TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

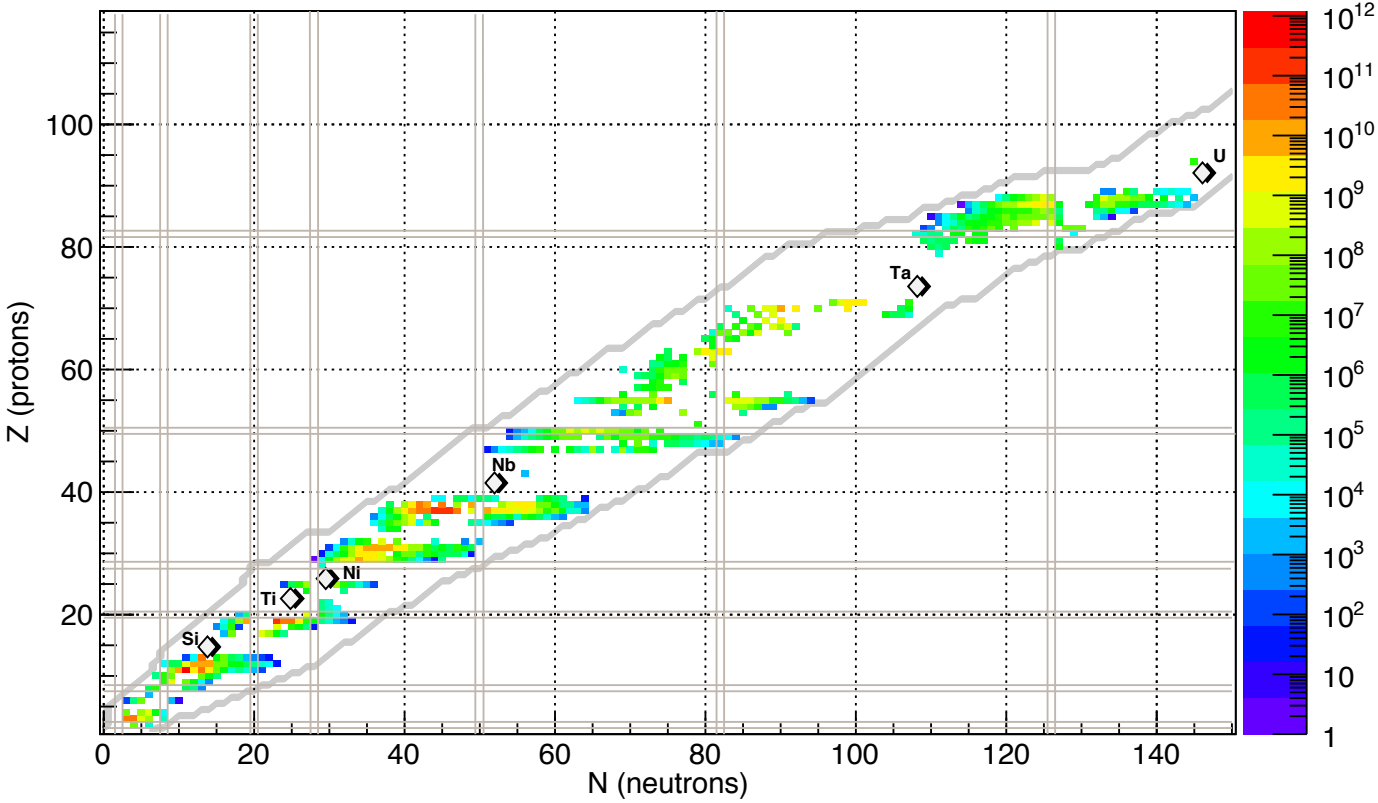
Experience with GRIFFIN

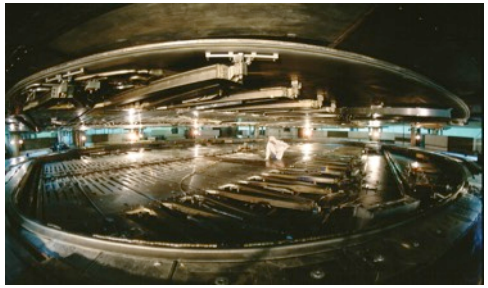
Adam Garnsworthy
ARIEL Principal Scientist and TRIUMF Research Scientist

FRIB Decay Station Workshop

25-26th January 2018

Isotopes delivered at ISAC (P.Kunz, Updated June 2016)





Target materials:
SiC, TiC, NiO, Nb, ZrC, Ta, U

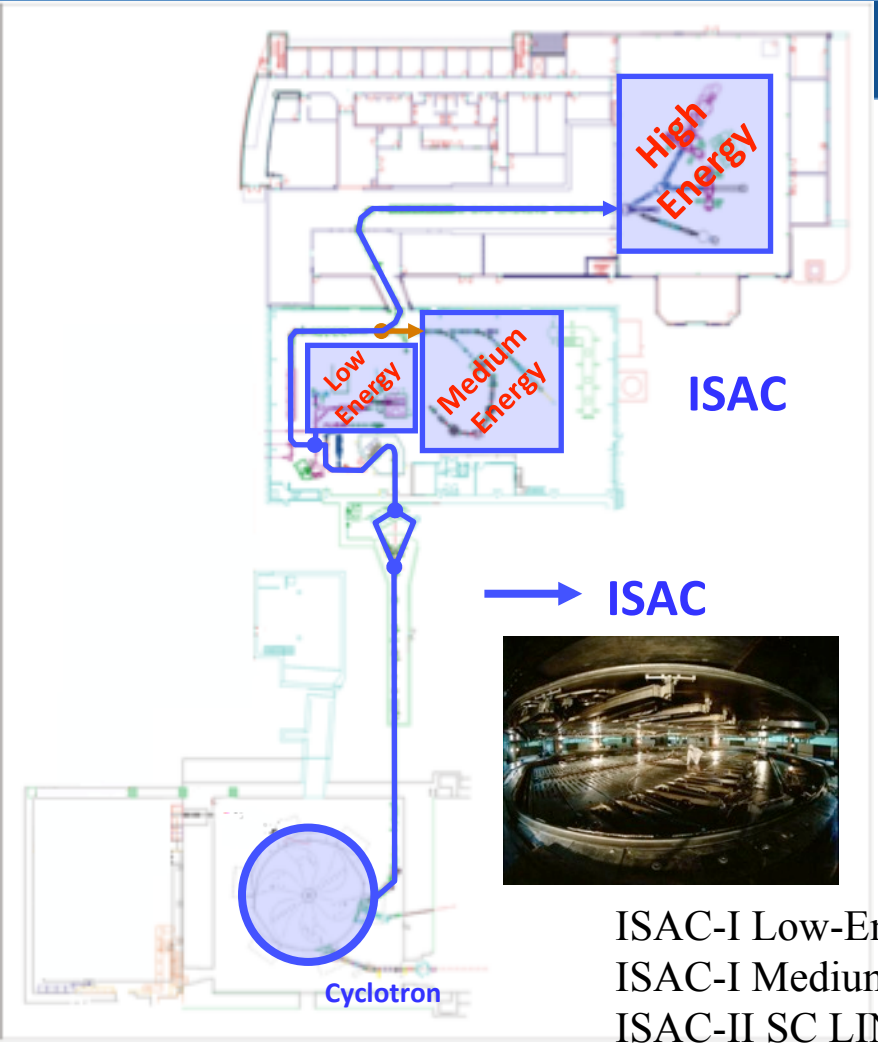
Ion sources:
Surface, FEBIAD, IG-LIS

TRIUMF-ISAC

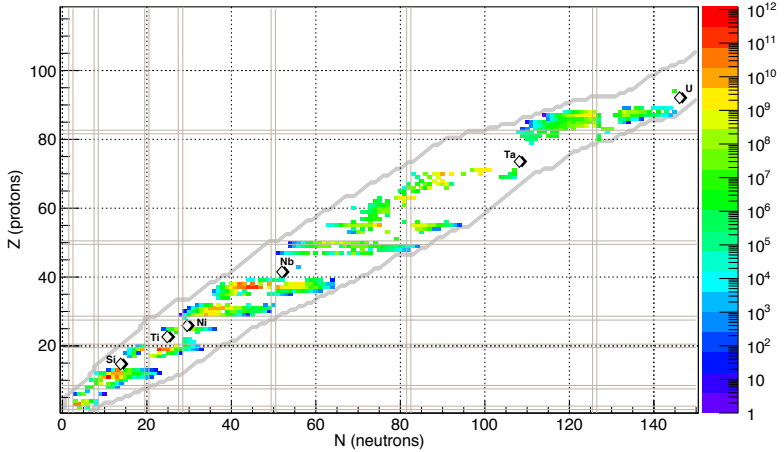
Isotope Separator and ACcelerator

1 RIB delivery to experiments

500MeV p^+ at 100μA on ISOL target



SiC, NiO, Nb, ZrC, Ta, UC_x Targets
Surface, FEBIAD, IG-LIS ion sources



ISAC-I Low-Energy <60keV — Ground state + decay, material science
ISAC-I Medium E <1.5MeV/u — Astrophysics
ISAC-II SC LINAC <10MeV/u — Nuclear reactions and structure

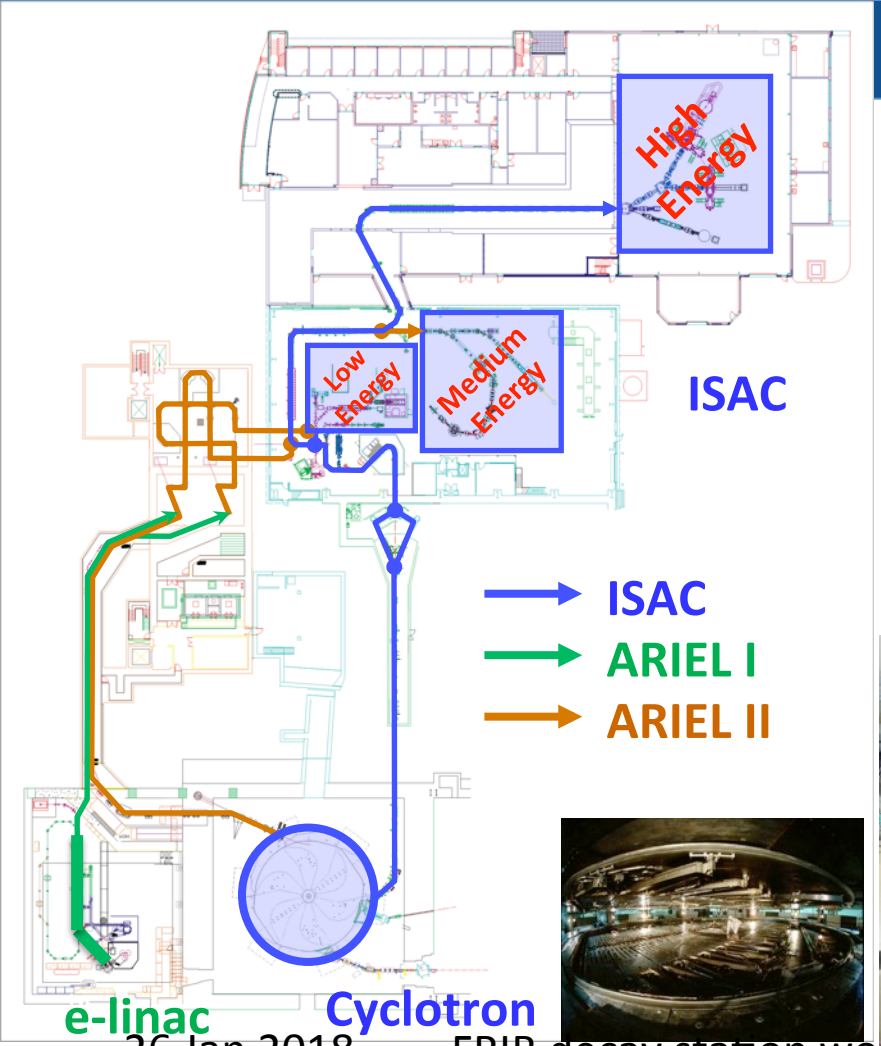
TRIUMF-ARIEL

Advanced Rare-IsotopE Laboratory

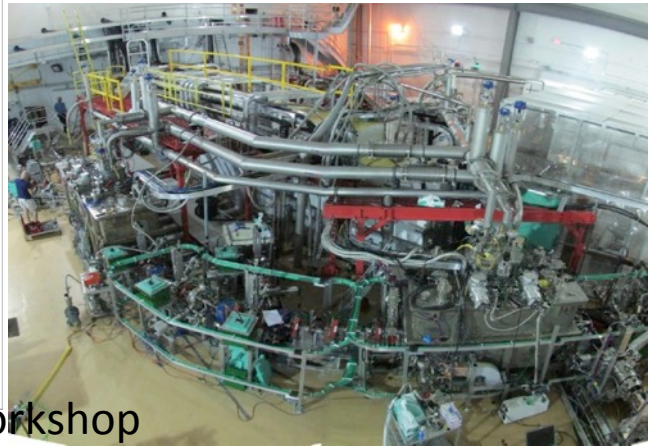
1 RIB ➔ 3 simultaneous RIBs

ARIEL Project:

- new electron linac driver for photo-fission
- new target stations and front end
- new proton beamline

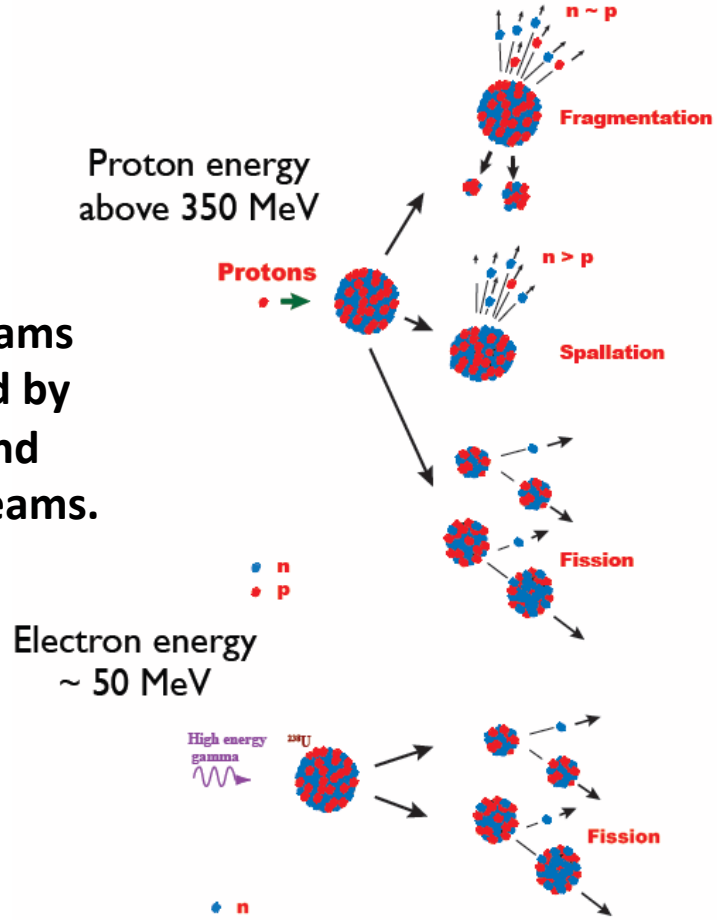


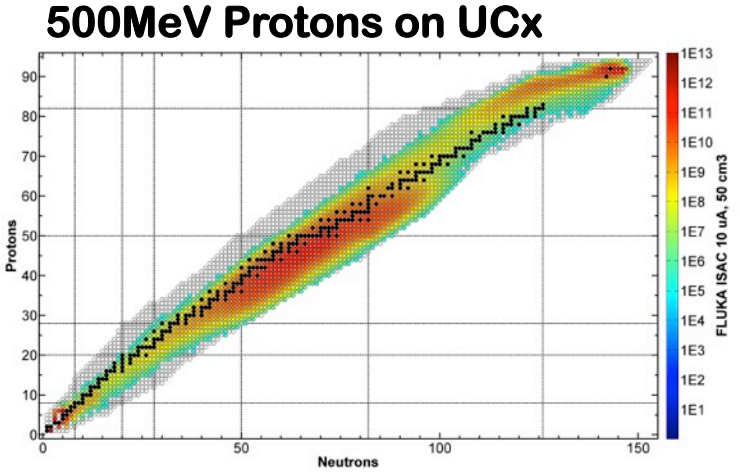
E-linac and electron beamline
Sept. 2014

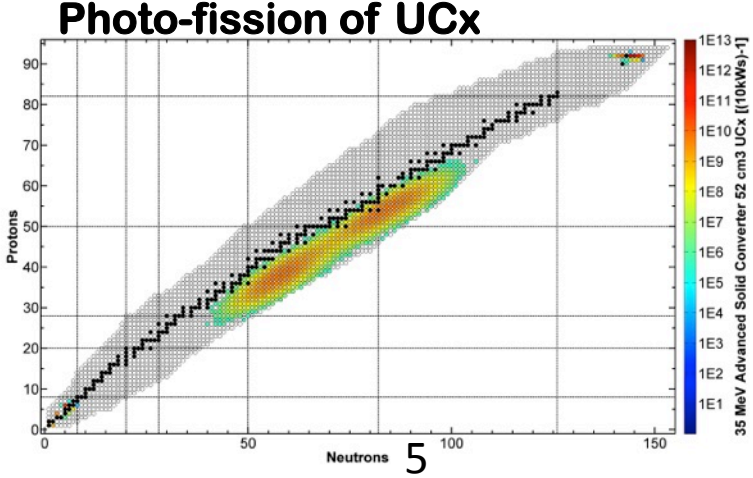


ARIEL beams to ISAC experiments

Rare-isotope beams will be produced by from proton and electron driver beams.

