Recent highlights from the GRIFFIN spectrometer

Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei

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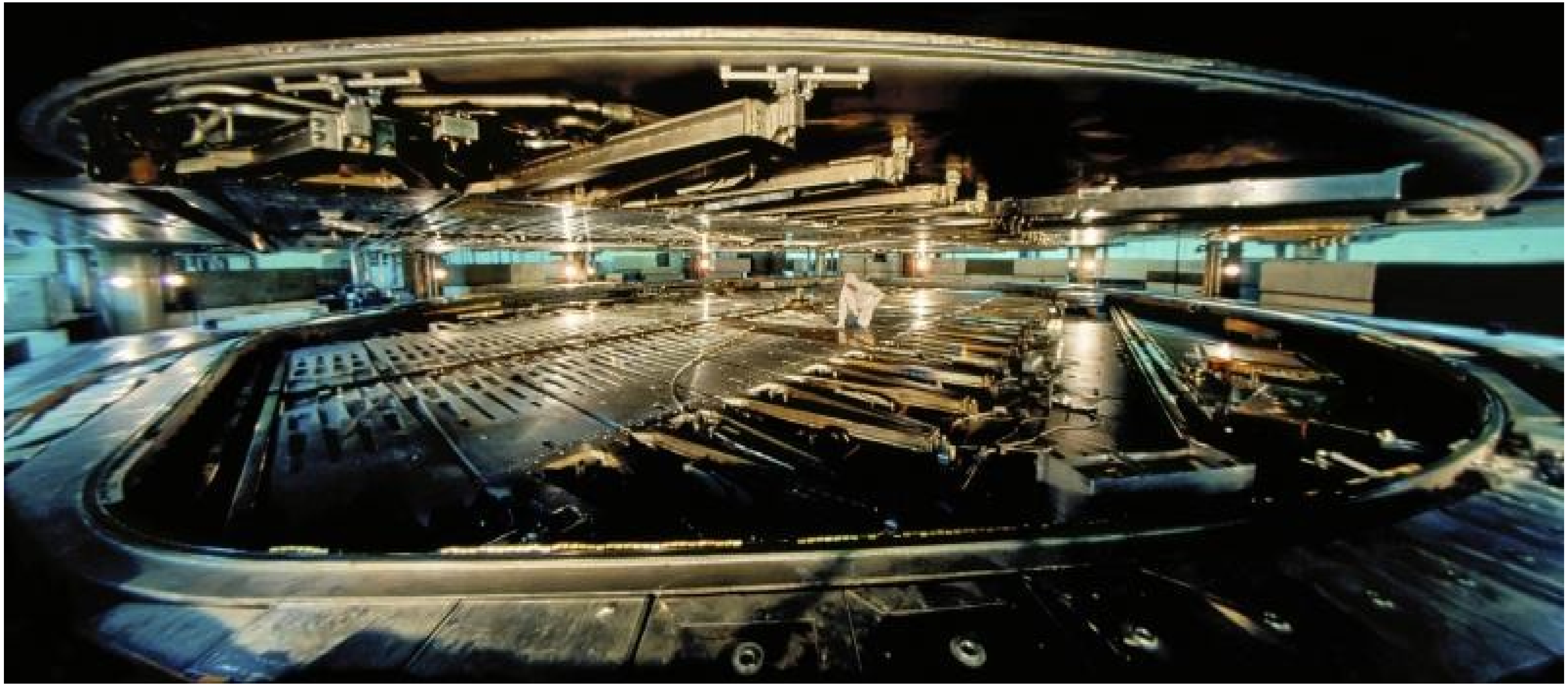
TRIUMF

GRIFFIN

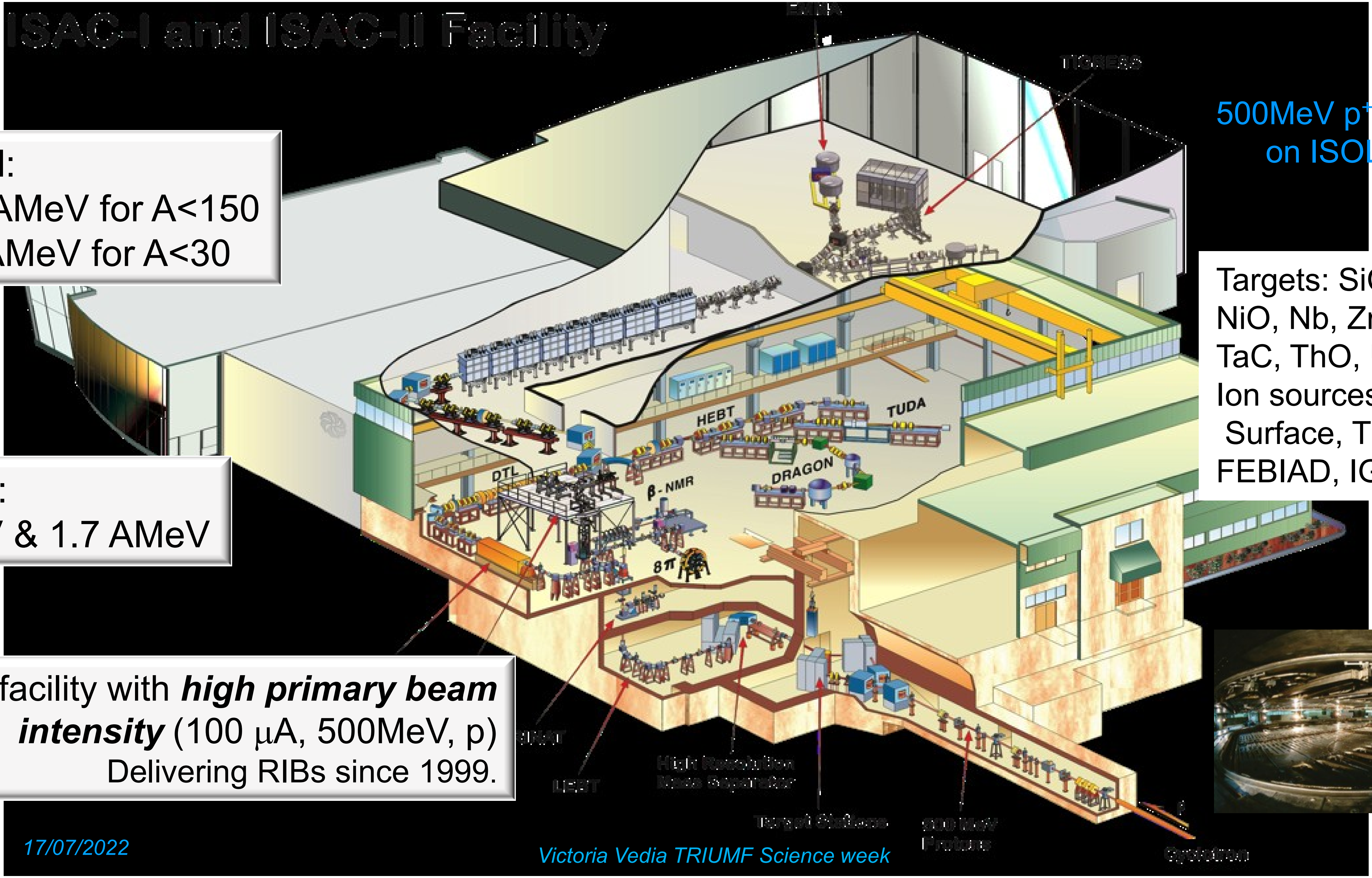
TRIUMF: Canada's National Laboratory for Accelerator-based science



