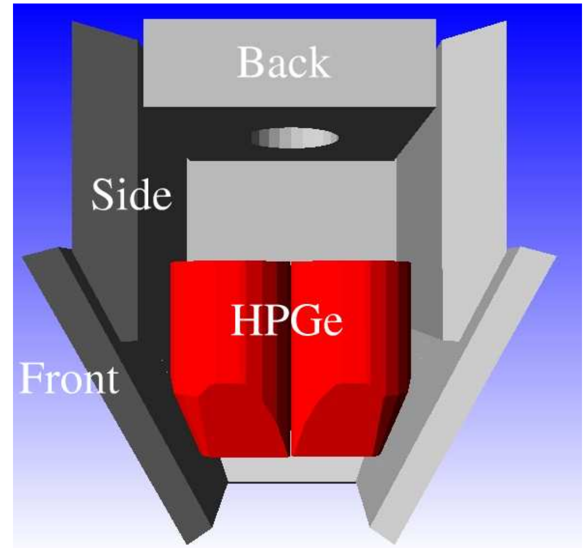


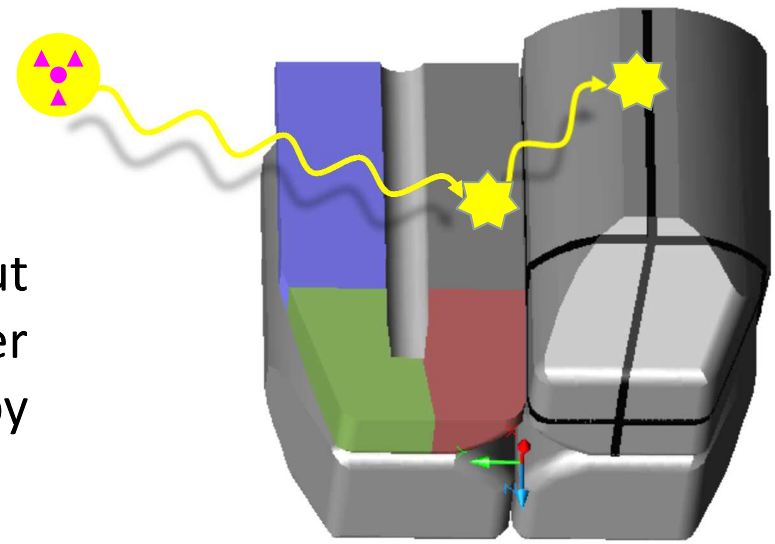
Ground state configuration of ^{36}Ar

Source	$B(E2; 0^+_1 \rightarrow 2^+_1)$ [e^2fm^4]	τ [ps]
DSAM [1]	211(6)	0.65(2)
Shell Model [1]	322(*)	0.43(*)
Int. Energy Coulex [2]	286(23)	0.48(4)
Int. Energy Coulex [3]	310(31)	0.44(4)