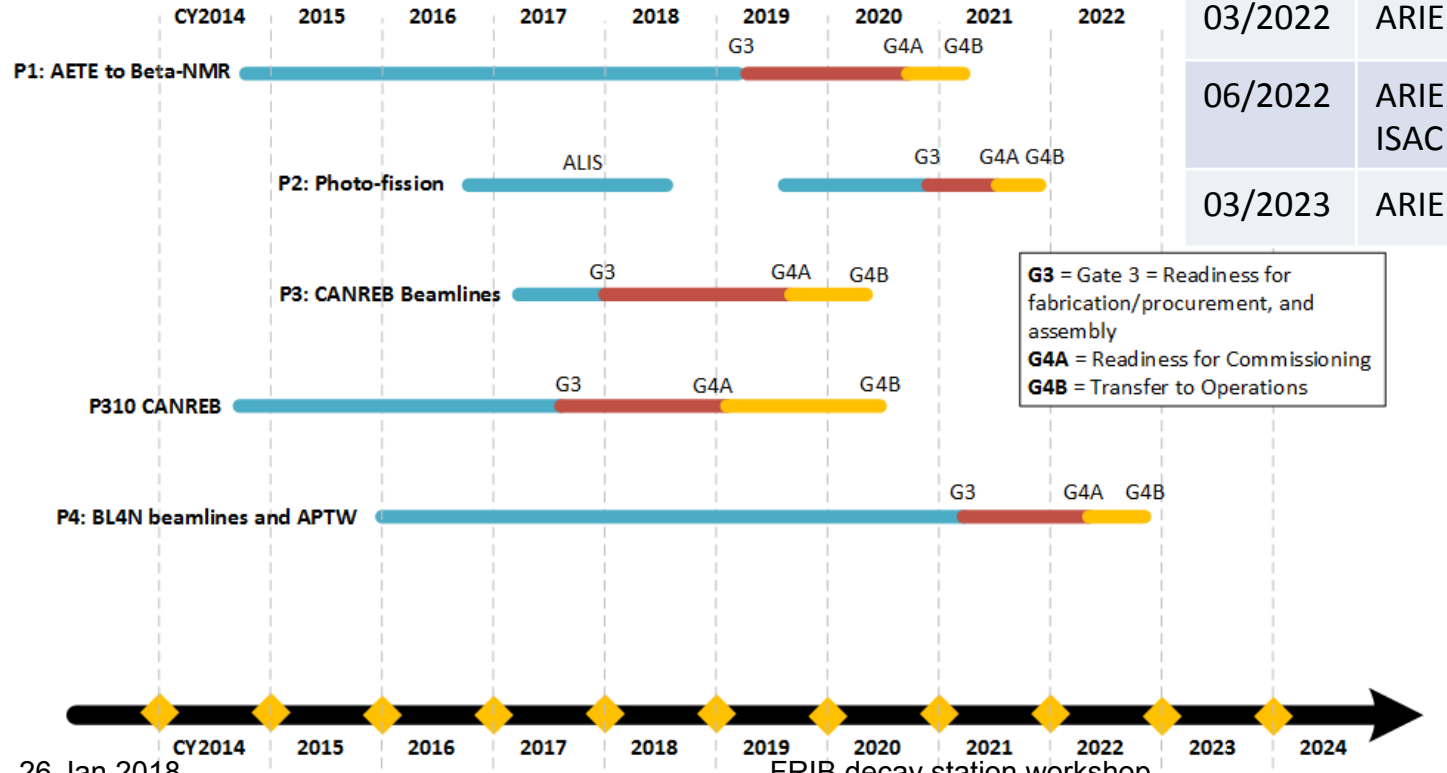




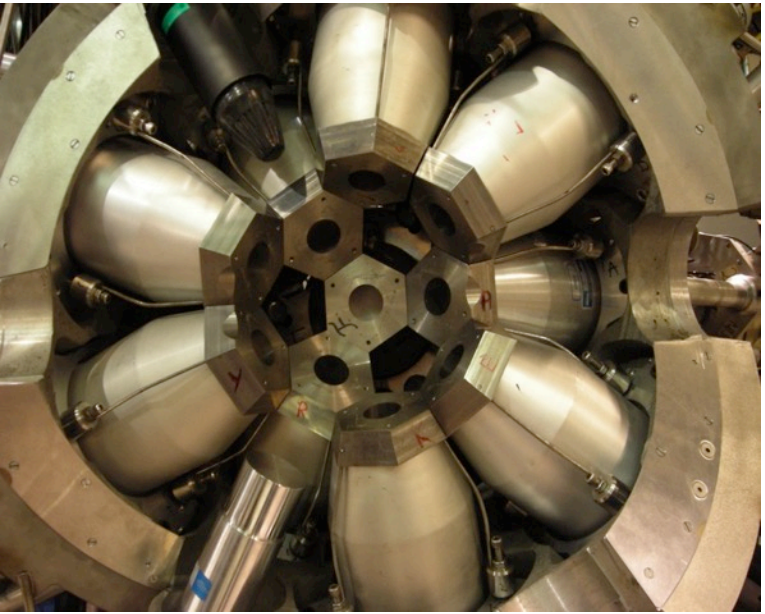


ARIEL Completion to Science

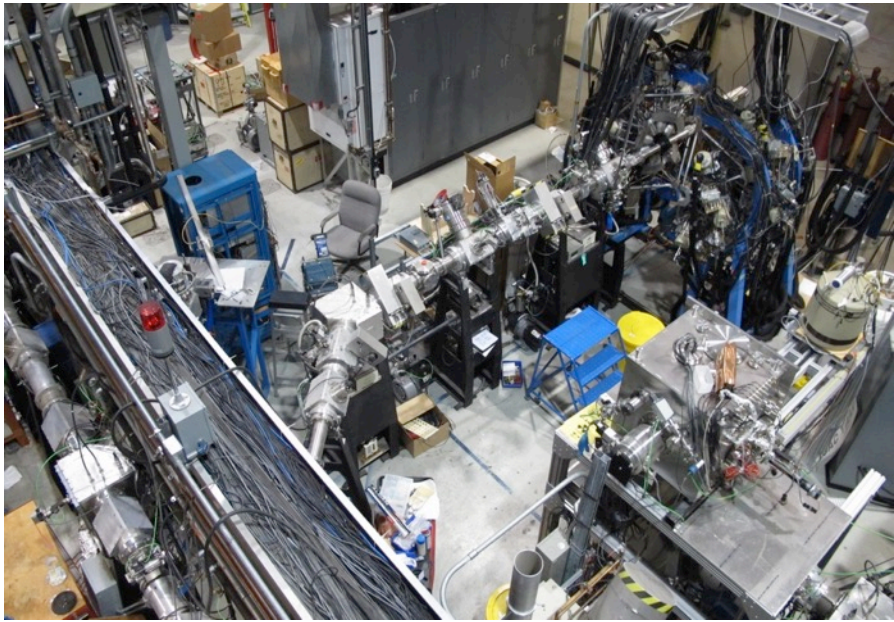
1999	Low-energy ISAC beams
10/2019	ISAC-CANREB-ISAC beams
03/2022	ARIEL beam to β-NMR
06/2022	ARIEL photo-fission beams to ISAC
03/2023	ARIEL spallation beams to ISAC



The 8π Spectrometer



Performed decay spectroscopy at TRIUMF-ISAC-I from 2000 to 2013



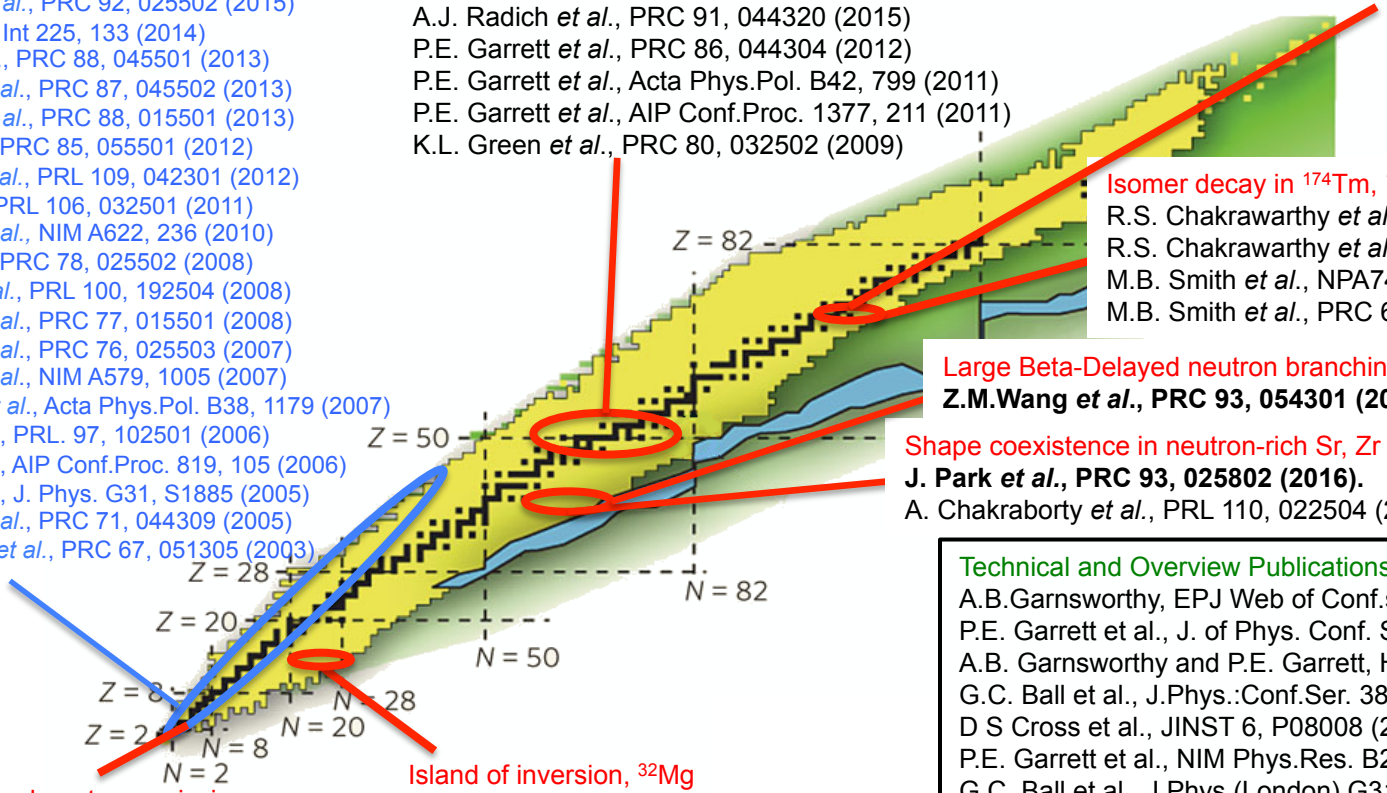
Researchers from 24 institutions from 8 countries.
25 post-docs,
5PhD, 12MSc, 1MPhys
Several Grad. Students still in progress

The 8π Spectrometer at TRIUMF-ISAC

Superallowed/Mirror Beta Decay
^{10}C, ^{14}O,^{18}Ne, ^{19}Ne, ^{26m}Al, ^{38m}K, ^{62}Ga, ^{74}Rb
M.R. Dunlop et al, PRL. 116, 172501 (2016).
A.T. Laffoley *et al.*, PRC 92, 025502 (2015)
G.C. Ball, Hyp. Int 225, 133 (2014)
R. Dunlop *et al.*, PRC 88, 045501 (2013)
G.F. Grinyer *et al.*, PRC 87, 045502 (2013)
A.T. Laffoley *et al.*, PRC 88, 015501 (2013)
P. Finlay *et al.*, PRC 85, 055501 (2012)
S. Triambak *et al.*, PRL 109, 042301 (2012)
P. Finlay et al, PRL 106, 032501 (2011)
G.F. Grinyer *et al.*, NIM A622, 236 (2010)
P. Finlay *et al.*, PRC 78, 025502 (2008)
K.G. Leach *et al.*, PRL 100, 192504 (2008)
G.F. Grinyer *et al.*, PRC 77, 015501 (2008)
G.F. Grinyer *et al.*, PRC 76, 025503 (2007)
G.F. Grinyer *et al.*, NIM A579, 1005 (2007)
E.F. Zganyar *et al.*, Acta Phys.Pol. B38, 1179 (2007)
B. Hyland *et al.*, PRL. 97, 102501 (2006)
B. Hyland *et al.*, AIP Conf.Proc. 819, 105 (2006)
B. Hyland *et al.*, J. Phys. G31, S1885 (2005)
G.F. Grinyer *et al.*, PRC 71, 044309 (2005)
A. Piechaczek *et al.*, PRC 67, 051305 (2003)

High-statistics studies of Cd, Sn, Xe
B. Jigmeddorj *et al.*, Eur. Phys. J. A 52, 36 (2016).
B. Jigmeddorj, *et al.*, EPJ Web Conf. 107, 03014 (2016).
A.J. Radich *et al.*, PRC 91, 044320 (2015)
P.E. Garrett *et al.*, PRC 86, 044304 (2012)
P.E. Garrett *et al.*, Acta Phys.Pol. B42, 799 (2011)
P.E. Garrett *et al.*, AIP Conf.Proc. 1377, 211 (2011)
K.L. Green *et al.*, PRC 80, 032502 (2009)

Half Life of geochronometer, ^{176}Lu
G.F. Grinyer *et al.*, PRC 67, 014302 (2003)



Isomer decay in ^{174}Tm, ^{178}Hf, ^{179}Lu
R.S. Chakrawarthy *et al.*, PRC 73, 024306 (2006)
R.S. Chakrawarthy *et al.*, EPJ. A 25, S1, 125 (2005)
M.B. Smith *et al.*, NPA746, 617c (2004)
M.B. Smith *et al.*, PRC 68, 031302 (2003)

Large Beta-Delayed neutron branching ratio observed from ^{102}Rb
Z.M.Wang *et al.*, PRC 93, 054301 (2016).

Shape coexistence in neutron-rich Sr, Zr
J. Park *et al.*, PRC 93, 025802 (2016).
A. Chakraborty *et al.*, PRL 110, 022504 (2013)

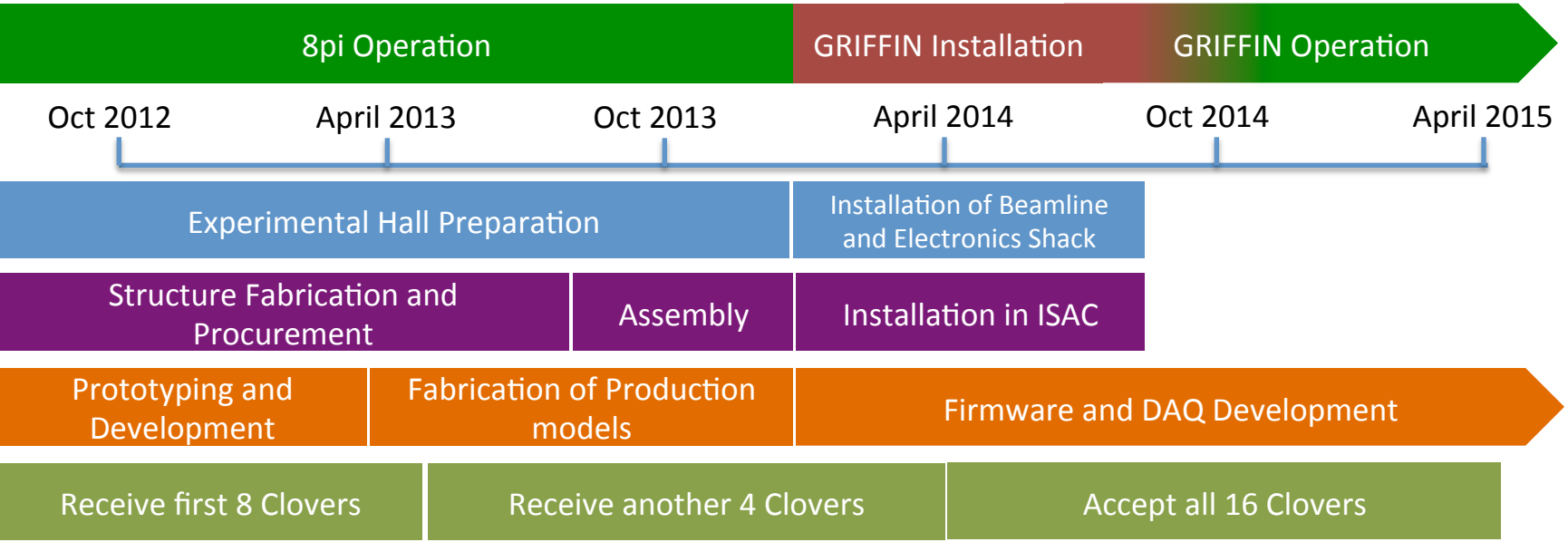
Technical and Overview Publications
A.B.Garnsworthy, EPJ Web of Conf.s 93, 01032 (2015)
P.E. Garrett et al., J. of Phys. Conf. Series 639, 012006 (2015).
A.B. Garnsworthy and P.E. Garrett, Hyp. Int. 225, 121 (2014)
G.C. Ball et al., J.Phys.:Conf.Ser. 387, 012014 (2012)
D S Cross et al., JINST 6, P08008 (2011)
P.E. Garrett et al., NIM Phys.Res. B261, 1084 (2007)
G.C. Ball et al., J.Phys.(London) G31, S1491 (2005)
S.J. Williams et al., J.Phys.(London) G31, S1979 (2005)
C.E. Svensson et al., NIM Phys. Res. B204, 660 (2003)