- 18 m in diameter
- 520 MeV proton beam
- 4 beamlines

> 50 years of accelerator-based science and innovation

ISAC: Isotope Separator and ACcelerator



ISAC II:
- 10 AMeV for A<150
- 16AMeV for A<30

ISAC I:
60 keV & 1.7 AMeV

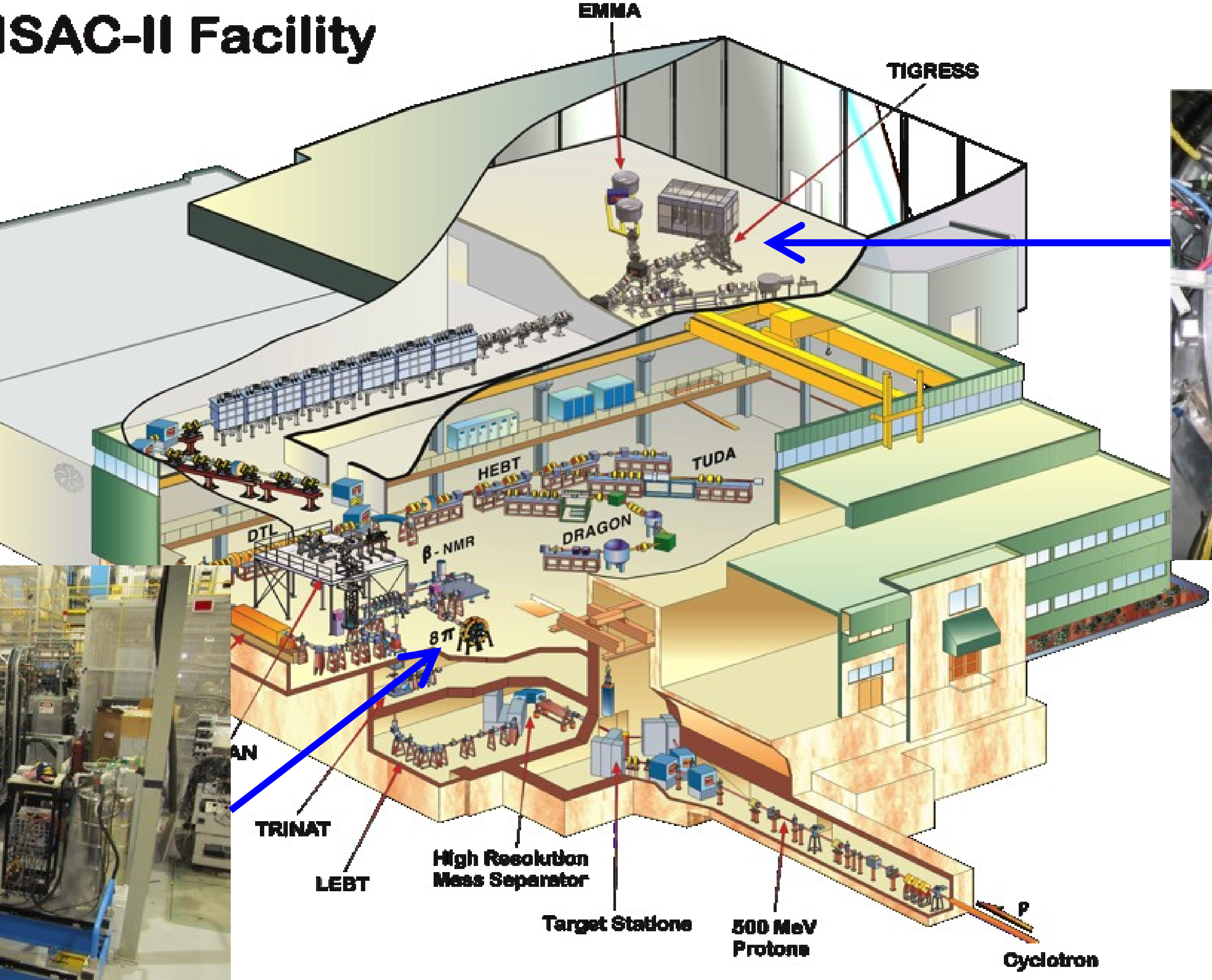
ISOL facility with ***high primary beam intensity*** (100 μA, 500MeV, p)
Delivering RIBs since 1999.

500MeV p^+ at 100μA on ISOL target

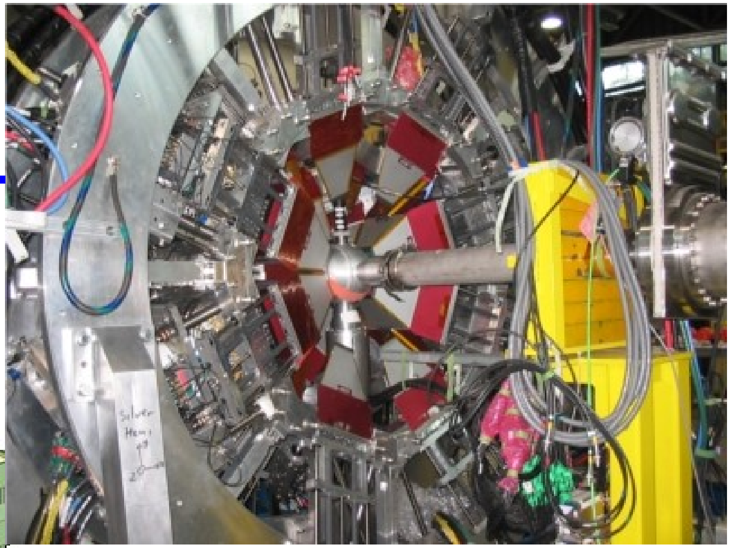
Targets: SiC, TiC, NiO, Nb, ZrC, Ta, TaC, ThO, UO, UCx
Ion sources:
Surface, TRILIS, FEBIAD, IG-LIS