TRIUMF ISAC Gamma-Ray Escape Suppressed Spectrometer



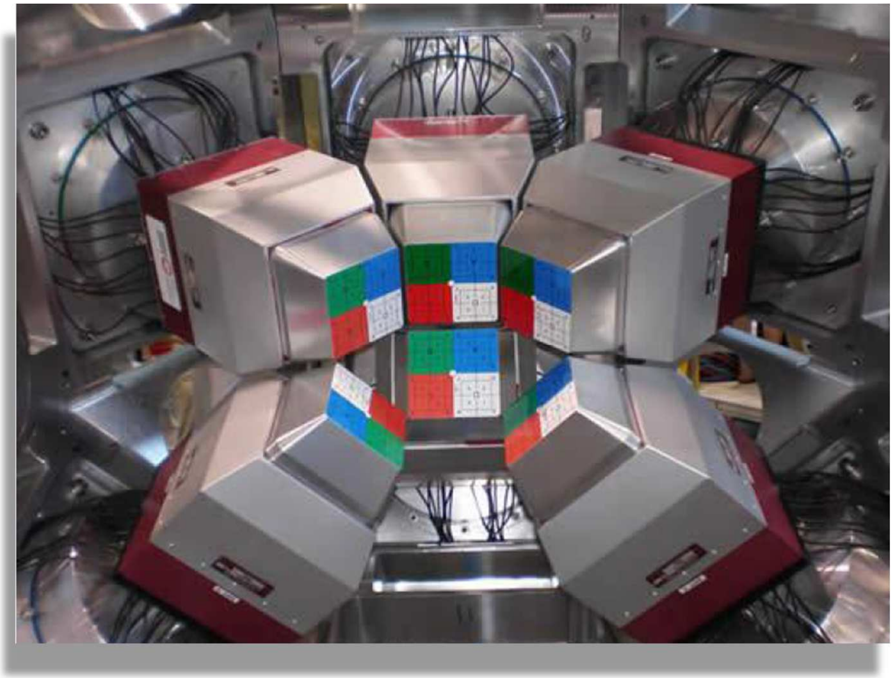


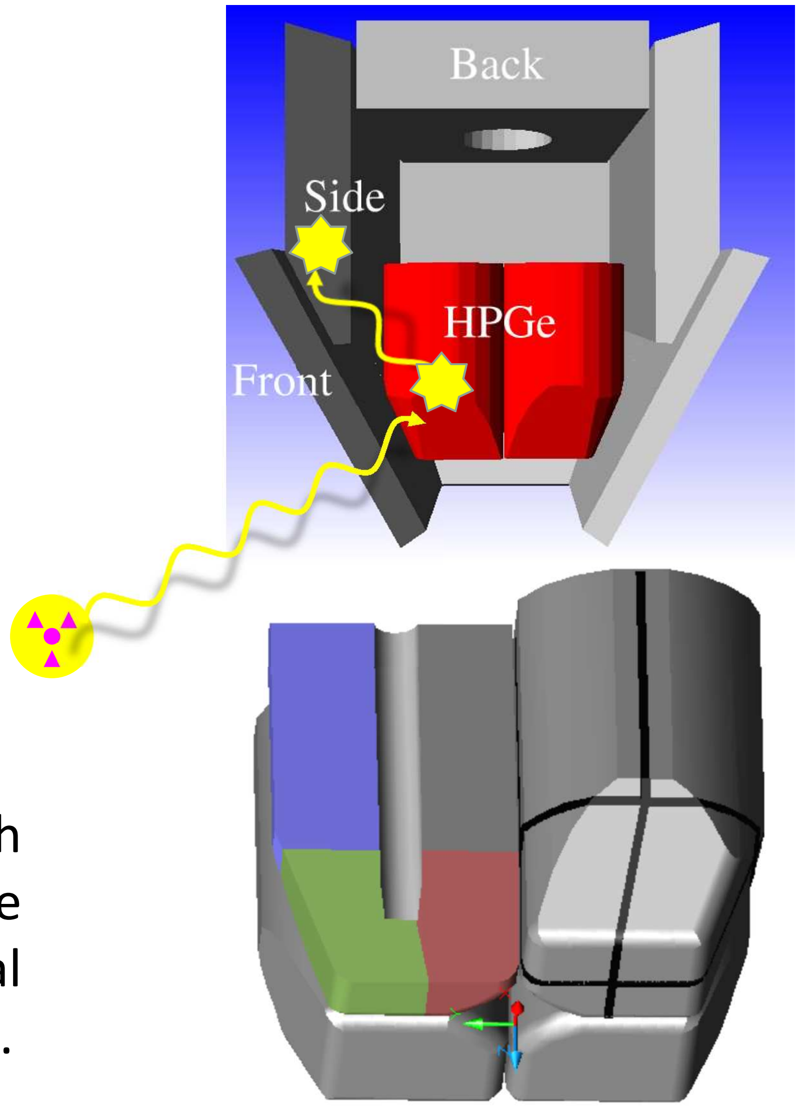


Segmented Germanium Clover

Large germanium solid angle coverage without compromising good angular resolution for Doppler reconstruction. Improvement of peak-to-total by **add-back** of several partial energy deposits.

TRIUMF ISAC Gamma-Ray Escape Suppressed Spectrometer





<u>Compton Suppressed Germanium Clover</u>

Active and passive vetoing of events which Compton scatter out of active germanium volume and into suppressor. Improvement of peak-to-total by **suppression** of these partial energy depositions.