Island of inversion, ^{32}Mg
C.M. Mattoon *et al.*, PRC 75, 017302 (2007)

^{11}Li beta-delayed neutron emission
C.M. Mattoon *et al.*, PRC 80, 034318 (2009)
F. Sarazin *et al.*, PRC 70, 031302 (2004)

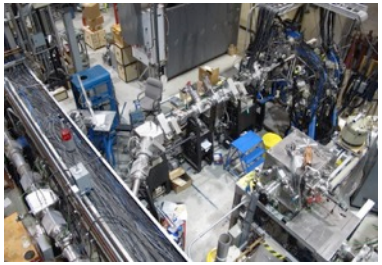
GRIFFIN Timeline

Phase One: Infrastructure + HPGe (CAD$8.7M). Oct 2012 – April 2015



Installation in 2014, Commissioning runs in Fall 2014, Completion in May 2015

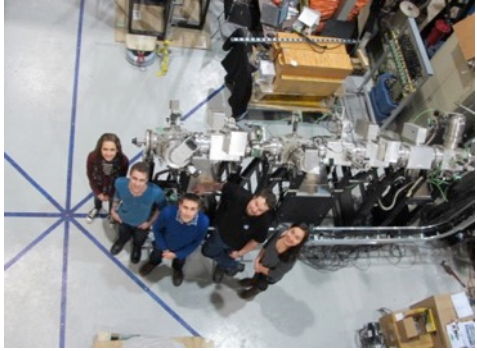
Phase Two: Suppression Shields (CAD$3.57M). June 2016 – May 2018



Dec 2013, 8pi →

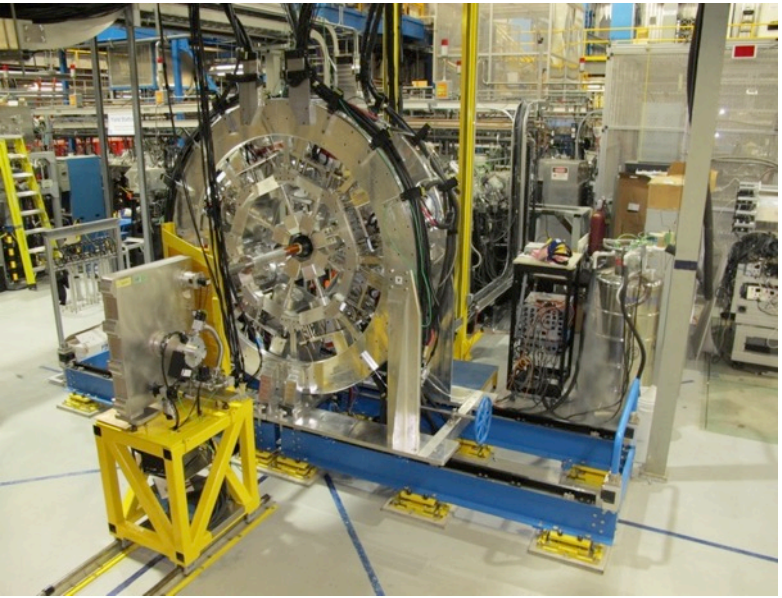
Jan →

Feb →



Apr

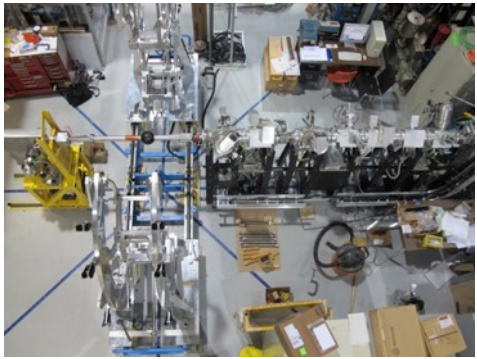
GRIFFIN Installation in 2014



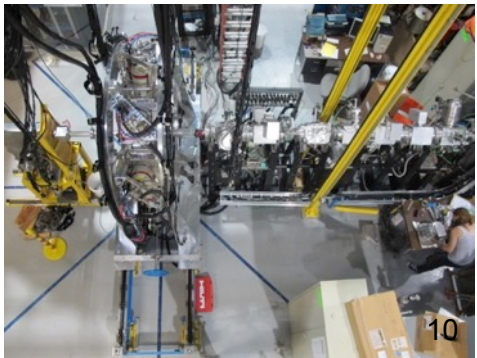
First RIB
24th Sept 2014

↓

May



July

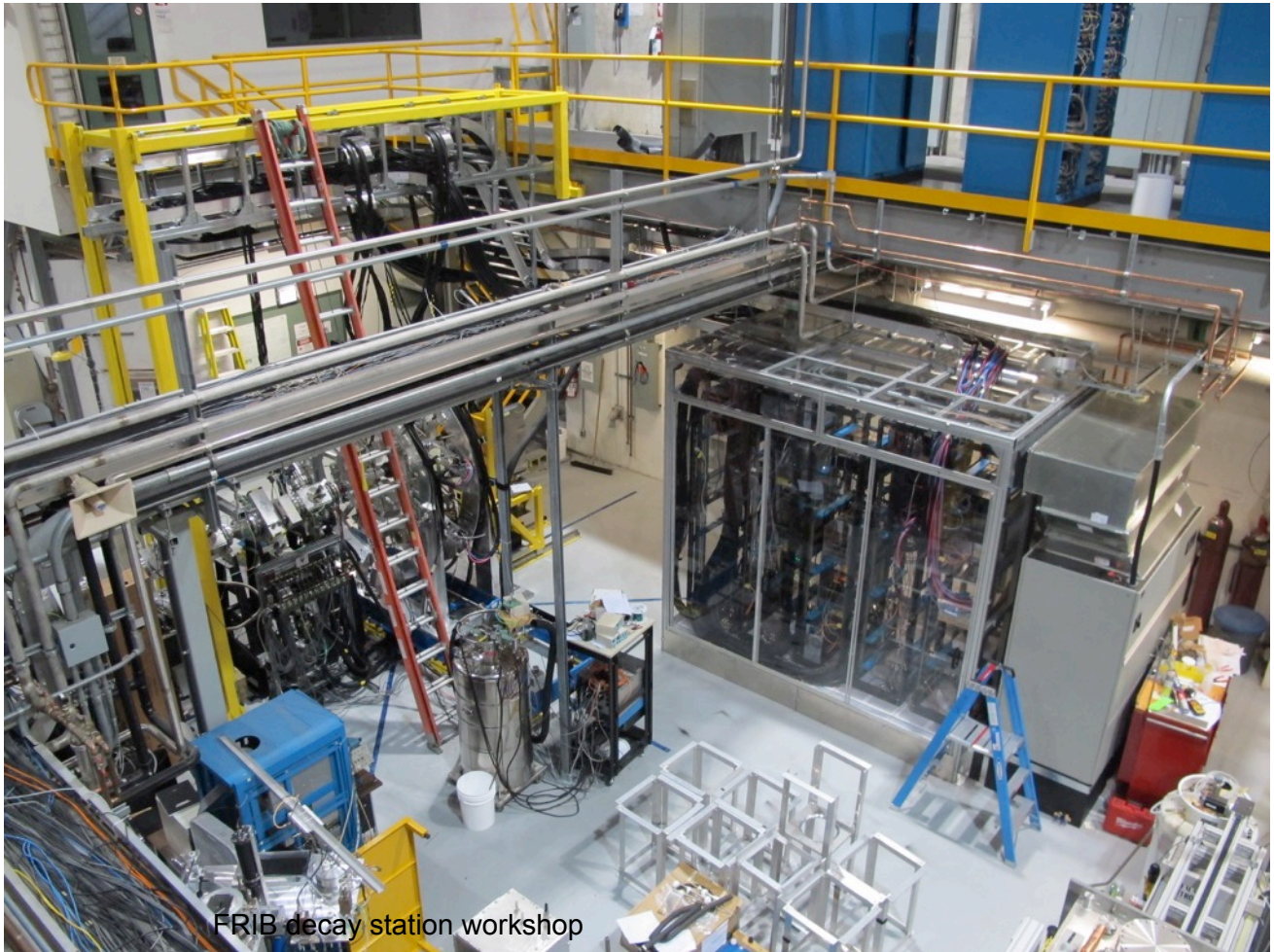


GRIFFIN Footprint

Support structure:
5.2m x 1.8m
2.7m tall

Electronics Shack:
4.2m x 2.1m
3.2m tall

Total area:
9m x 9m



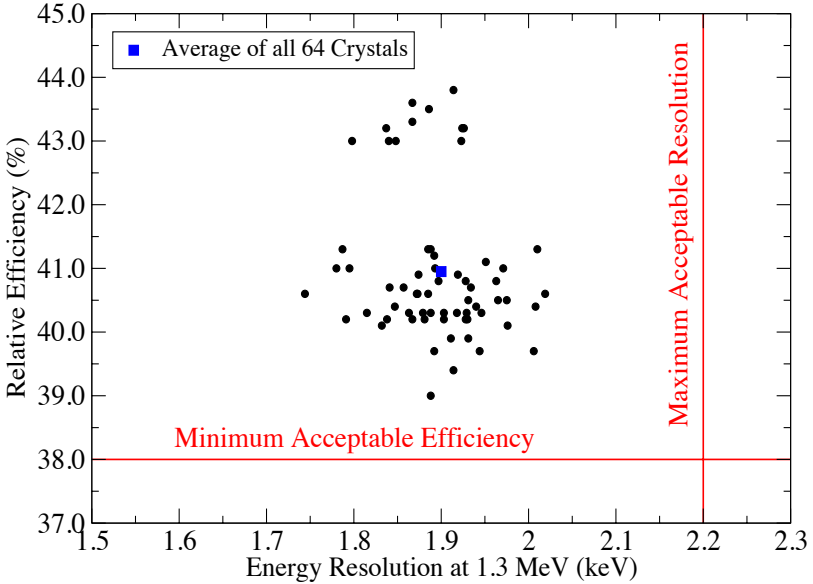
GRIFFIN HPGe Clover Detectors

Average Performance of all 64 crystals (16 clovers):

Energy resolution@ 121keV = 1.12(6) keV

Energy resolution@ 1.3MeV = 1.89(6) keV

Photo-peak Rel. Eff. @ 1.3MeV = 41(1) %



Testing performed at SFU

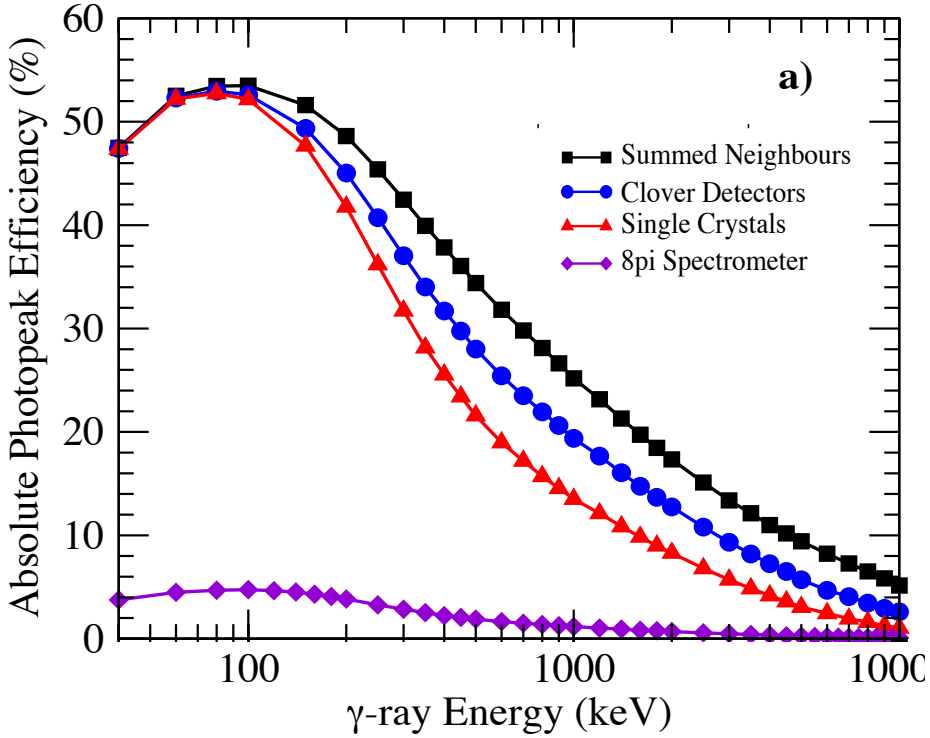
Dec 2012	4 Accepted
April 2013	8 Accepted
Jan 2014	9 Accepted
May 2014	13 Accepted
Oct 2014	16 Accepted

6 months ahead of schedule

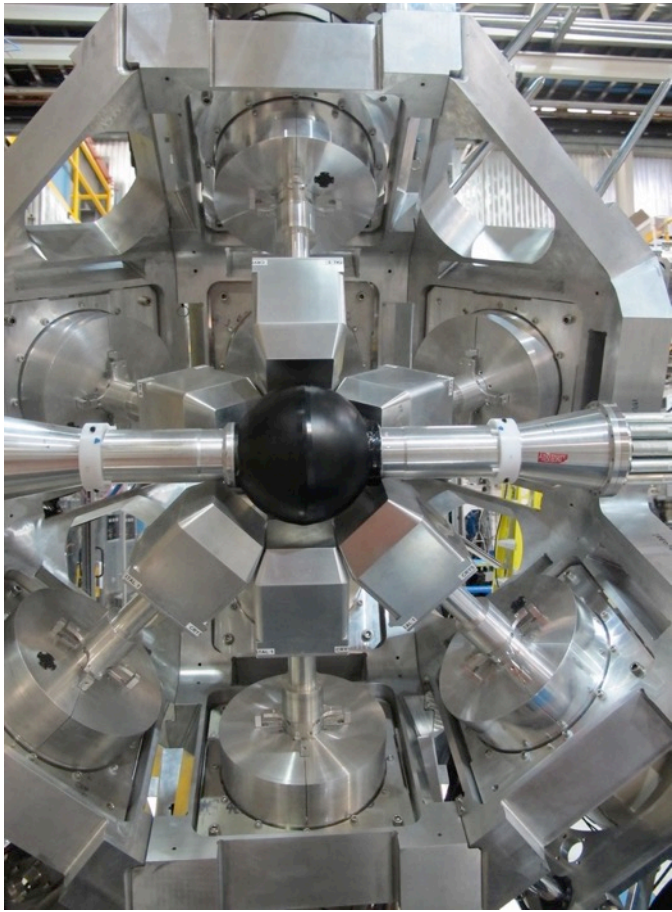
U. Rizwan *et al.*, NIM A 820, 126 (2016).