Gamma-Ray Spectroscopy at ISAC

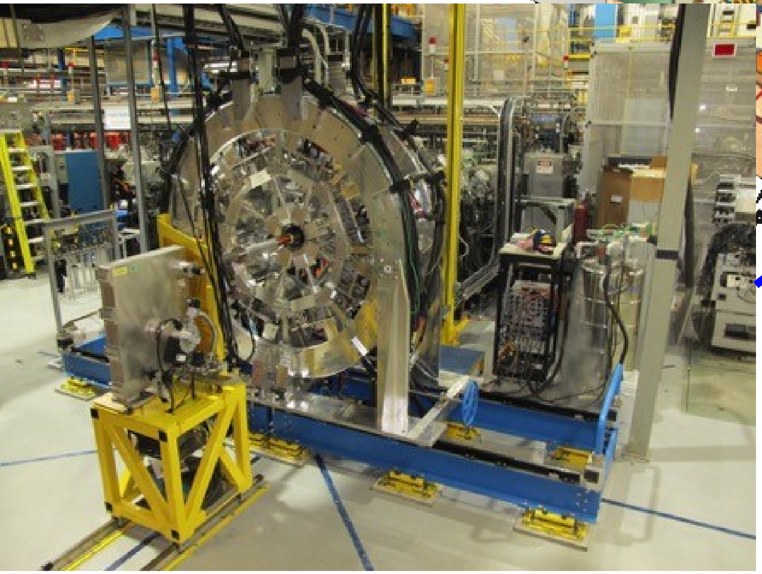
ISAC-I and ISAC-II Facility



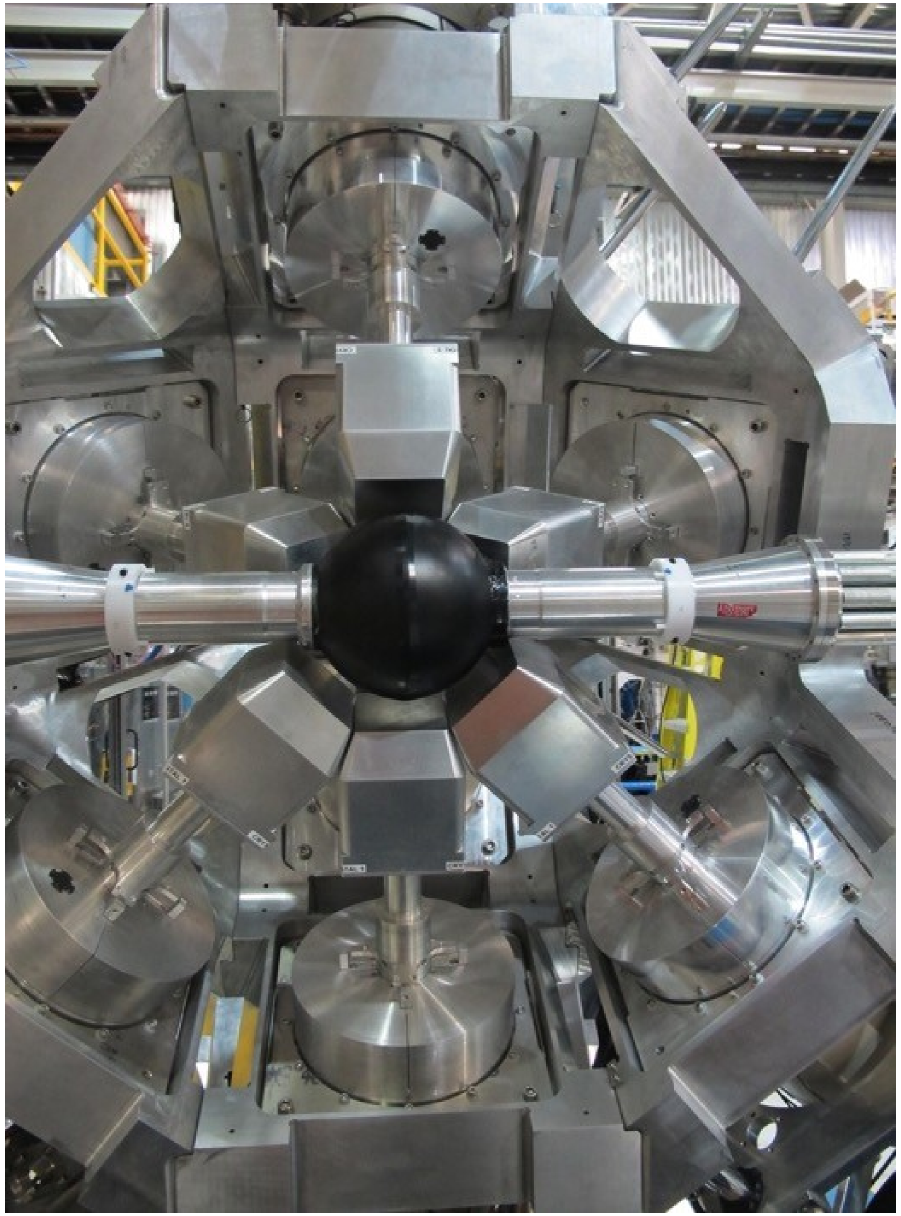
TIGRESS

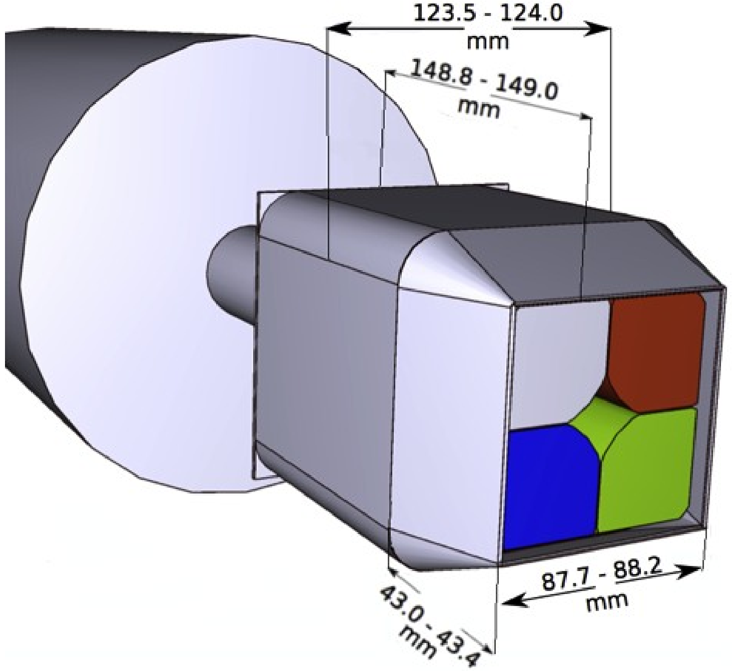


GRIFFIN



GRIFFIN spectrometer





- 16 Clover HpGe detectors
- 4 HPGe crystals in each cryostat (addback)

Average Performance of all 64 crystals (16 clovers):