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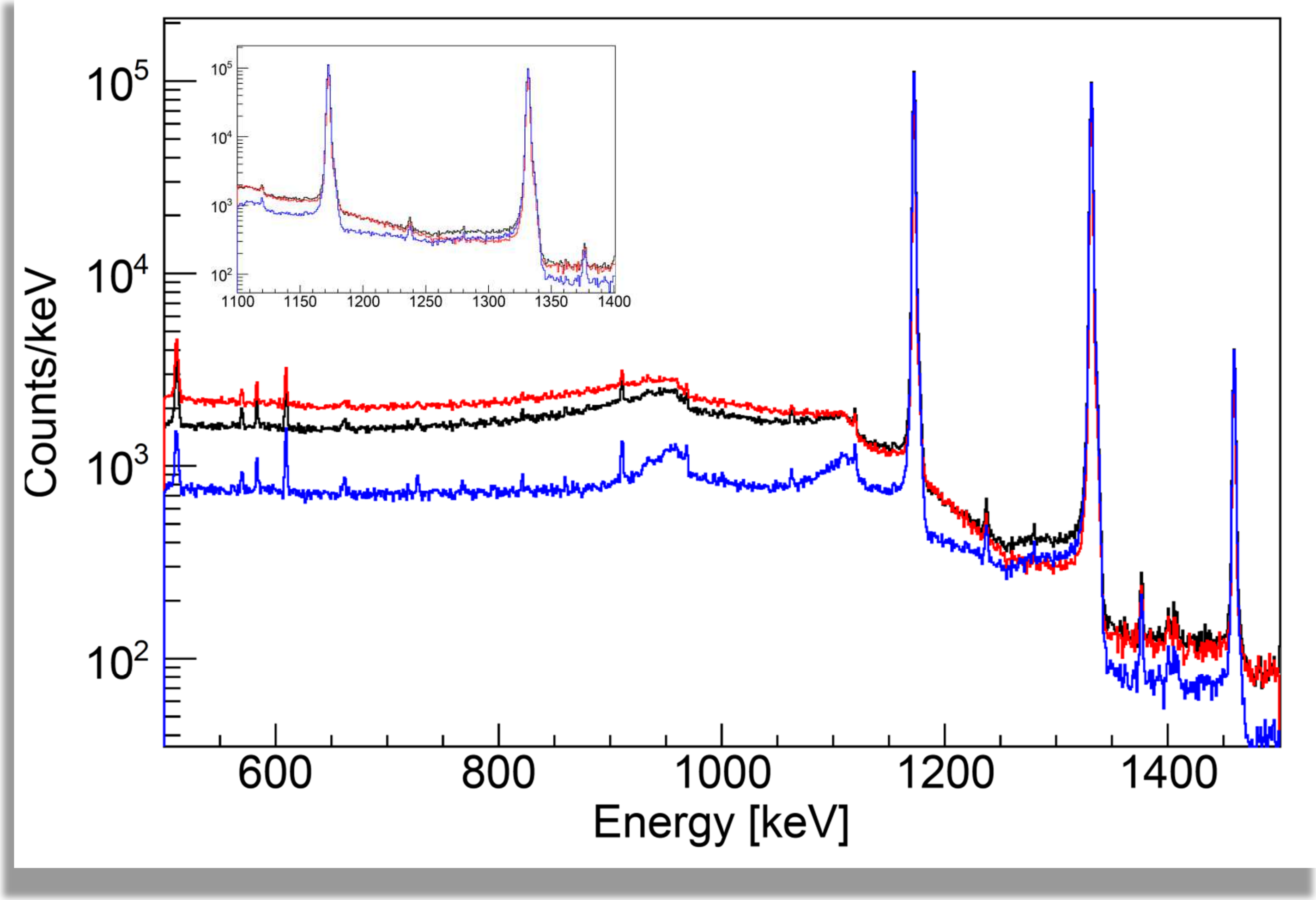
TRIUMF ISAC Gamma-Ray Escape Suppressed Spectrometer



TIGRESS 90° clovers summed: ^{60}Co source spectra illustrating effect of **add back** and **Compton suppression**.

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