GRIFFIN HPGe Clover Detectors

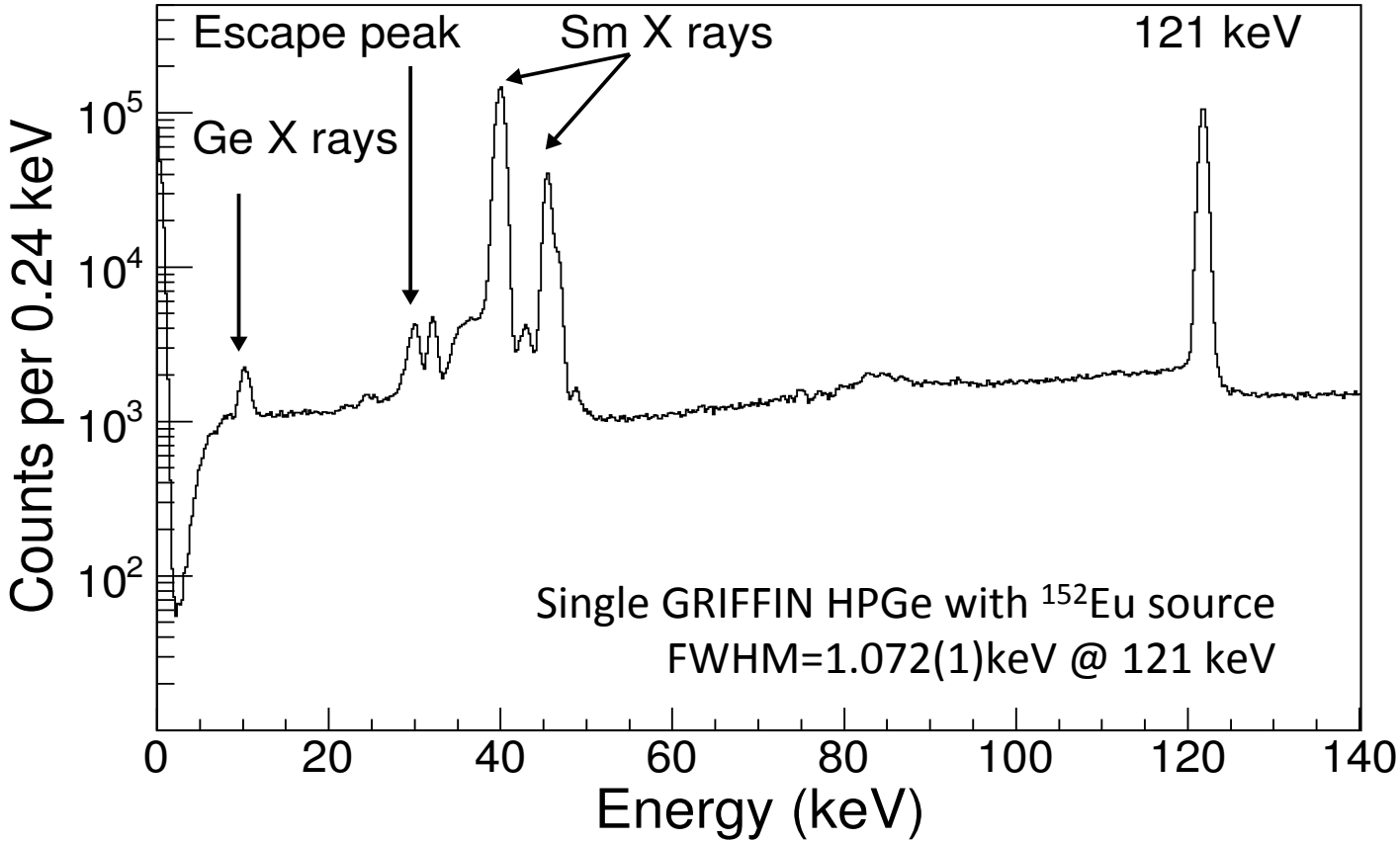
A close-packed array of 16 large-volume HPGe Clover detectors, 64 crystals



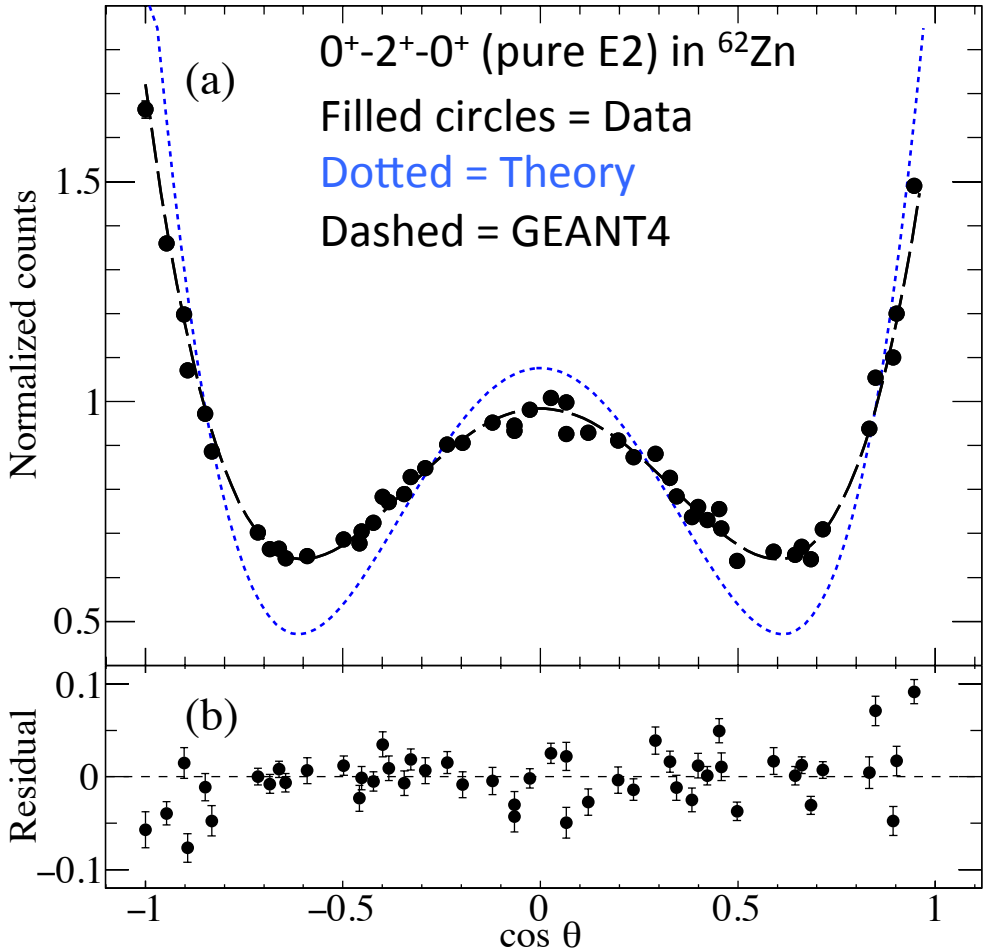
4096 crystal pairs at 52 unique angles for γ-γ angular correlations



Low-Energy Thresholds



Gamma-Gamma Angular Correlation Analysis



J.K. Smith, A.C. MacLean *et al. In preparation for NIM A (2018).*

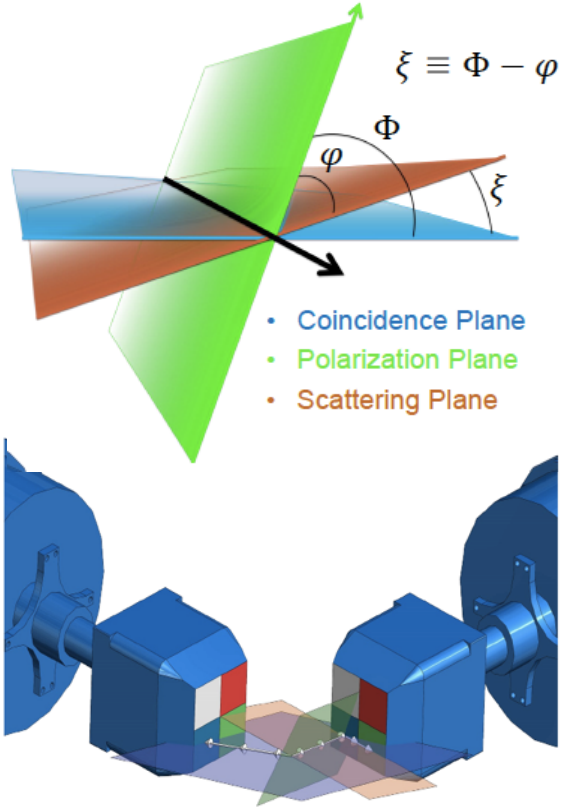
Development of γ–γ angular correlation analysis techniques with GRIFFIN.

- Finite size and shape of crystals means theoretical distribution is attenuated.
- Obtain 'template' from high-statistics GEANT4 simulation
- Fit template to experimental data.

Ideally:

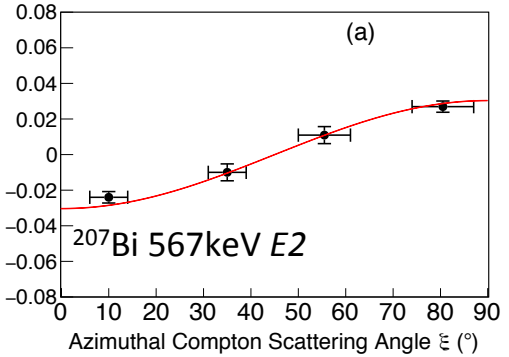
- Fit experimental data
- Plug coefficients into simple equations
- Obtain corrected 'true' coefficients

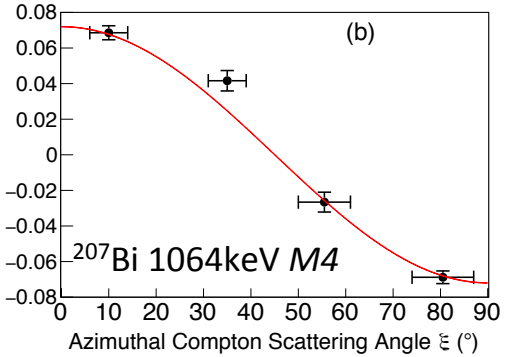
Compton Polarimetry using GRIFFIN



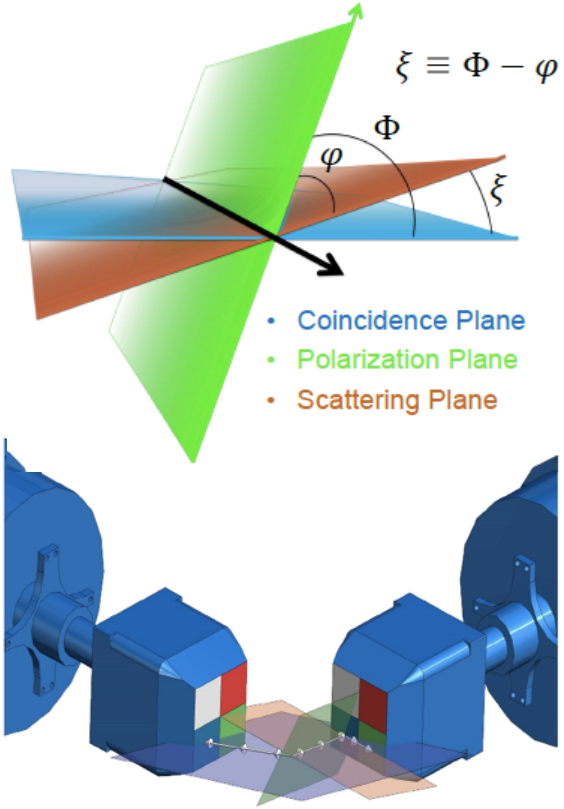
Dan Southall, TRIUMF research student, 2016

Define Polarization plane from γ–γ coincidence detection. Then examine azimuthal scattering angle to determine electric or magnetic nature of the radiation.





Compton Polarimetry using GRIFFIN



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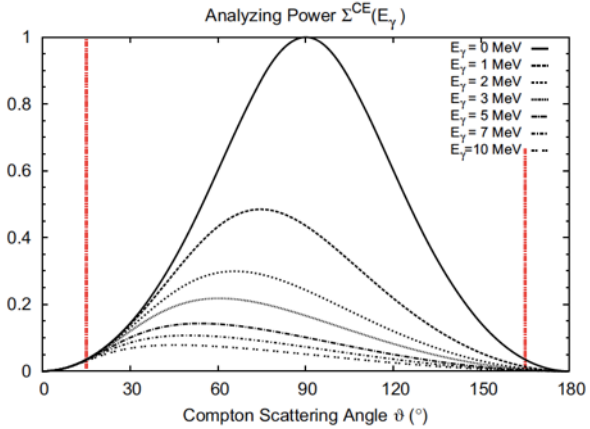
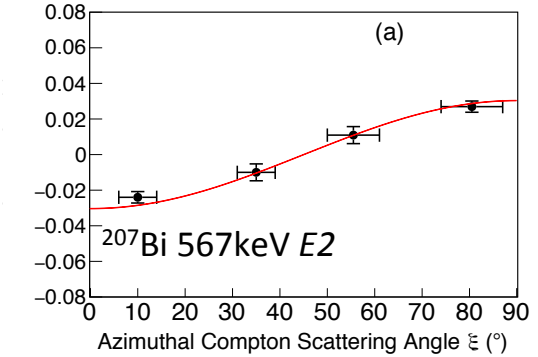
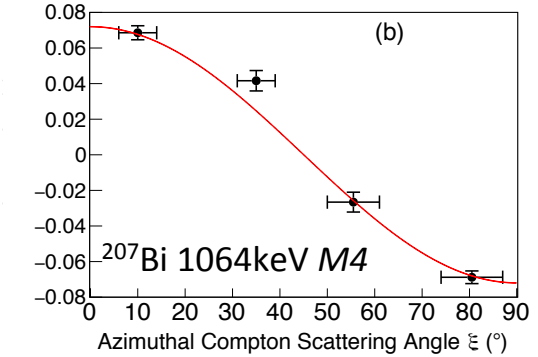




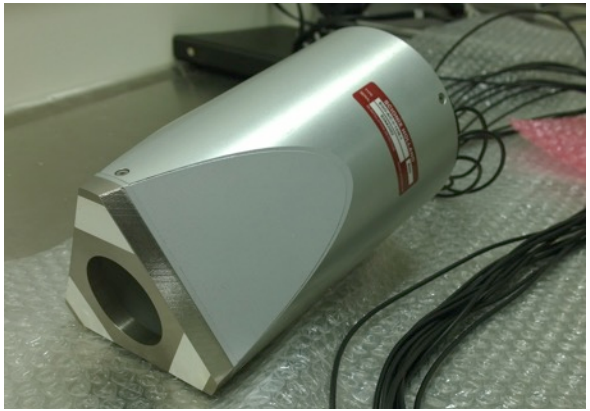


Dan Southall, TRIUMF research student, 2016

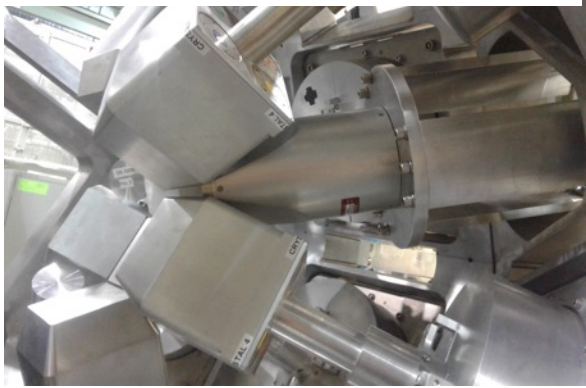
GRIFFIN Compton and Background Suppression Shields

- First Suppression shield sets have been accepted (March 2017)!
- All performance acceptance testing completed at SFU
  (Kenneth Whitmore, Kevin Ortner, Corina Andreoiu)
- Mechanical checks completed at TRIUMF.

- HPGe 5 sets accepted. All sets expected by May 2018.
- Ancil. Det. sets expected by April 2018.

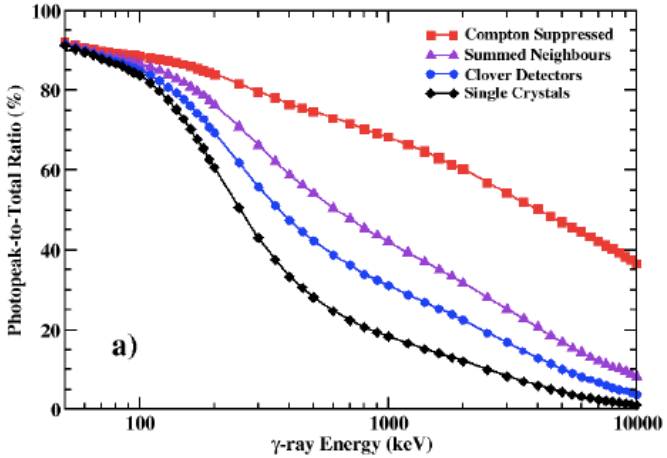


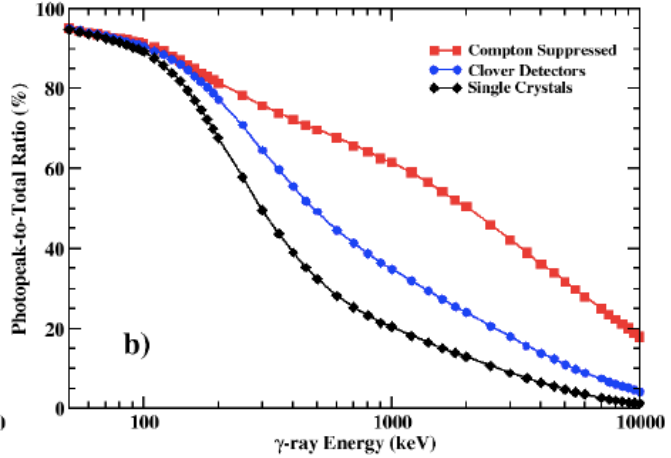
GRIFFIN ancillary-detector BGO shield #1