Energy resolution@ 121keV = 1.12(6) keV

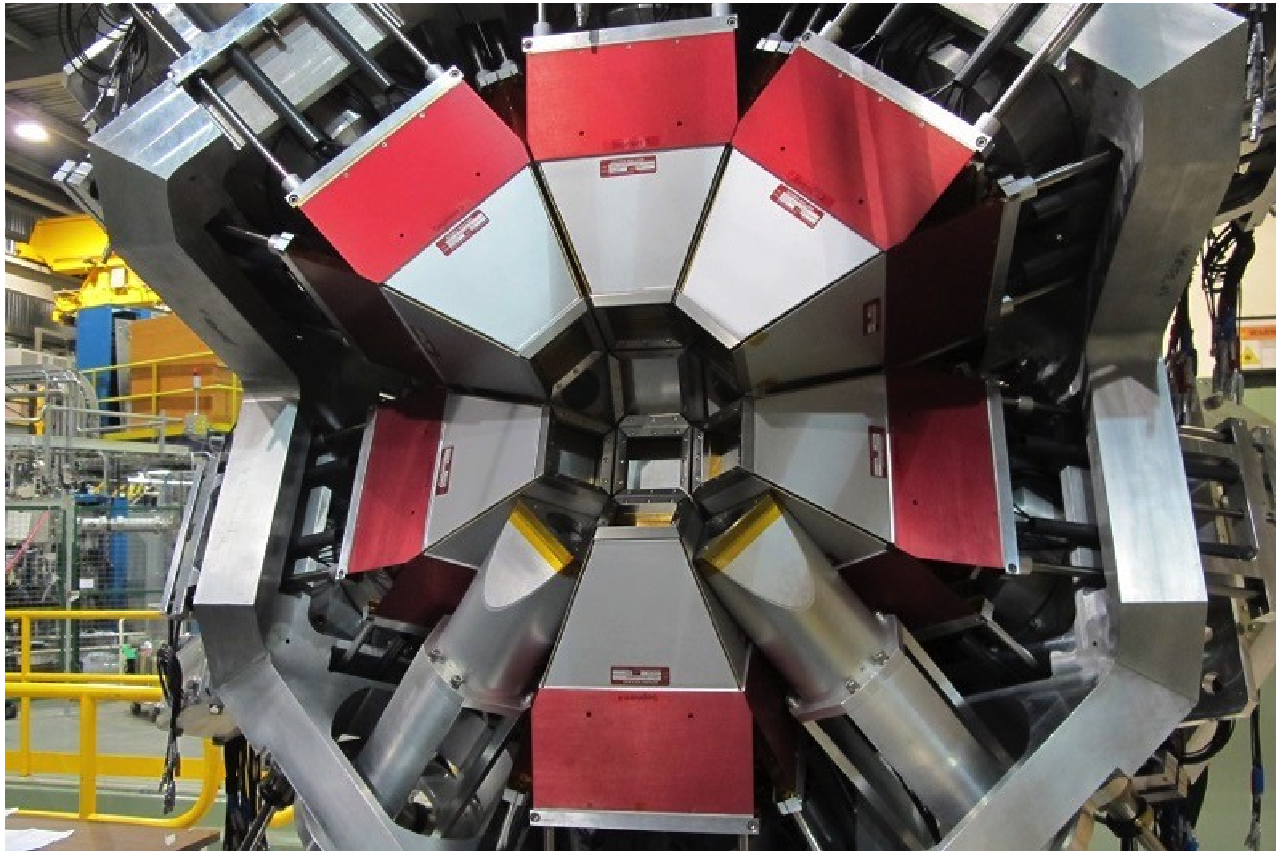
Energy resolution@ 1.3MeV = 1.89(6) keV

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

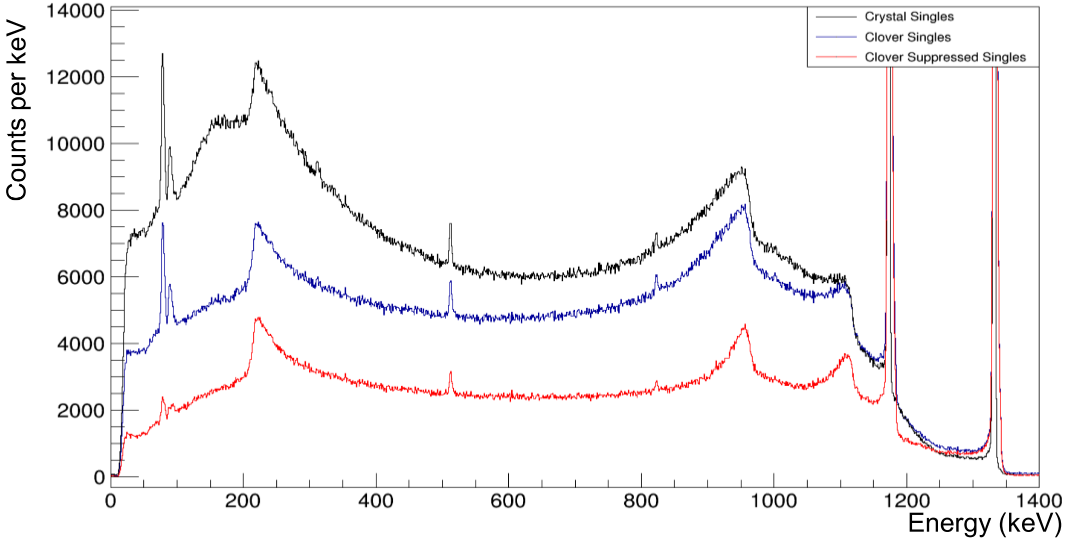
U. Rizwan *et al*., NIM A 820, 126 (2016)

GRIFFIN Compton and Background Suppression Shields

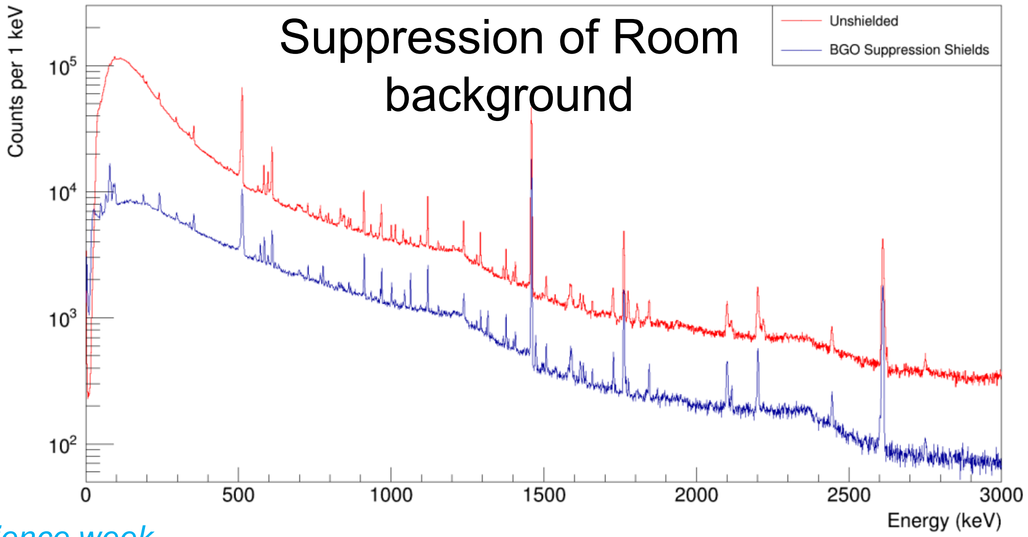
- All performance acceptance testing completed at Simon Fraser University
- Array has operated with full-suppression since June 2018.



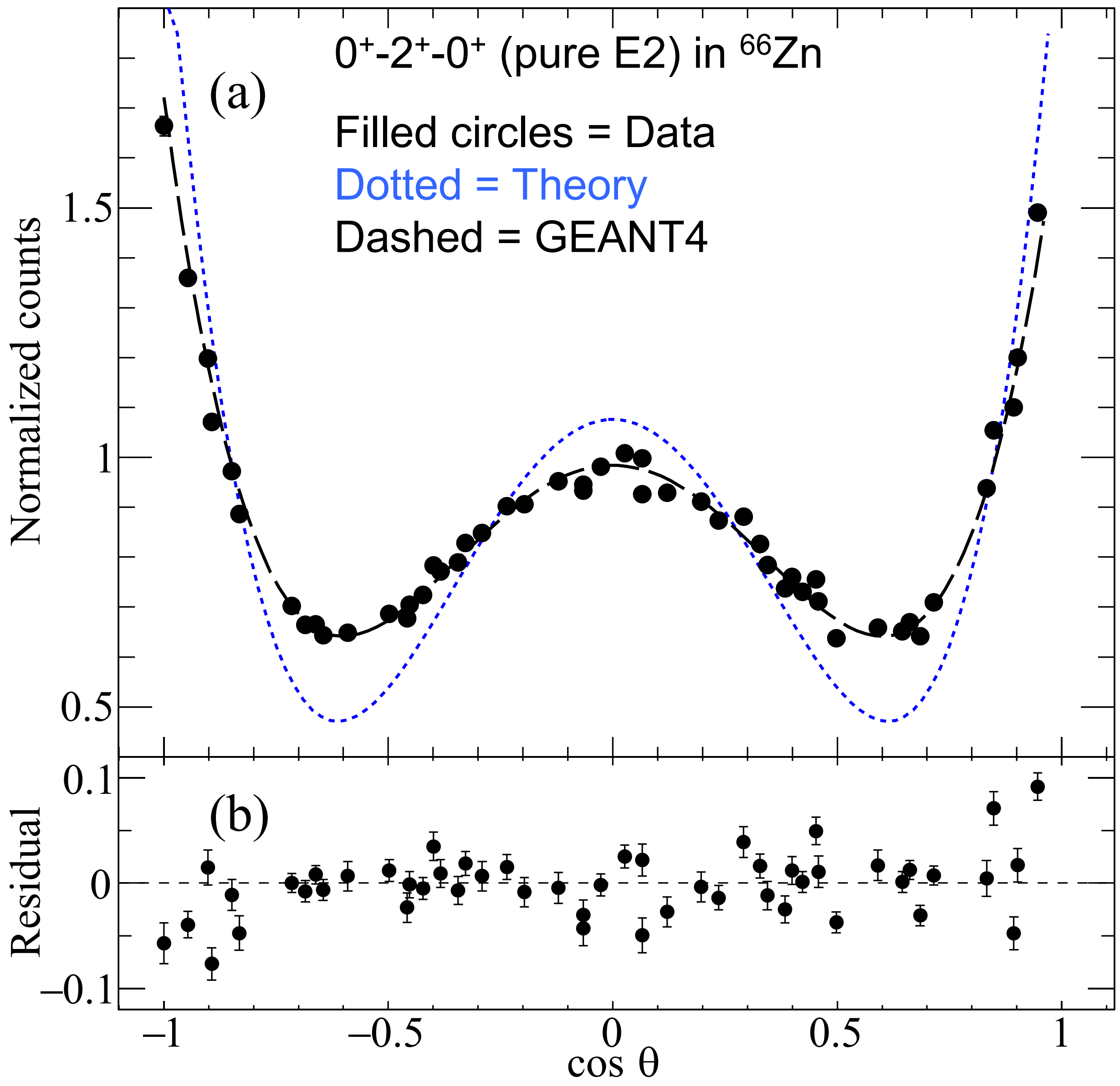
Online hardware suppression now available in GRIF-C filter