GRIFFIN Compton and Background Suppression Shields

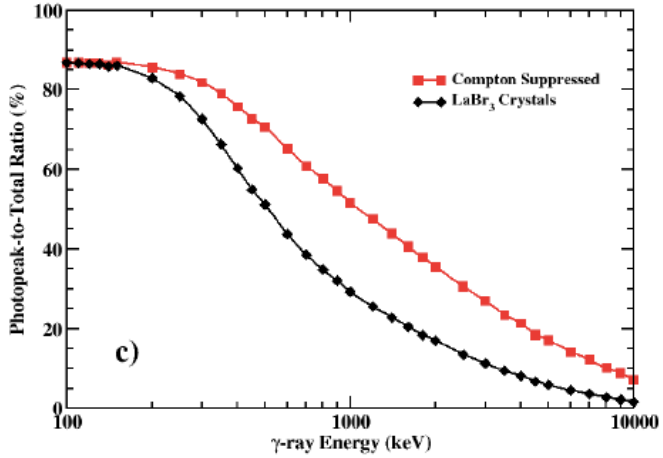
HPGe at 11cm

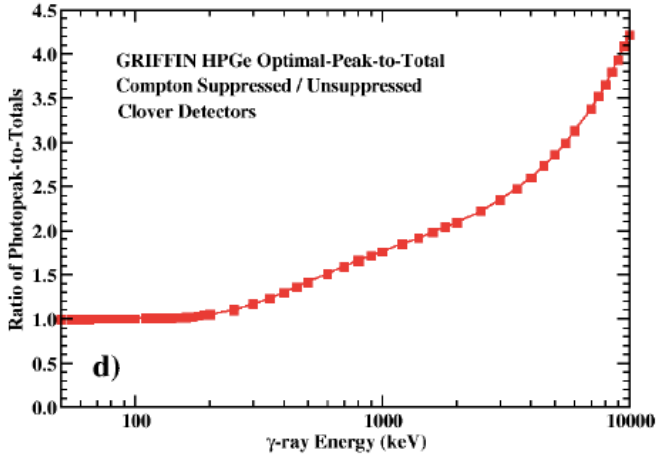




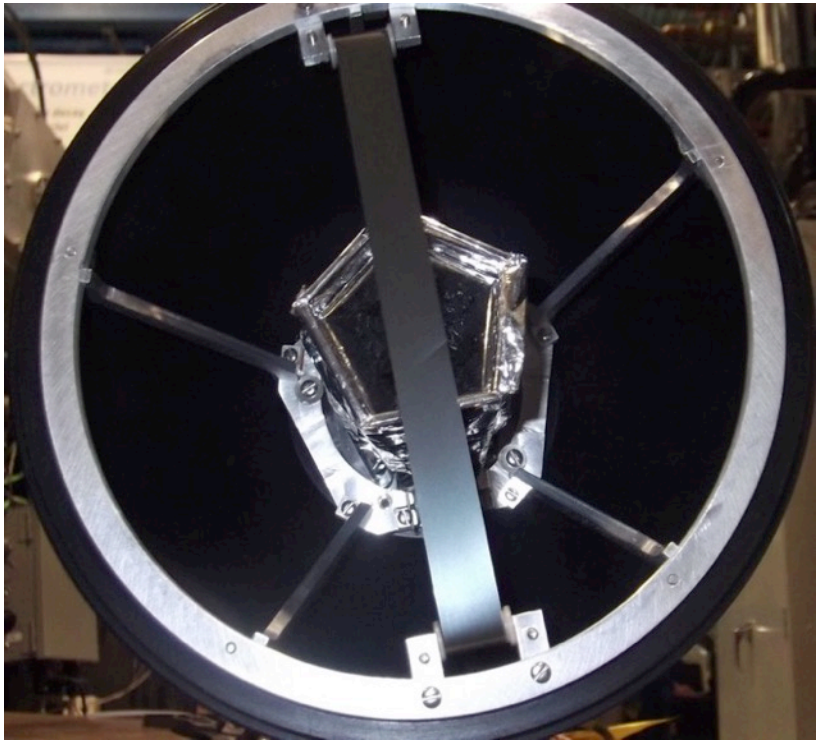
HPGe at 14.5cm

$LaBr_3$ shield

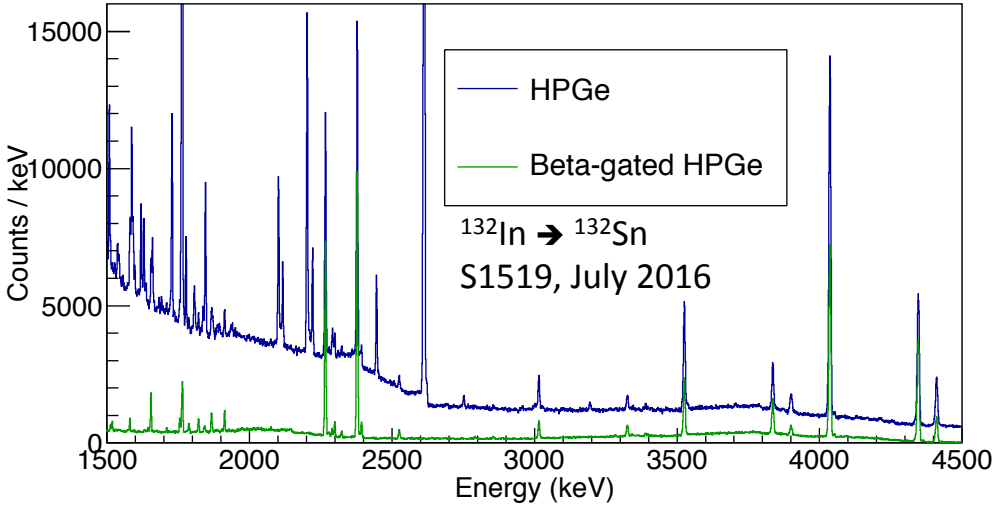




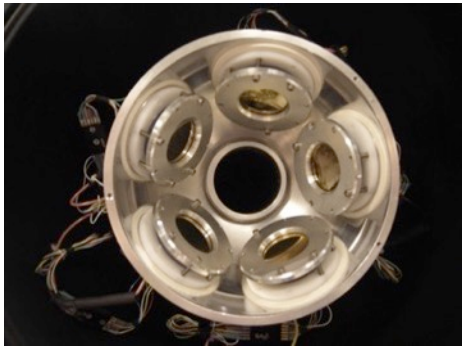
SCEPTAR - SCintillating Electron-Positron Tagging ARray



- Two hemispheres of 10 plastic scintillators
- Detects beta particles with ~80% solid angle coverage
- Improves peak-to-background of HPGe spectra
- Reduces random background by ~5 orders of magnitude



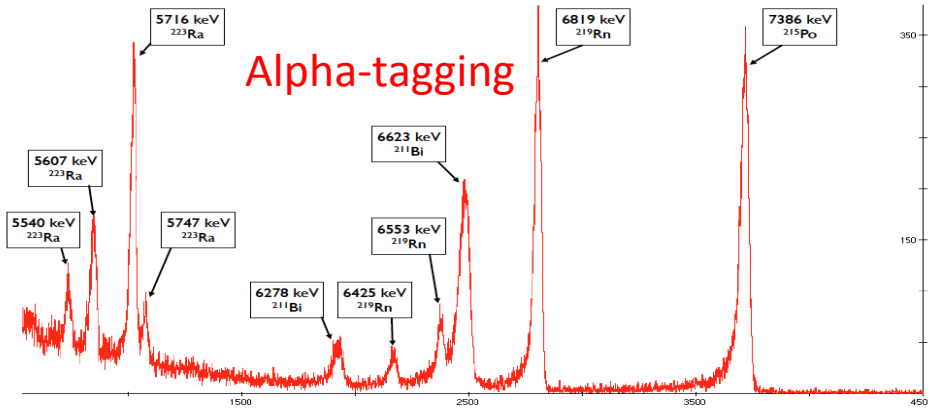
PACES - Pentagonal Array for Conversion Electron



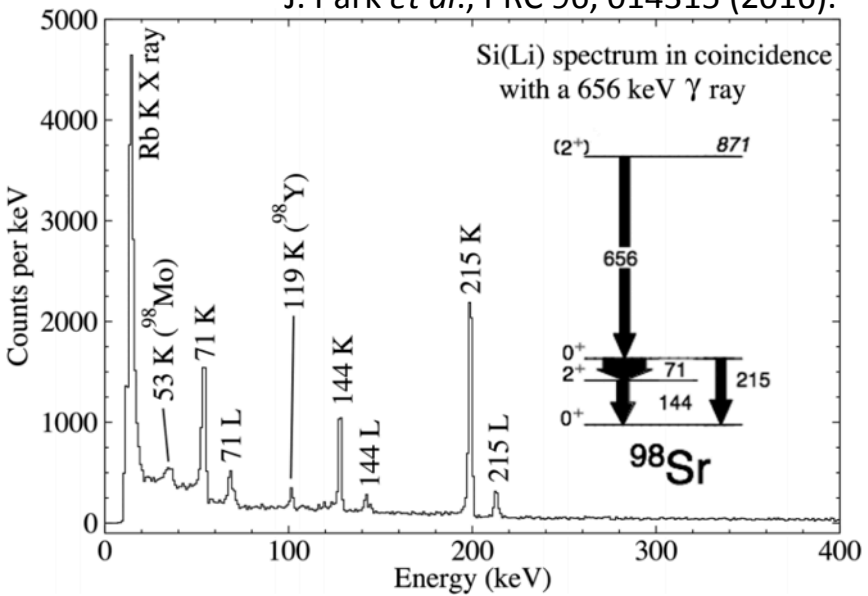
Five 5mm thick, 200mm^2 Si(Li), LN_2-cooled Si diode and FET

Solid angle coverage: 1.4% each, 7% total

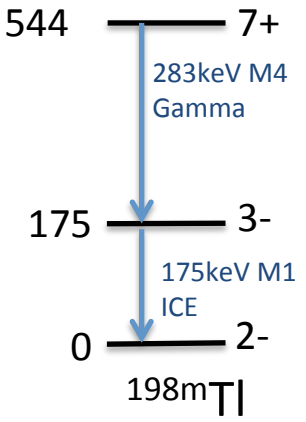
~2keV resolution for electrons



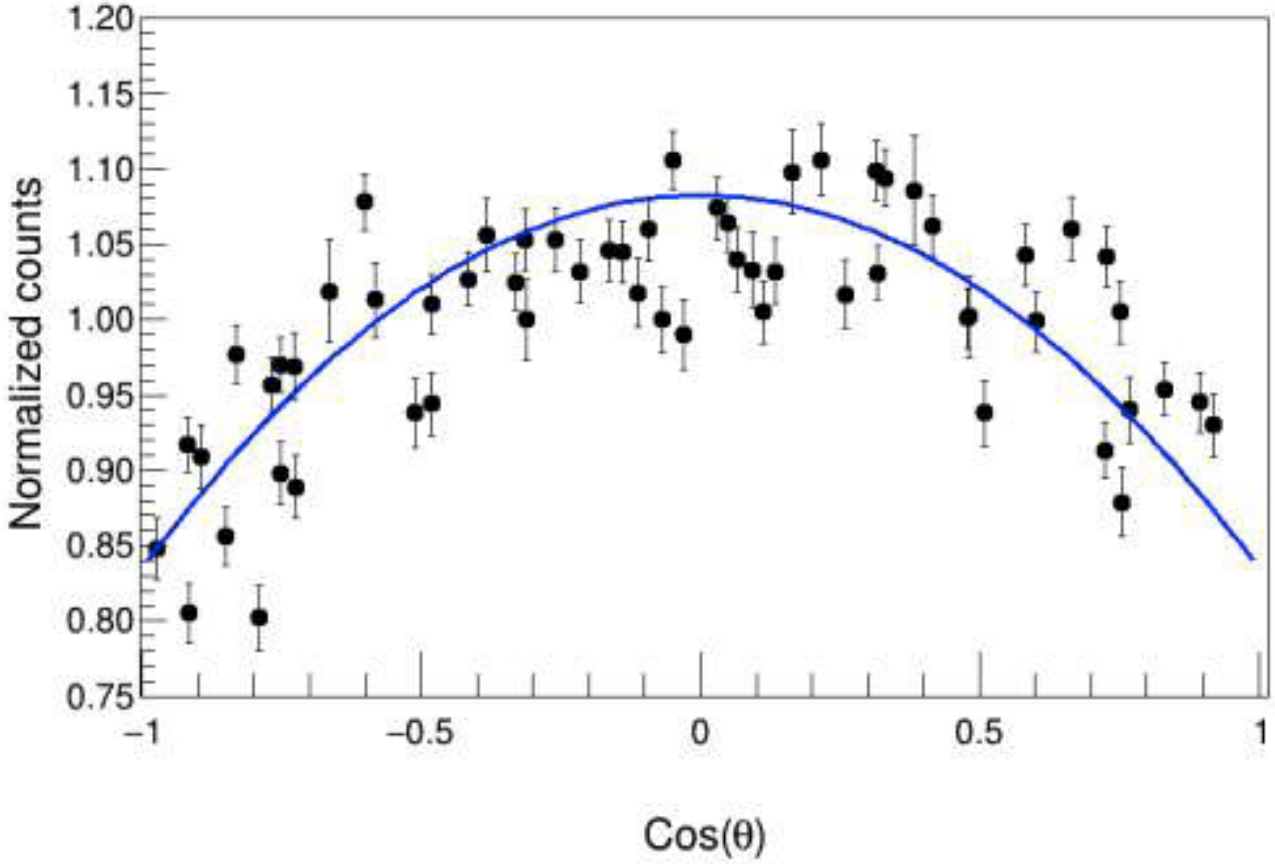
J. Park *et al.*, PRC 96, 014315 (2016).



Gamma-Electron Angular correlations



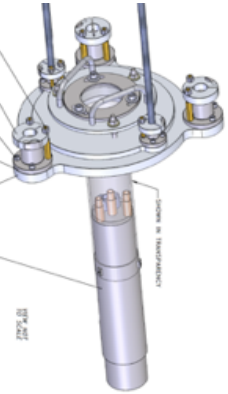
300 Ge-Si(Li) pairs at 18 unique angles for γ-e⁻ angular correlations

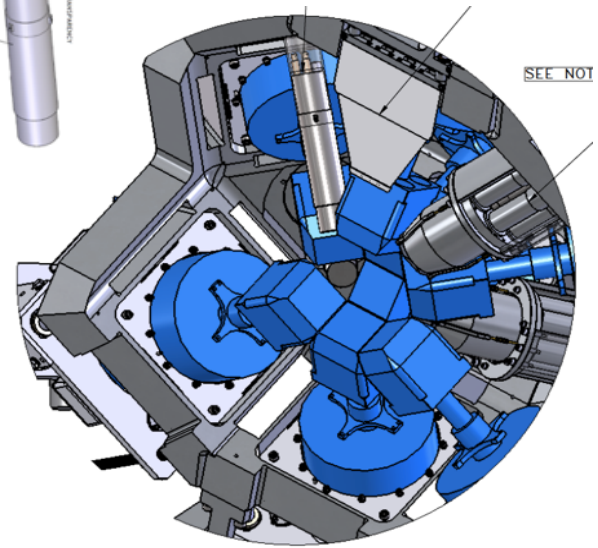


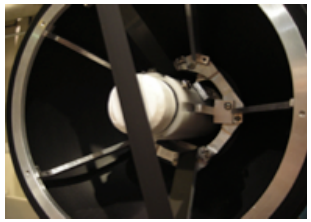
$LaBr_3$ Fast-Scintillator Array for Excited-State Lifetime

- Eight $LaBr_3$(Ce) 2”x2” cylindrical crystal
- Source-detector distance=12.5 cm.
- GEANT4 simulated efficiency 1.4%@1.3MeV

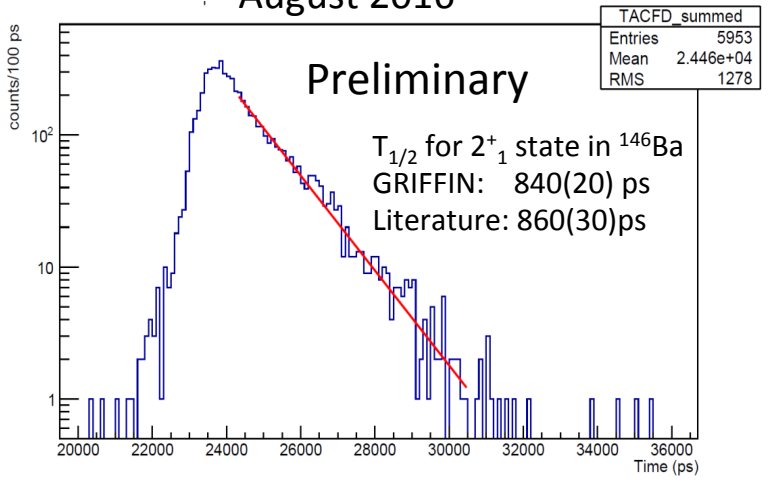
- Hybrid analogue + digital electronics, excellent time resolution
- Effort led by Bruno Olaizola





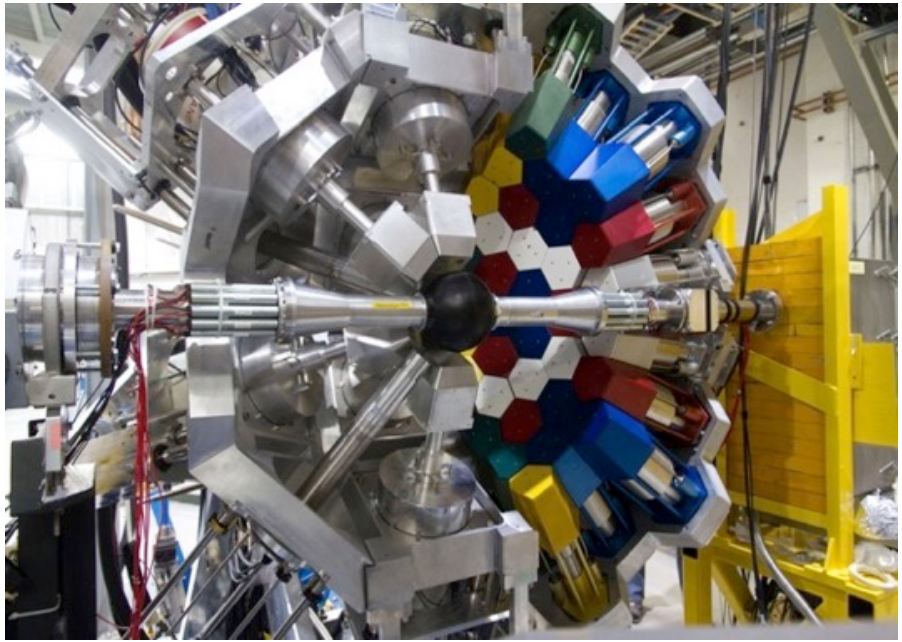


^{146}Cs β decay: GRIFFIN +DESCANT +$LaBr_3$
August 2016

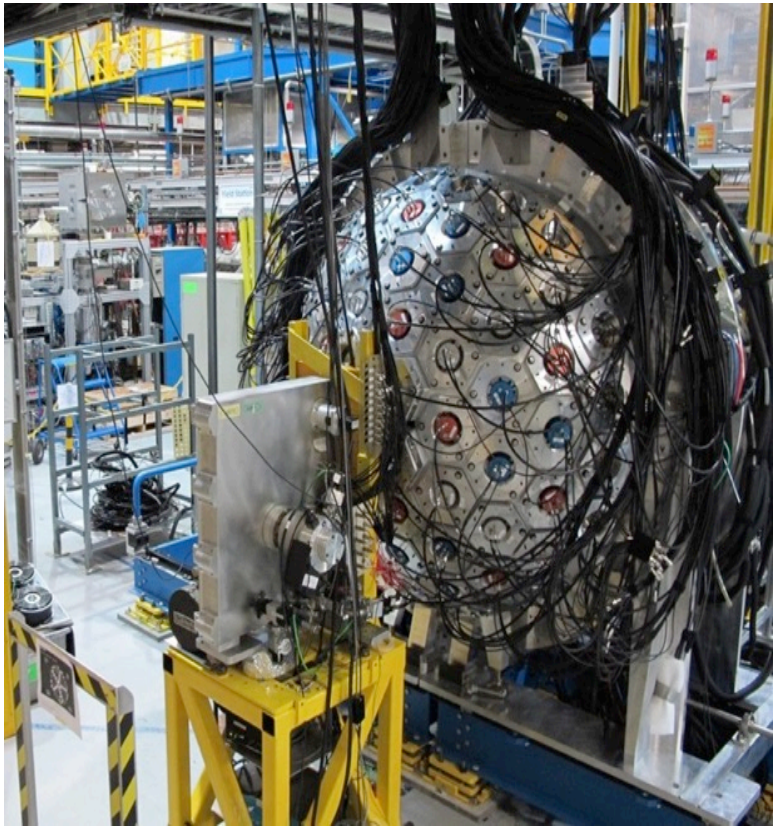


GRIFFIN+DESCANT

- 70 element array of deuterated scintillator for neutron detection
- Enables beta-gamma-ICE-neutron spectroscopy
- ~1π solid angle
- Neutron energy from time-of-flight (50cm flight path)
- Online neutron-gamma discrimination from pulse shape



GRIFFIN + DESCANT, August 2016

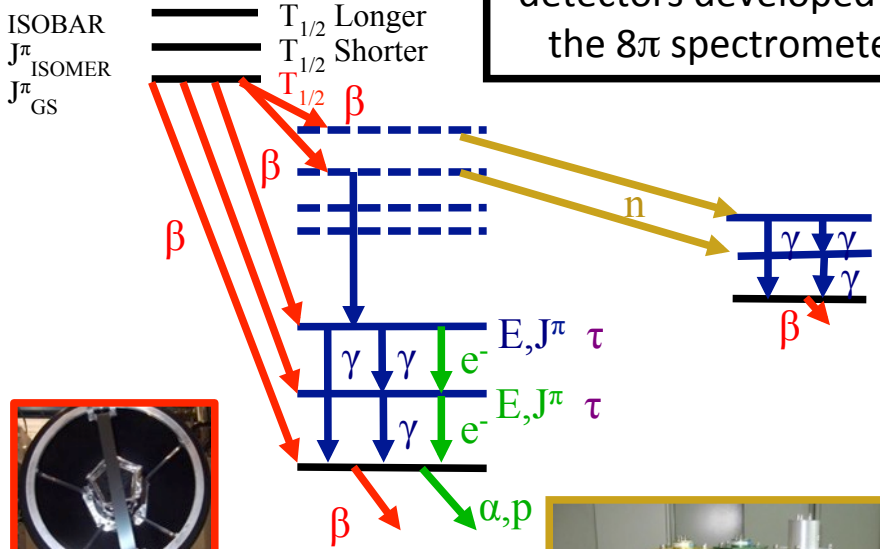


GRIFFIN Ancillary Detectors

Fast, in-vacuum tape system

Enhances decay of interest

GRIFFIN reuses the full suite of ancillary detectors developed for the 8π spectrometer

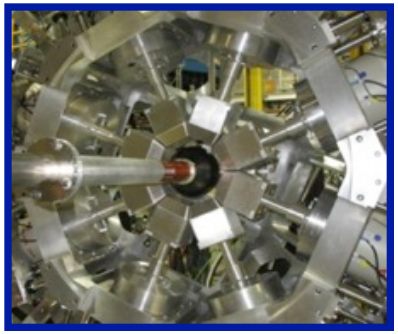


SCEPTAR: 10+10 plastic scintillators

Detects beta decays and determines branching ratios

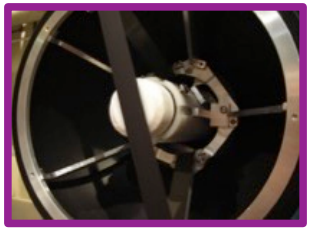
DESCANT Neutron array

Detects neutrons to measure beta-delayed neutron branching ratios



HPGe: 16 Clovers

Detect gamma rays and determines branching ratios, multipolarities and mixing ratios



Zero-Degree Fast scintillator

Fast-timing signal for betas

$LaBr_3$: 8 $LaBr_3$

Fast-timing of photons to measure level lifetimes

PACES: 5 Cooled Si(Li)s

Detects Internal Conversion Electrons and alphas/protons

Custom Digital Electronics Modules designed and built by TRIUMF and Université de Montréal

High data through-put:

Each crystal running at 50kHz

300MB/s of filtered data, 1TB per hour

≈ 5×10^9 gamma-gamma coincidences/hour

…to enable ultra-high-statistics studies

High accountability:

Accurate deadtime knowledge

Pile-up handling

Event traceability from threshold crossing to disk

…to enable high-precision half-life/BR measurements

Custom Digital Electronics Modules designed and built by TRIUMF and Université de Montréal

Programmable Logic Pulse Generator

32 Channels
NIM or TTL

Clock Distribution Module

10MHz Atomic Clock
Low-jitter fan-out to all modules

GRIF-16 Module

16 chans
100MHz,
14bit

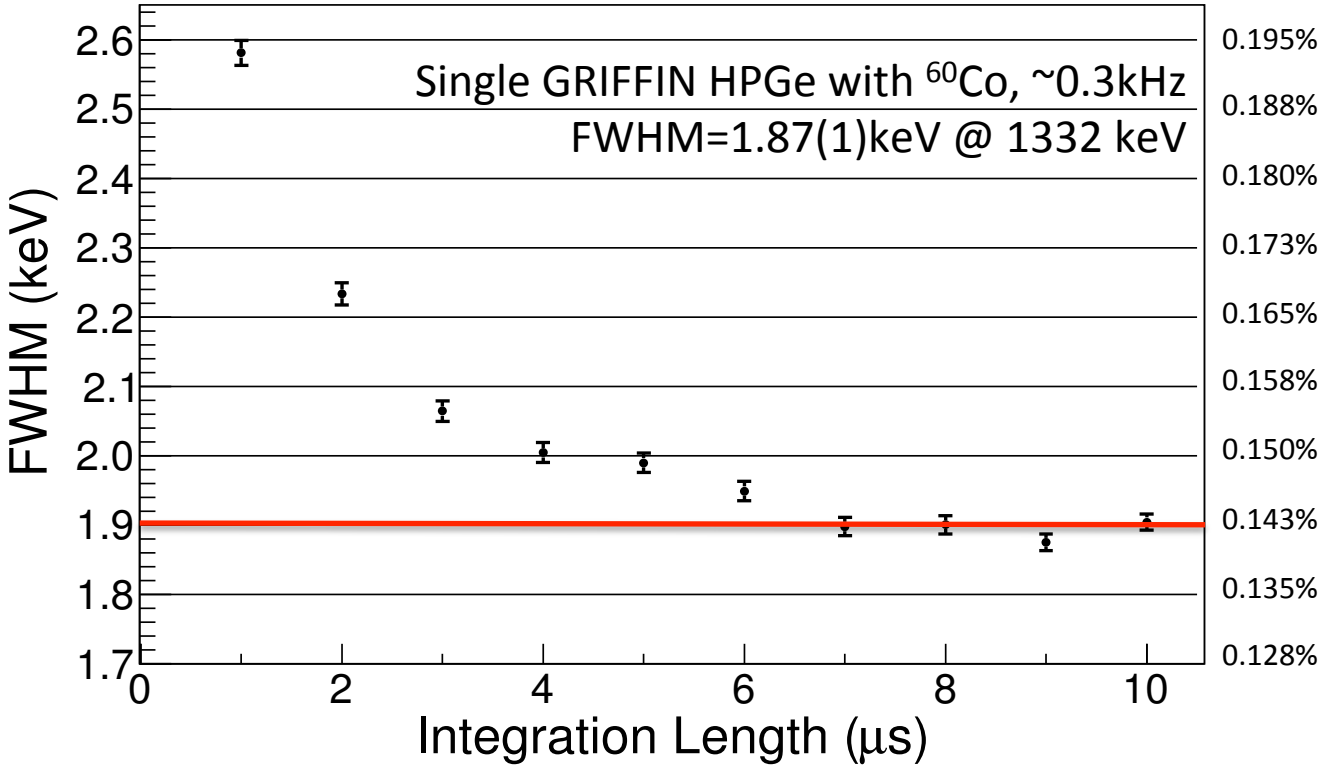
GRIF-4G Module

4 chans
1GHz, 12bit

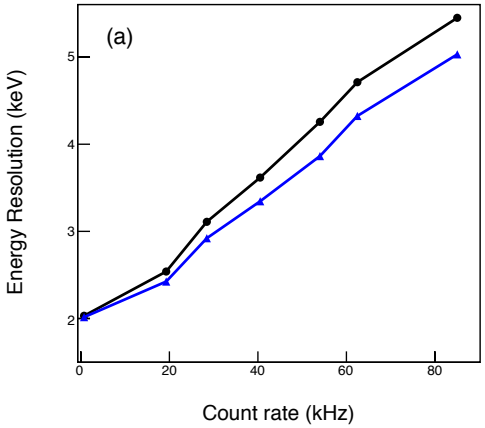
Master and Collector Module

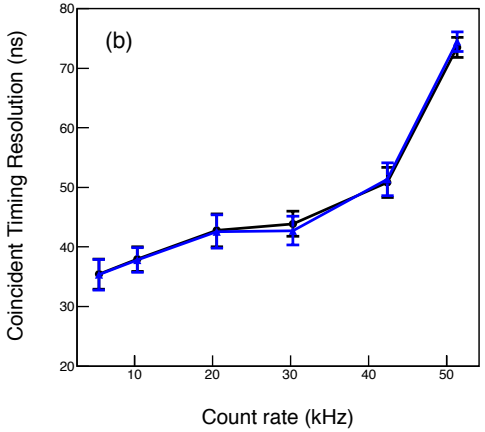
- 625MB/s link to each digitizer
- 1.25Gb/s link to data storage.

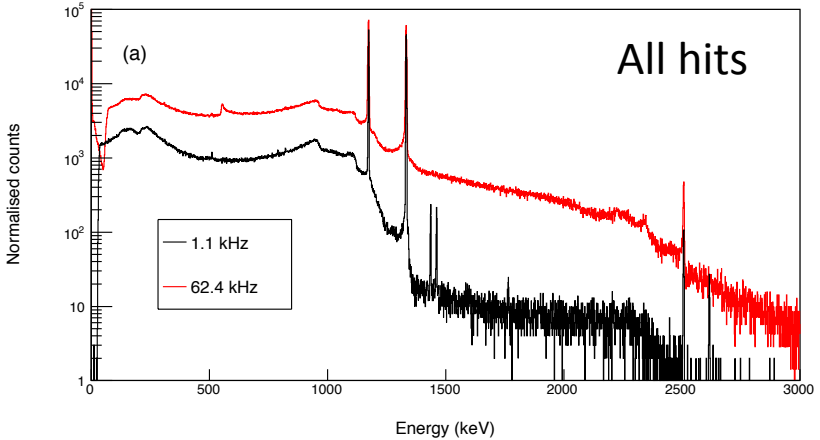
Excellent Energy Resolution with GRIFFIN Digital DAQ

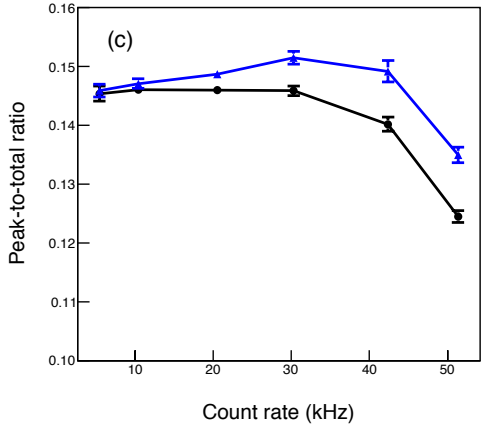


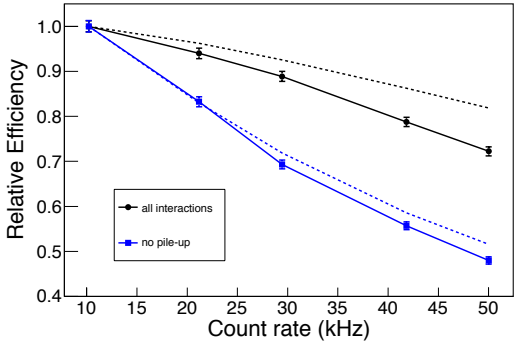
High counting rates

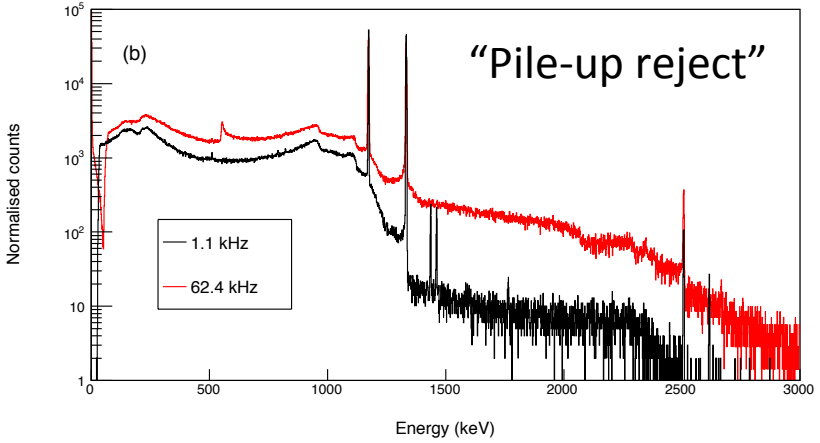




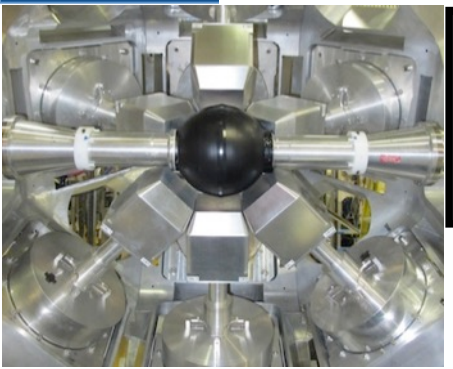




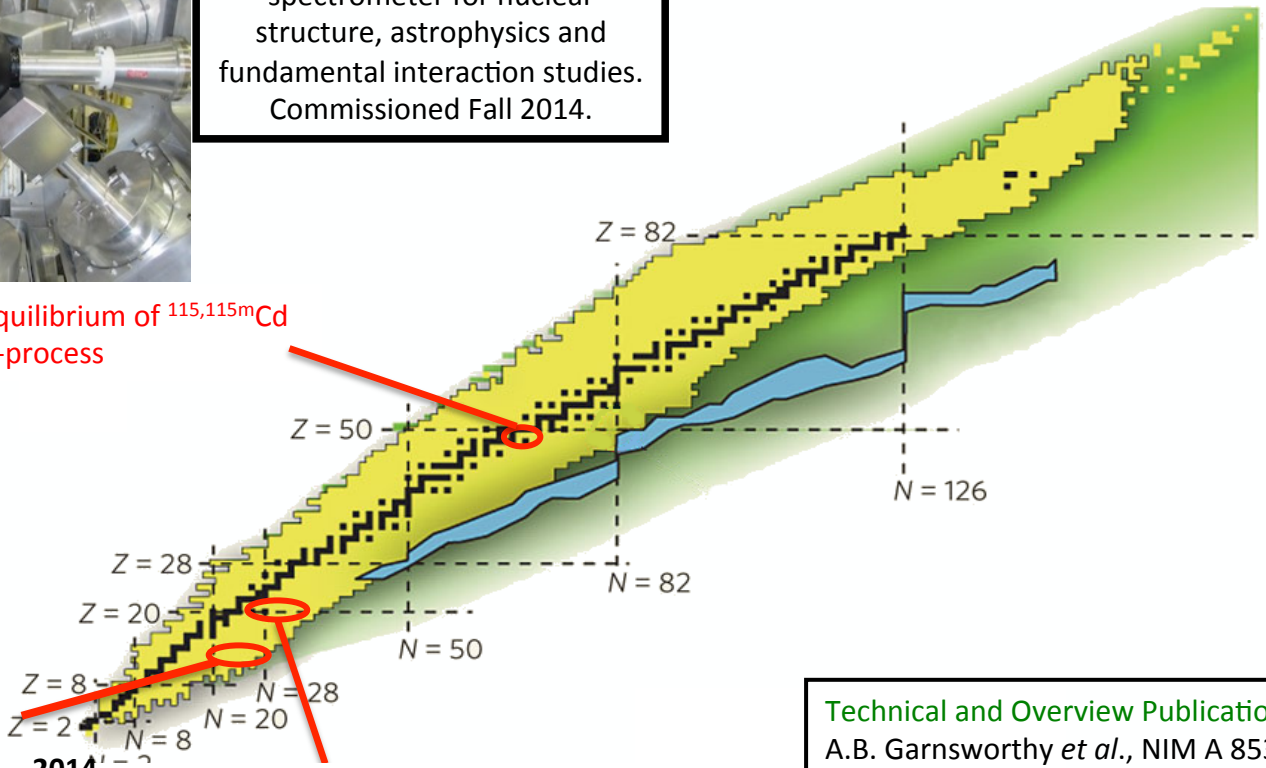




The GRIFFIN Spectrometer for precision decay studies at ISAC



GRIFFIN is a powerful decay spectrometer for nuclear structure, astrophysics and fundamental interaction studies. Commissioned Fall 2014.