3 Hour Room Background



Gamma-Gamma Angular Correlation Analysis



J.K. Smith, A.C. MacLean *et al.*
NIM A 922, 47 (2019).
https://arxiv.org/abs/1807.07570

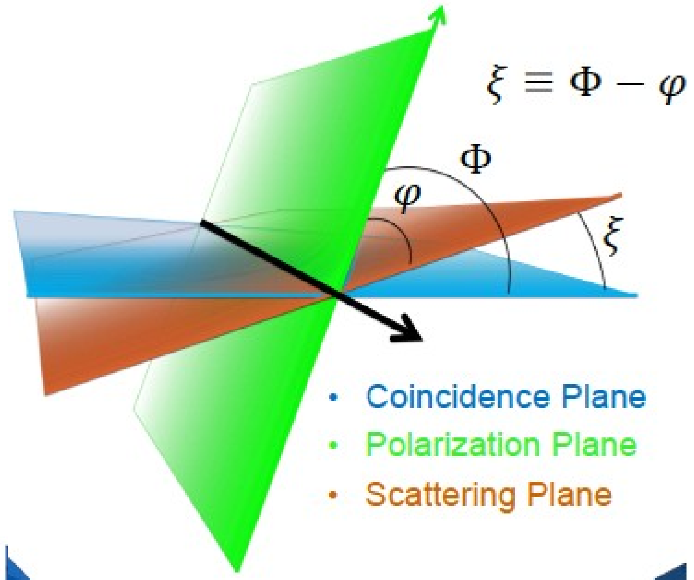
Development of γ–γ angular correlation analysis techniques with GRIFFIN.

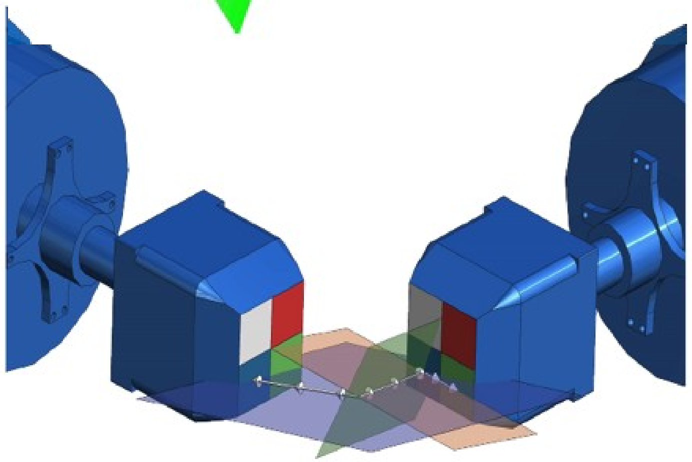
- Finite size and shape of crystals means theoretical distribution is attenuated.
- Obtain 'template' from high-statistics GEANT4 simulation
- Fit template to experimental data.

Ideally:

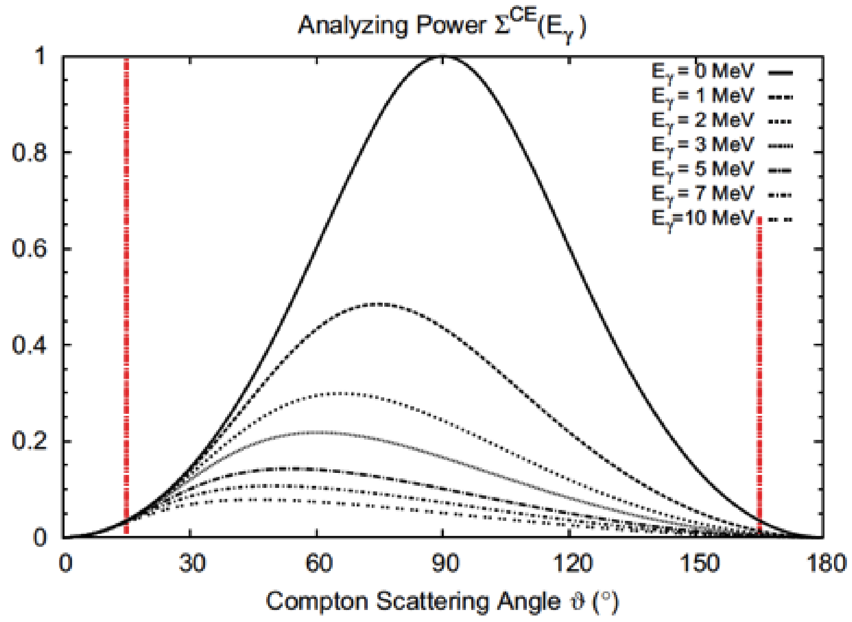
- Fit experimental data
- Plug coefficients into simple equations
- Obtain corrected 'true' coefficients

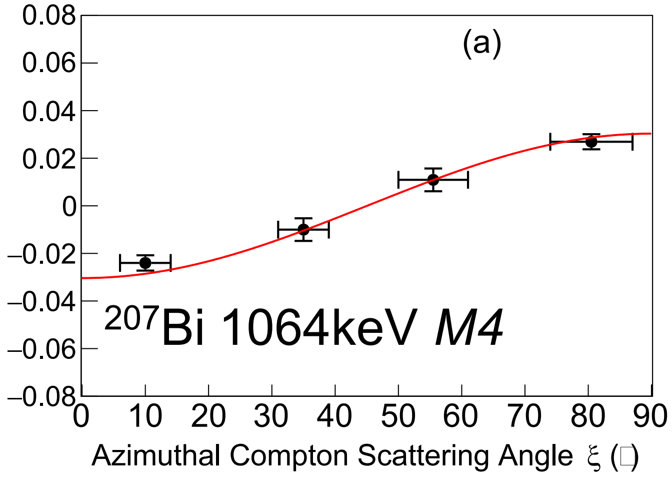
Compton Polarimetry using GRIFFIN

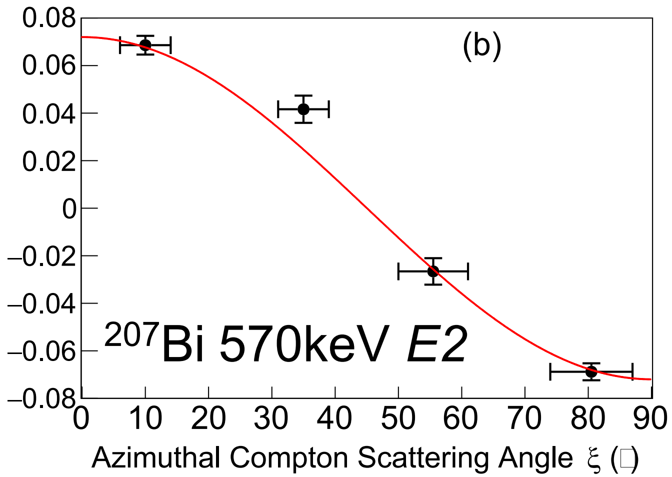




Define Polarization plane from γ–γ coincidence detection. Then examine azimuthal scattering angle to determine electric or magnetic nature of the radiation.