Calibrations and development with ^{26}Na beams

2014 ^{115,115m}Ag: Equilibrium of ^{115,115m}Cd during the s-process

2014 ^{31,32}Na: Island of inversion

2014 ^{46,47}K: Single-particle and pair states near doubly-magic ^{48}Ca

Technical and Overview Publications

A.B. Garnsworthy *et al.*, NIM A 853, 85 (2017).
U. Rizwan *et al.*, NIM A 820, 126 (2016).
A.B. Garnsworthy, Acta Phys.Pol. B, 47, 713 (2016).
C.E. Svensson and A.B. Garnsworthy, Hyp. Int. 225, 127 (2014).

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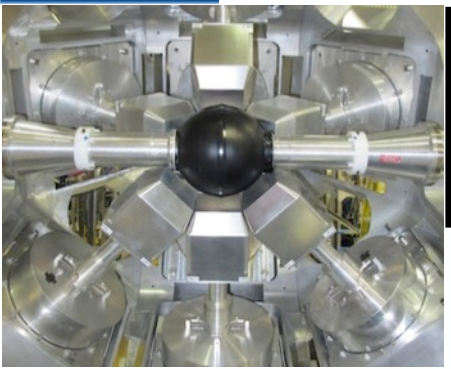

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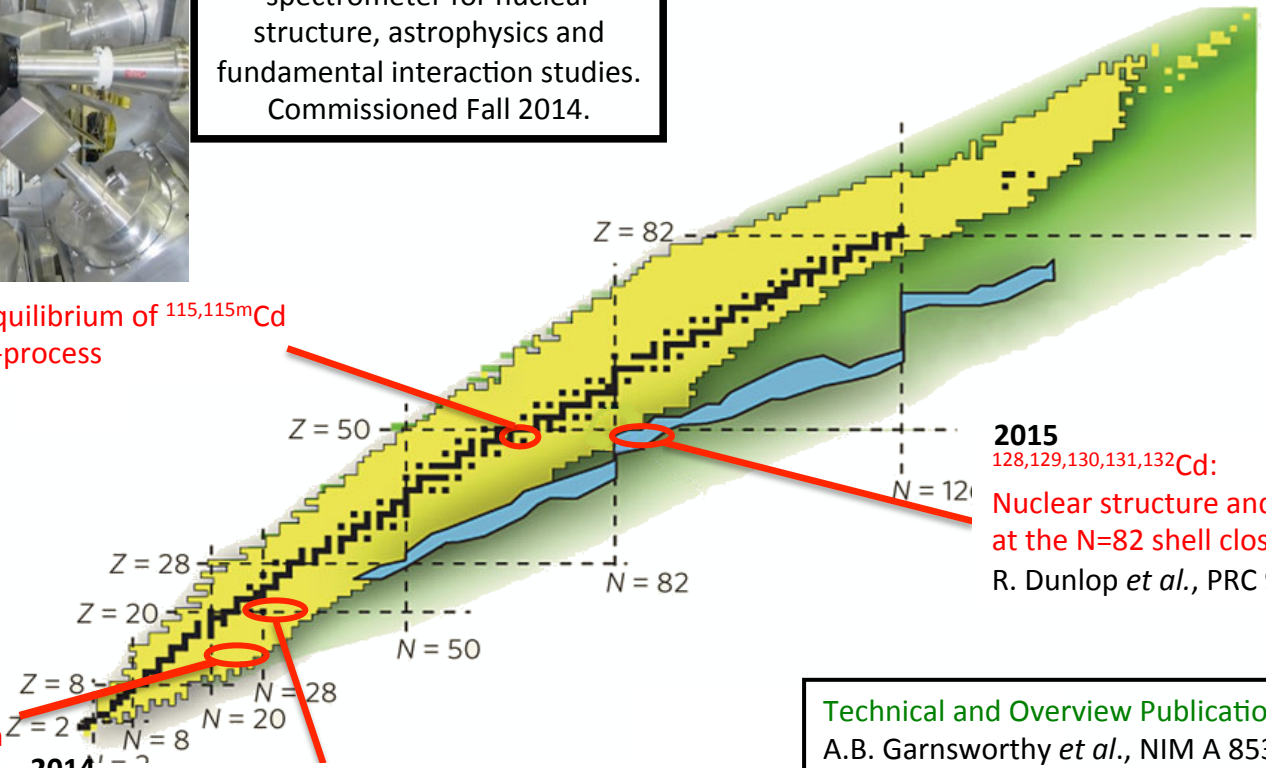

2015
^{128,129,130,131,132}Cd:
Nuclear structure and r-process nucleosynthesis at the N=82 shell closure
R. Dunlop *et al.*, PRC 93, 062801(R) (2016).

2014, 2015
^{31,32}Na, ^{33,34,35}Mg:
Island of inversion

2014
^{46,47}K: Single-particle and pair states near doubly-magic ^{48}Ca

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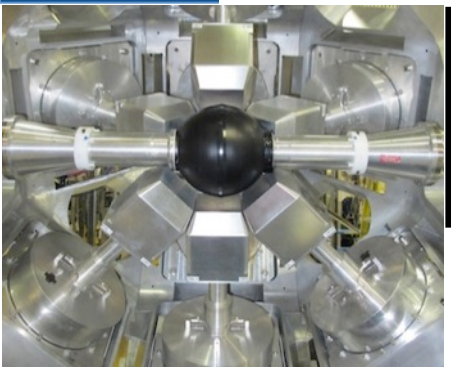
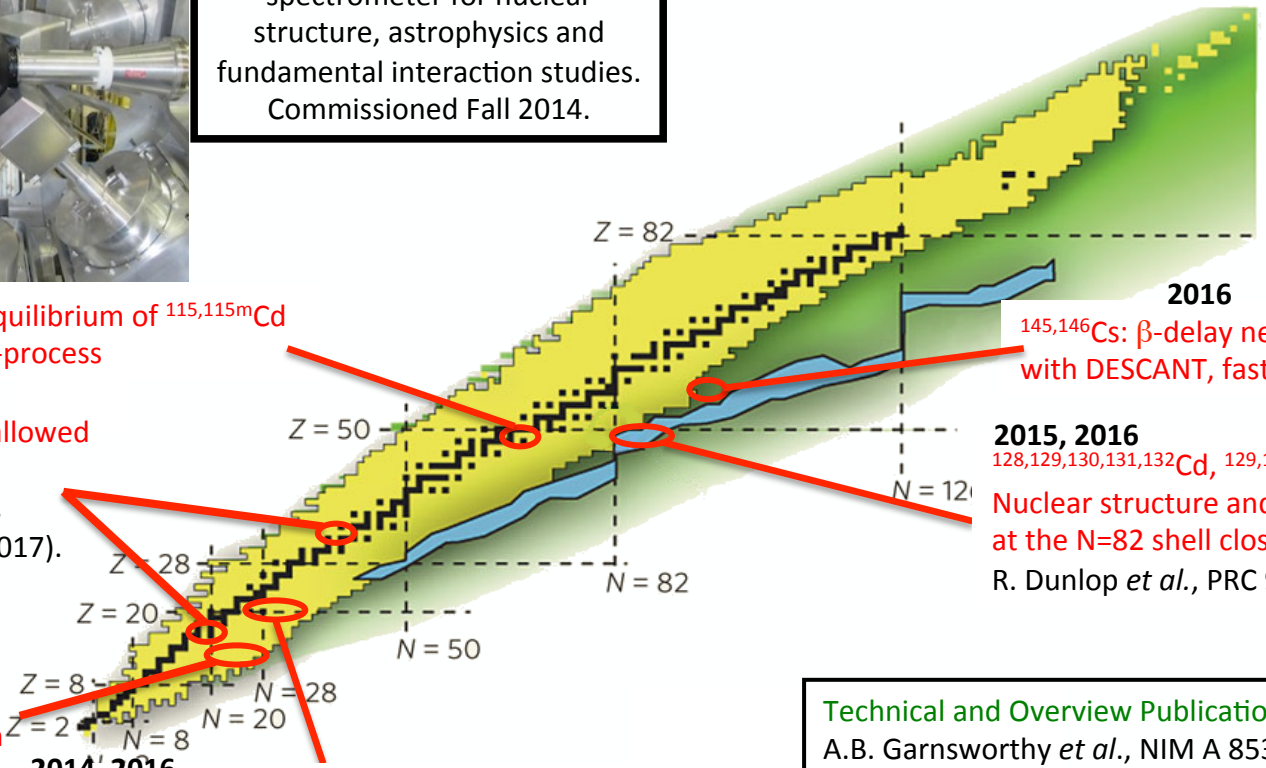


GRIFFIN is a powerful decay spectrometer for nuclear structure, astrophysics and fundamental interaction studies. Commissioned Fall 2014.

Calibrations and development with ^{9}Li, ^{26}Na, ^{66}Ga beams



2014 ^{115,115m}Ag: Equilibrium of ^{115,115m}Cd during the s-process

2016
^{22}Mg, ^{62}Ga: Superallowed Fermi beta decays
M.R. Dunlop *et al.*, PRC 96, 045502 (2017).

2014, 2015
^{31,32}Na, ^{33,34,35}Mg: Island of inversion

2014, 2016
^{46,47}K, ^{50}Ca: Single-particle and pair states near doubly-magic ^{48}Ca
A.B. Garnsworthy *et al.*, PRC 96, 044329 (2017).

2016
^{145,146}Cs: β-delay neutron measurements with DESCANT, fast-timing with $LaBr_3$

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Nuclear structure and r-process nucleosynthesis at the N=82 shell closure
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A.B. Garnsworthy, Acta Phys.Pol. B, 47, 713 (2016).
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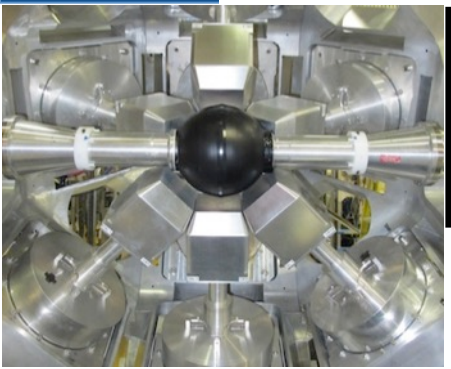

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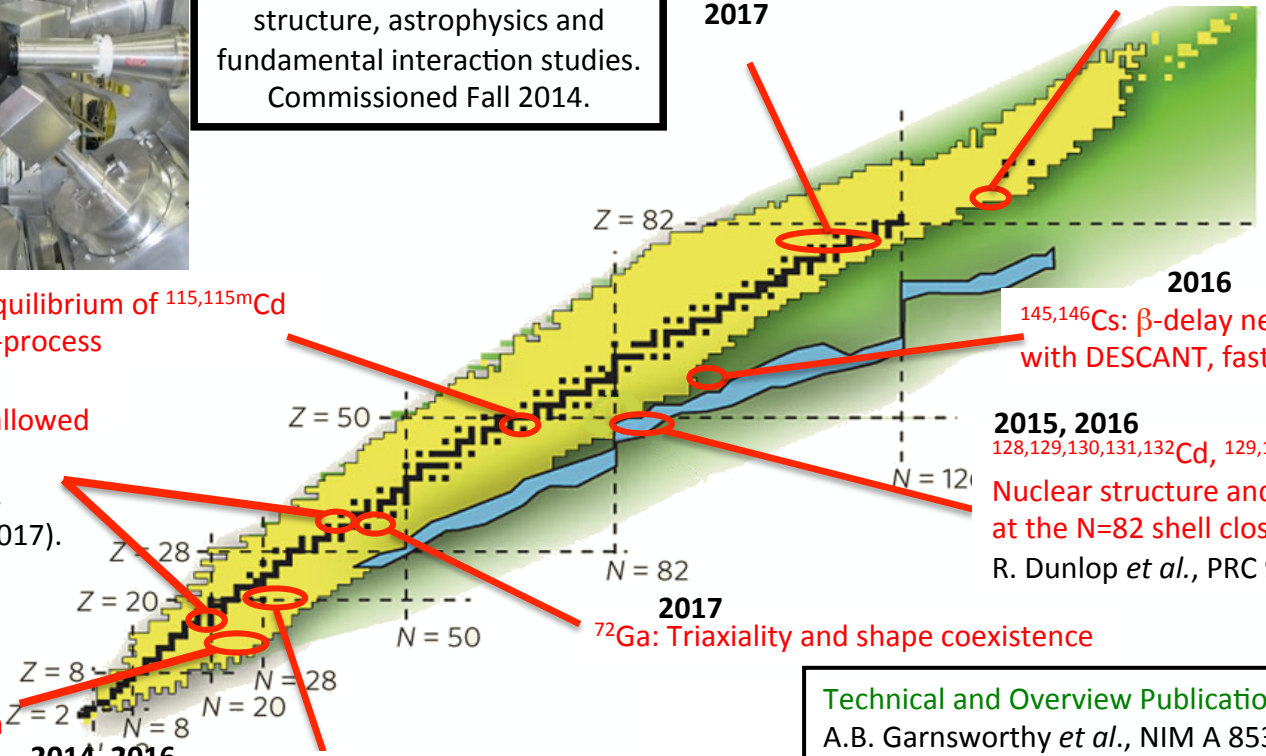

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A.B. Garnsworthy *et al.*, PRC 96, 044329 (2017).

$^{188\text{-}200}$Tl: Development of collectivity in Hg isotopes **2017**

^{228,230}Fr: Probing Octupole deformation and collectivity in Radium isotopes. **2017**

Calibrations and development with ^{9}Li, ^{26}Na, ^{66}Ga beams

2016
^{145,146}Cs: β-delay neutron measurements with DESCANT, fast-timing with $LaBr_3$

2015, 2016
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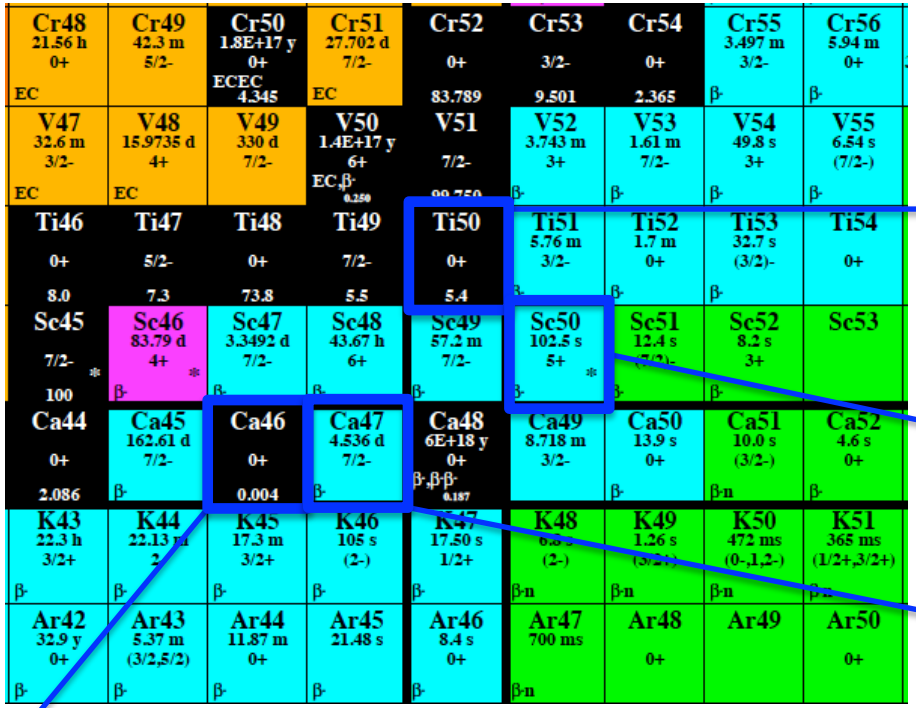
Nuclear structure and r-process nucleosynthesis at the N=82 shell closure
R. Dunlop *et al.*, PRC 93, 062801(R) (2016).