Dan Southall, TRIUMF research student, 2016

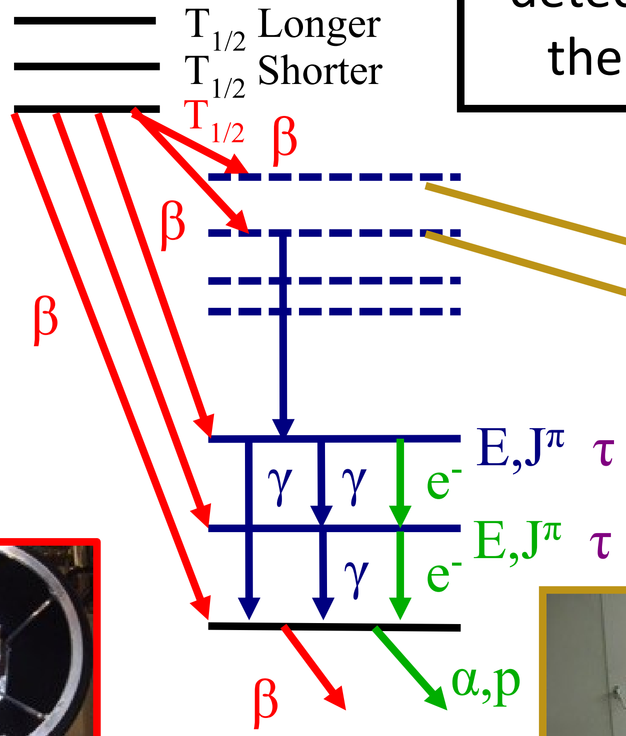
A.B. Garnsworthy *et al.,* NIMA 918, 9 (2019)

B. Alikhani *et al*., NIMA 675, 144 (2012).

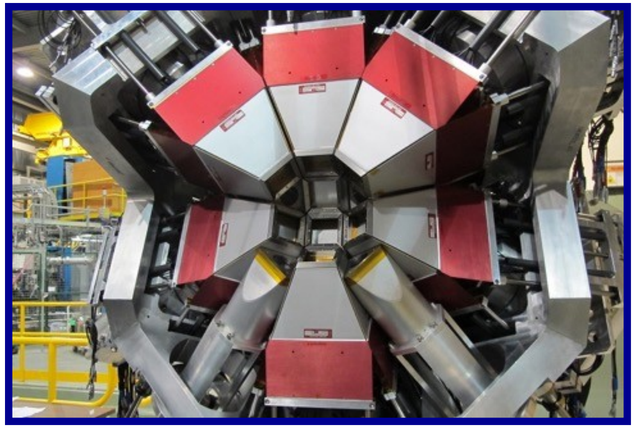
GRIFFIN Ancillary Detectors

Fast, in-vacuum tape system

Enhances decay of interest



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

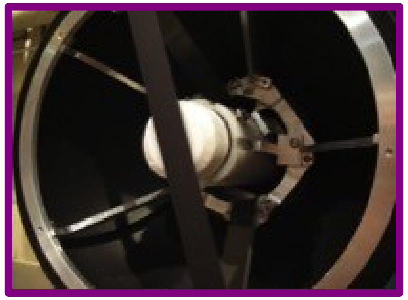


HPGe: 16 Compton-suppressed Clovers

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

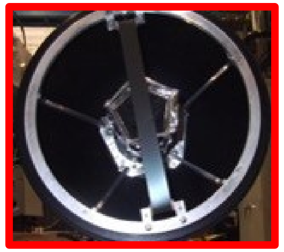
$LaBr_3$: 8 Compton-suppressed $LaBr_3$

Fast-timing of photons to measure level lifetimes



Zero-Degree Fast scintillator

Fast-timing signal for betas



SCEPTAR: 10+10 plastic scintillators

Detects beta decays and determines branching ratios

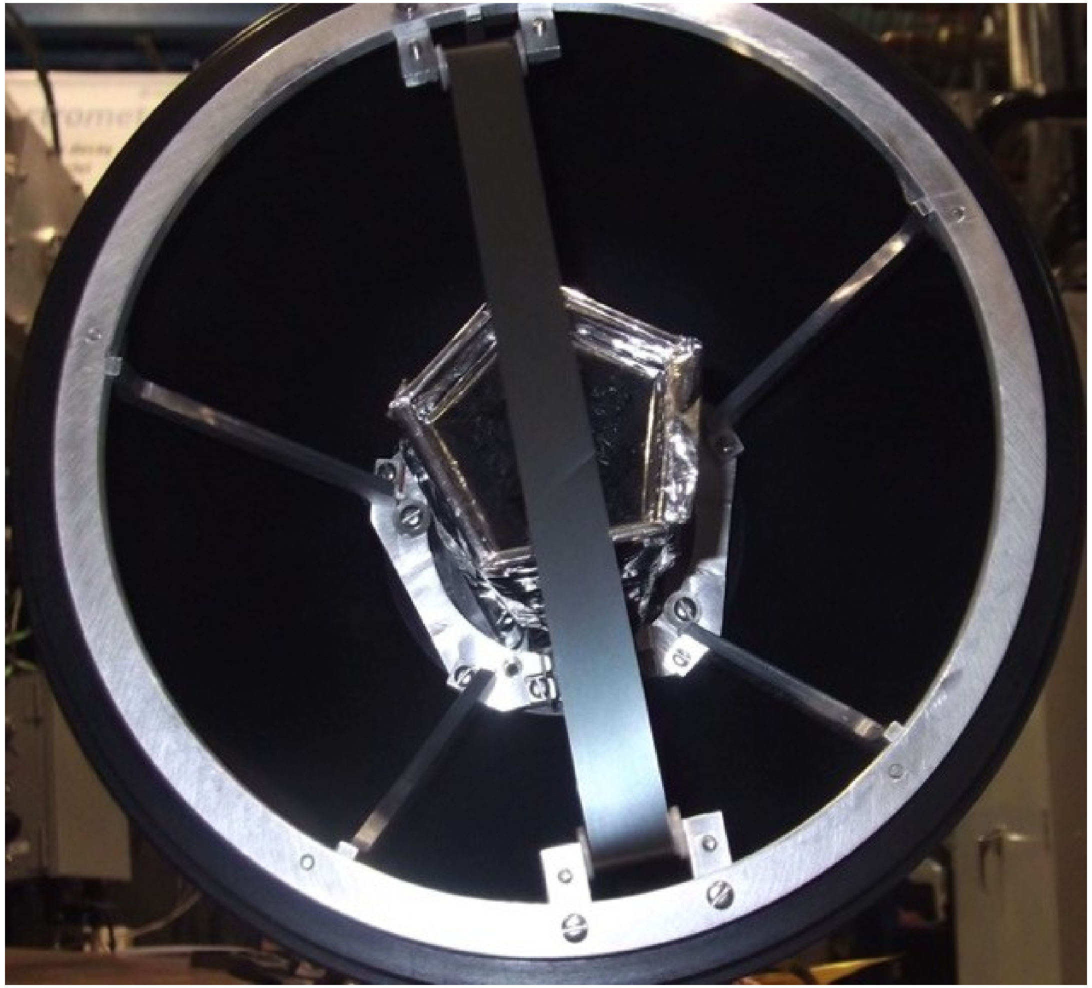
DESCANT Neutron array

Detects neutrons to measure beta-delayed neutron branching ratios

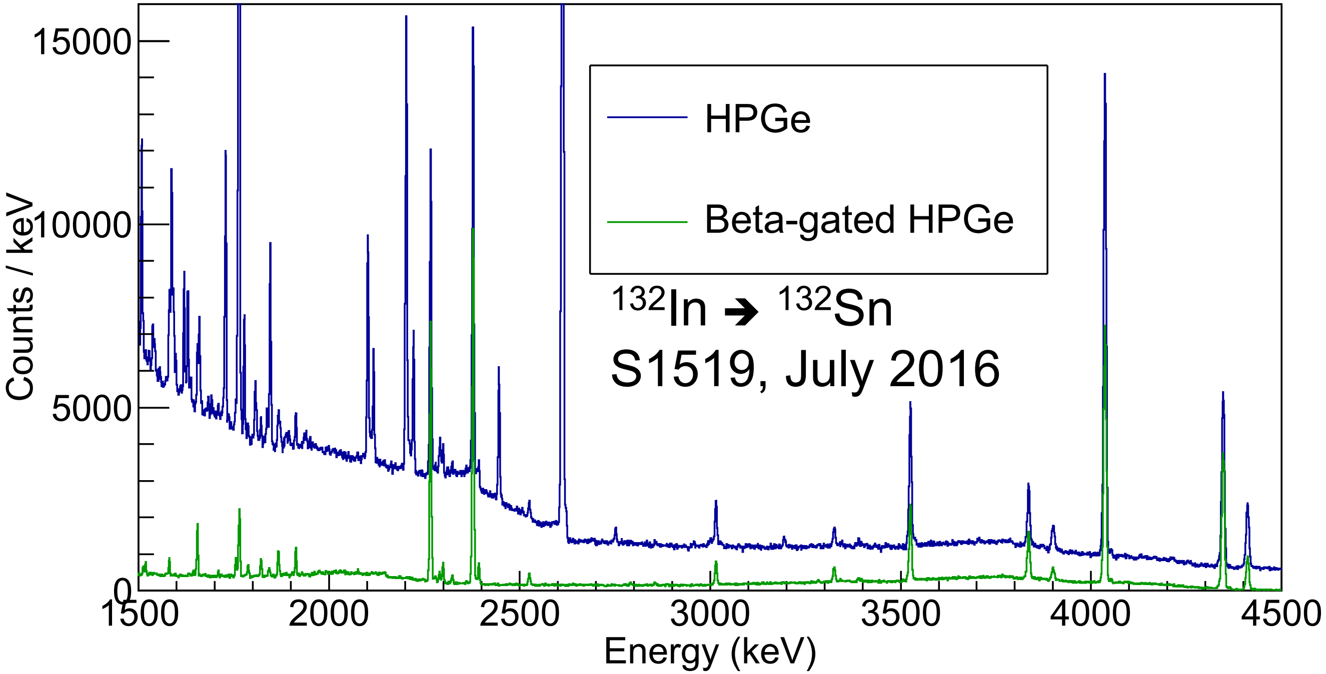
PACES: 5 Cooled Si(Li)s

Detects Internal Conversion Electrons and alphas/protons

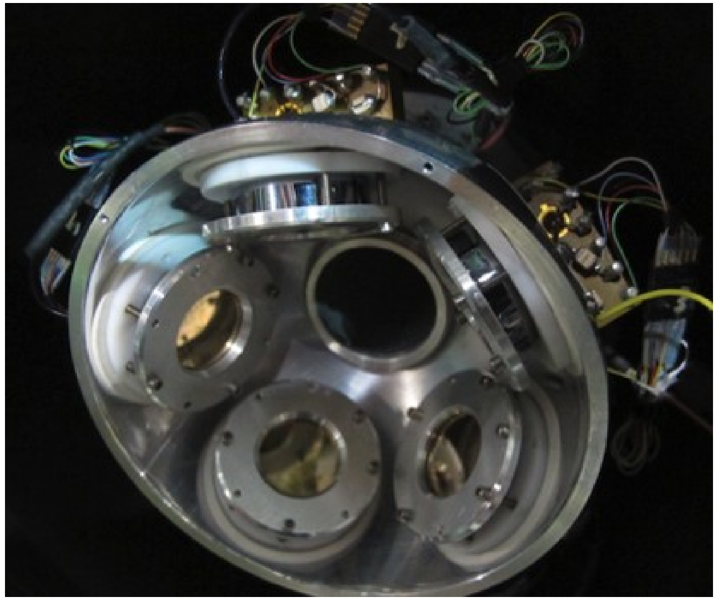
SCEPTAR - SCintillating Electron-Positron Tagging ARray



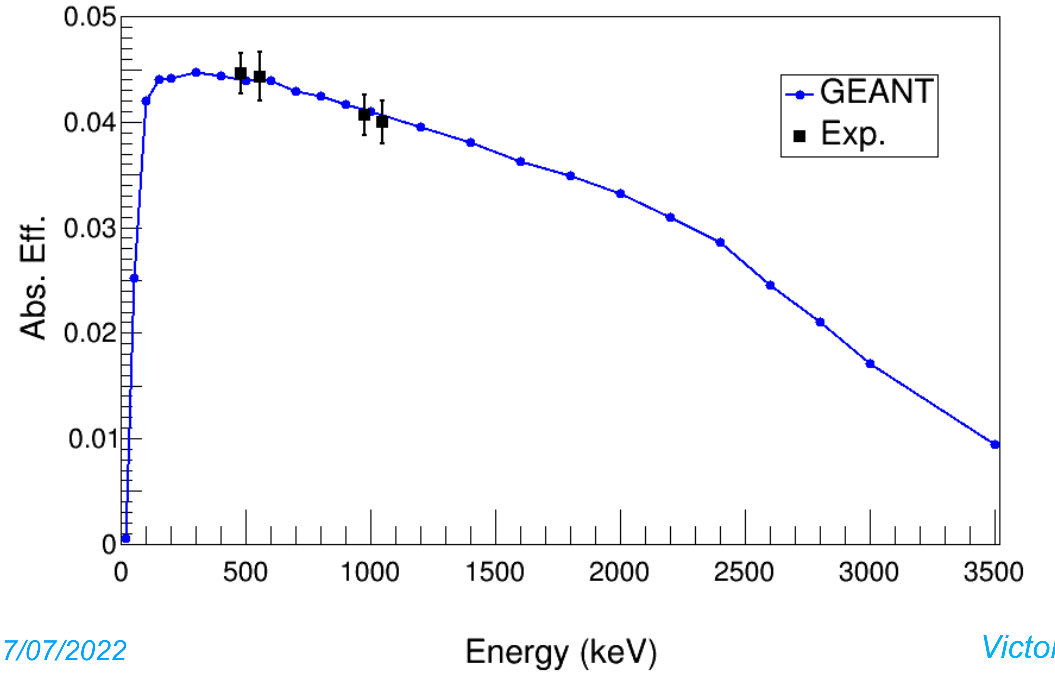
- Two hemispheres of 10 plastic scintillators
- Detects beta particles with ~80% solid angle coverage
- Improves peak-to-background of HPGe spectra
- Reduces random background by ~5 orders of magnitude