2017
^{72}Ga: Triaxiality and shape coexistence

Technical and Overview Publications
A.B. Garnsworthy *et al.*, NIM A 853, 85 (2017).
U. Rizwan *et al.*, NIM A 820, 126 (2016).
A.B. Garnsworthy, Acta Phys.Pol. B, 47, 713 (2016).
C.E. Svensson and A.B. Garnsworthy, Hyp. Int. 225, 127 (2014).

GRIFFIN studies around doubly-magic ^{48}Ca



Two beamtime periods with GRIFFIN ~5.5 days

- **1 publication, 3 in preparation**
- **1 PhD thesis, 1 Masters thesis**

^{50}Sc - ^{50}Ti, Nov 2016, 1x10^{6}pps, ~5hrs
"Search for particle-hole excitations across the *N*=28 shell closure", C. Jones, Masters thesis (Jan 2018), in preparation for Phys. Rev. C (2018).

^{50}Ca - ^{50}Sc, Nov 2016, 1x10^{6}pps, ~2hrs
"Spectroscopy of ^{50}Sc and the first calculation of *B(M3)* strengths using *ab initio* methods", A.B. Garnsworthy, Phys. Rev. C 96, 044329 (2017).

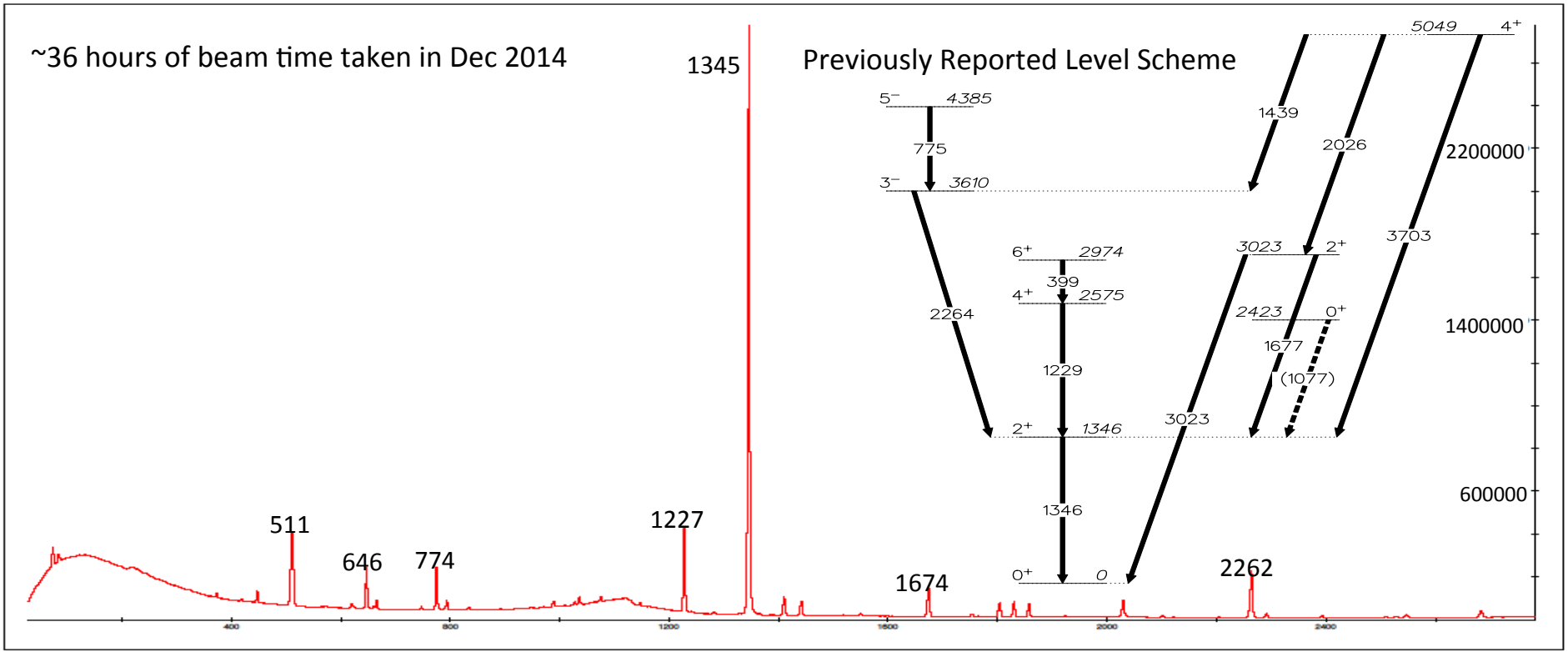
^{47}K – ^{47}Ca, Dec 2014, 1x10^{5}pps, ~90hrs
"Detailed decay spectroscopy of ^{47}Ca",
J.K. Smith, in preparation for Phys. Rev. C (2018).

^{46}K – ^{46}Ca, Dec 2014, 4x10^{5}pps, ~40hrs
"Detailed spectroscopy of ^{46}Ca: The investigation of the β decay of ^{46}K with the GRIFFIN γ-ray spectrometer", J.L. Pore, PhD thesis (2017), in preparation for Phys. Rev. C (2018).

^{46}K to ^{46}Ca Beta-Decay G-G Coincidences

Jennifer Pore, Corina Andreoiu, *SFU*

~36 hours of beam time taken in Dec 2014

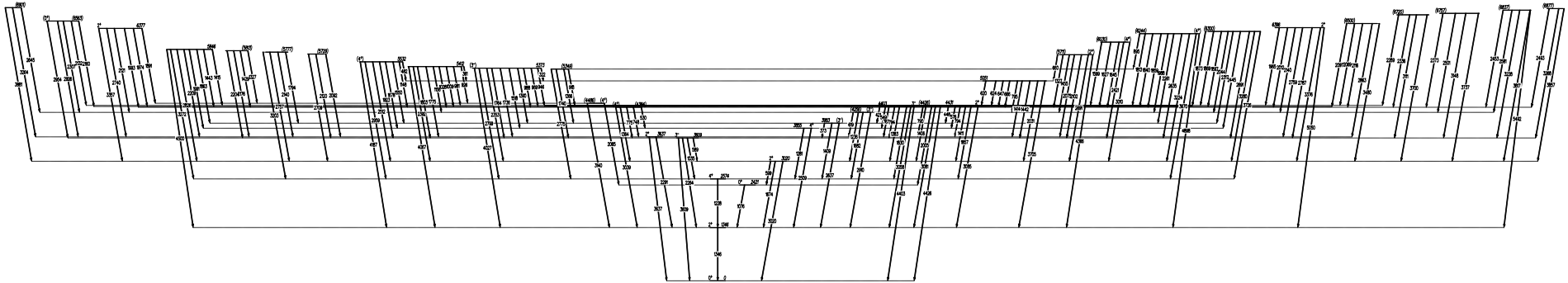


^{46}K to ^{46}Ca Beta-Decay

^{46}K beam of 4x10^{5}pps for ~40hrs

~200 gamma-ray transitions newly placed.

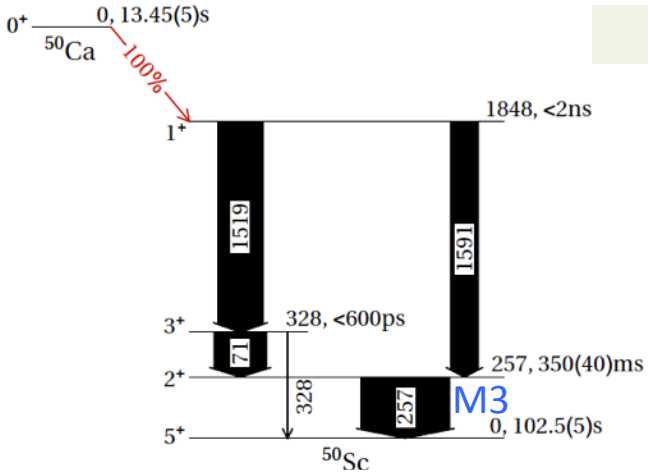
14 previously unobserved excited states (45 total observed).

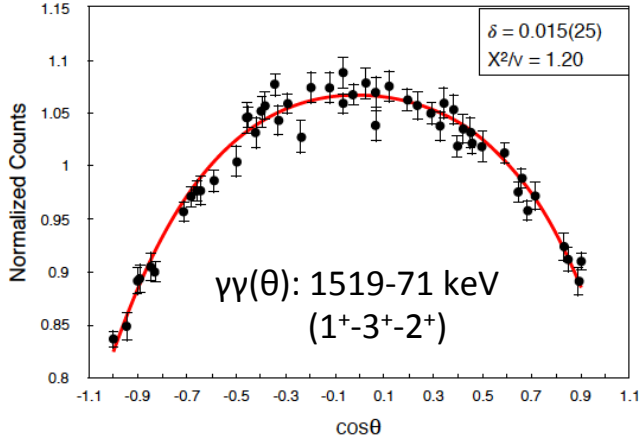


- States observed to within 815keV of the 7.7MeV *Q* value.
- Branching ratios observed down to 10^{-3}.
- Weakest γ-ray observed has intensity of 0.0015% that of the 2_1^+ to 0_1^+ transition.
- **Compton-Suppression shields would have allowed observation of even weaker transitions.**

- PhD thesis of J. Pore, Simon Fraser University.
- In preparation for PRC.

GRIFFIN Results: Spectroscopy of ^{50}Sc and *ab initio* calculations of *B(M3)* strengths





A.B. Garnsworthy, M. Bowry, B. Olaizola, J.D. Holt, S.R. Stroberg *et al.*, PRC 96, 44329 (2017).

Gamma-gamma angular correlations with GRIFFIN confirm *M3* isomer in ^{50}Sc.

Isotope	E_γ (keV)	$J_i^\pi \rightarrow J_f^\pi$	ΔT	$T_{1/2}$	I_γ	α_{Tot}	I_{Tot}	Exp. $B(M3)$
^{24}Na [46–49]	472.2074(8)	$1^+ \rightarrow 4^+$	0	20.18(10)ms	0.9995(5)	0.000469(7)	0.9995(5)	9.10(7)
^{24}Al [50]	425.8(1)	$4^+ \rightarrow 1^+$	0	131.3(25)ms	0.83(3)	0.001144(16)	0.83(3)	2.4(6)
^{34}Cl [51]	146.36(3)	$3^+ \rightarrow 0^+$	1	31.99(3)min	0.383(5)	0.1656(24)	0.446(6)	0.10(1)
^{38}Cl [48, 52, 53]	671.365(8)	$5^- \rightarrow 2^-$	0	715(3)ms	0.3826(8)	0.000599(9)	1	0.0118(8)
^{38}K [54]	130.1(2)	$0^+ \rightarrow 3^+$	1	924.33(27)ms	$8(1)\times10^{-6}$	0.394(7)	0.00033(4)	0.29(10)
^{50}Sc [33]	257.895(1)	$2^+ \rightarrow 5^+$	0	350(40)ms	0.97(3)	0.0350(5)	0.99(1)	13.6(7)

First calculation of *B(M3)* strengths using *ab initio* Valence-Space In-Medium Similarity Renormalization Group method and effective operator.

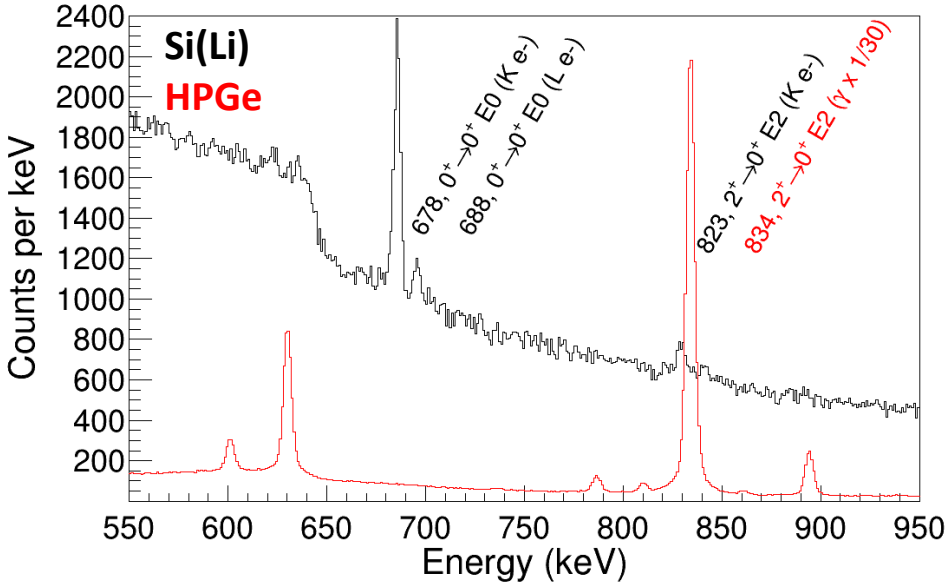
Isotope	$J_i^\pi \rightarrow J_f^\pi$	ΔT	Exp. $B(M3)$	Phenomenological shell model $B(M3)$	VS-IMSRG Effective Op.
^{24}Na	$1^+ \rightarrow 4^+$	0	9.10(7)	19.9	4.45
^{24}Al	$4^+ \rightarrow 1^+$	0	2.4(6)	2.72	1.76
^{34}Cl	$3^+ \rightarrow 0^+$	1	0.10(1)	0.157	0.0013
^{38}Cl	$5^- \rightarrow 2^-$	0	0.0118(8)	0.0003	0.022
^{38}K	$0^+ \rightarrow 3^+$	1	0.29(10)	0.324	0.015
^{50}Sc	$2^+ \rightarrow 5^+$	0	13.6(7)	13.9	9.62

Ultra-high statistics beta-decay spectroscopy of ^{72}Ga-^{72}Ge

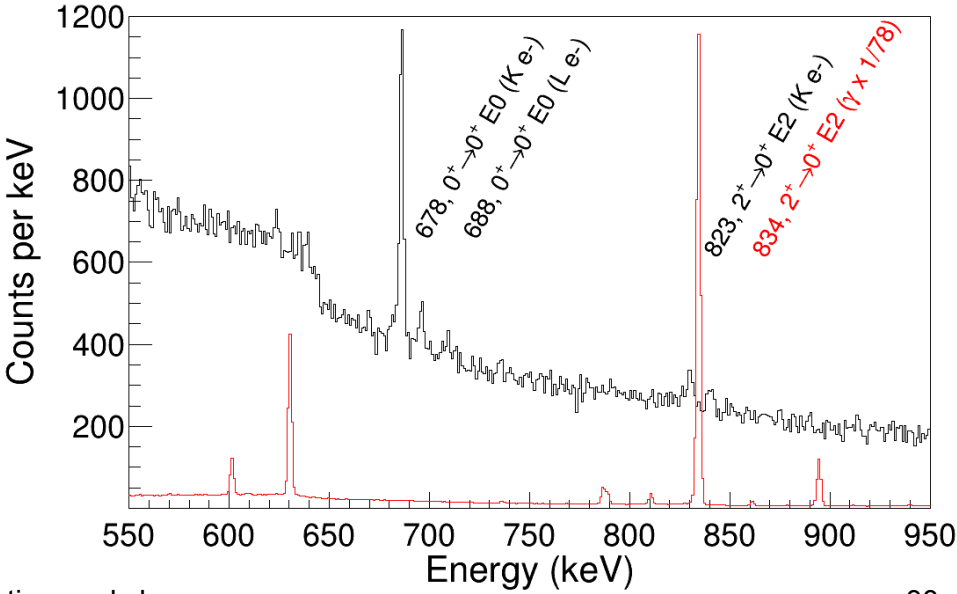
A.B. Garnsworthy, J. Henderson, J. Smallcombe, J.K. Smith, M. Bowry, *et al.*, Beamtime Oct 2017

$T_{1/2}$=14 hours. Data collected for ~12 half lives.
The two GRIFFIN and PACES spectra below each represent 10GB out of a total of 8,000GB = 0.125%!

High Rate, ~3MBq, ~84µCi, 80MB/s total DAQ rate
16kHz Si(Li), 24kHz HPGe per channel



Low Rate, ~25kBq, ~0.7µCi, ~2MB/s total DAQ rate
0.5kHz Si(Li), 0.2kHz HPGe per channel



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The GRIFFIN Facility for Decay-Spectroscopy Studies at TRIUMF-ISAC

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