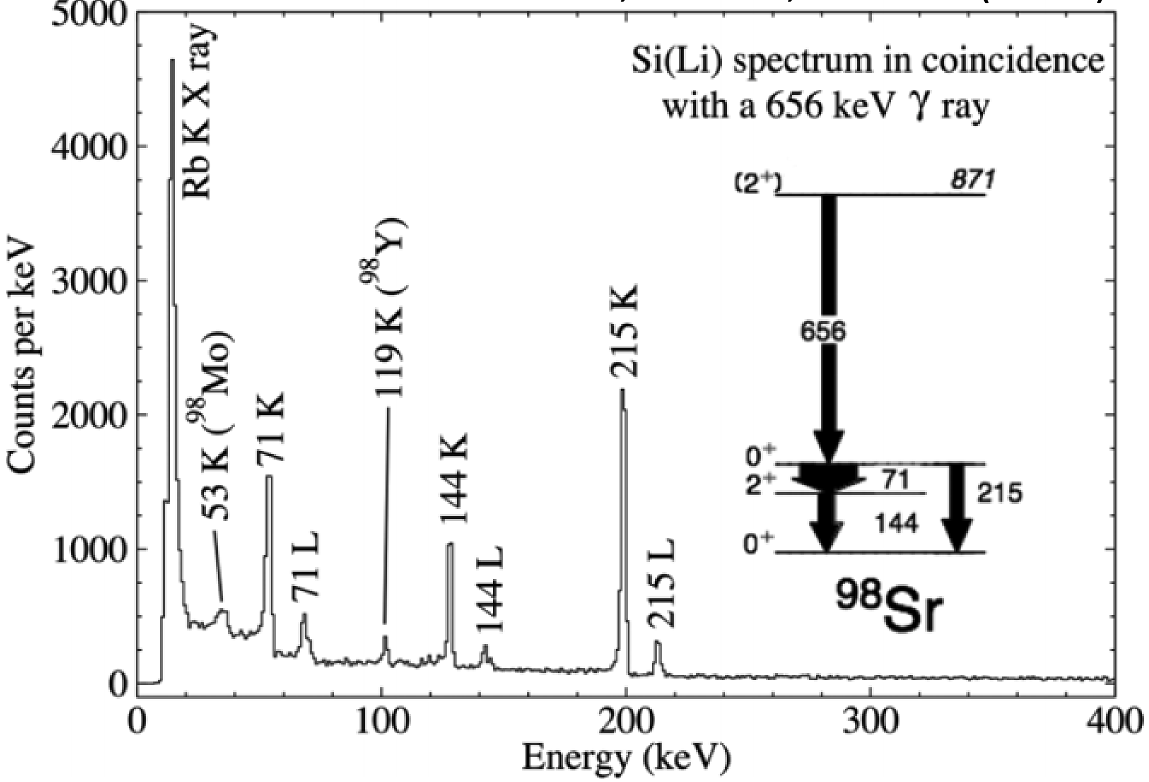
PACES - Pentagonal Array for Conversion Electron Spectroscopy



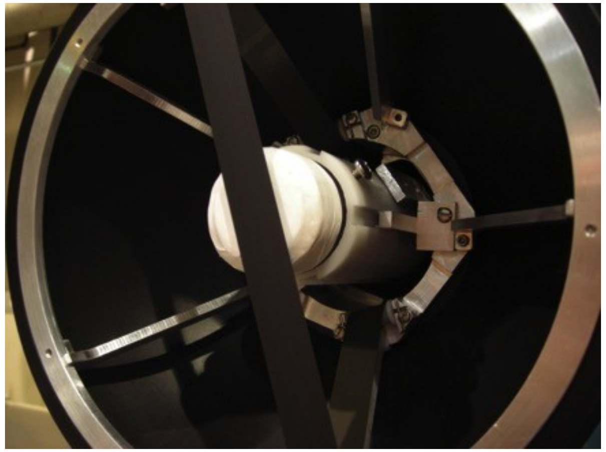
- Five 5mm thick, 200mm^2 Si(Li), LN_2-cooled Si diode and FET
- Solid angle coverage: 1.4% each, 7% total
- 2 keV resolution for electrons



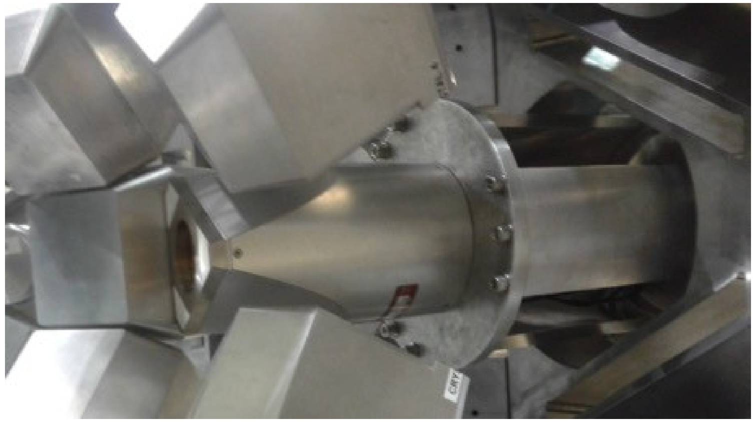
J. Park *et al.*, PRC 96, 014315 (2016).



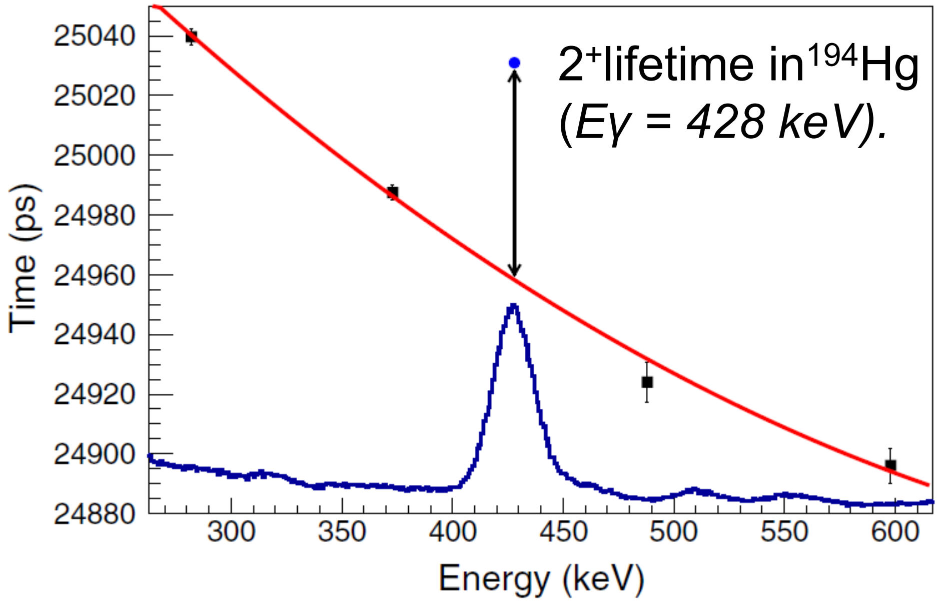
$LaBr_3$ Fast-Scintillator Array for Excited-State Lifetime Measurements

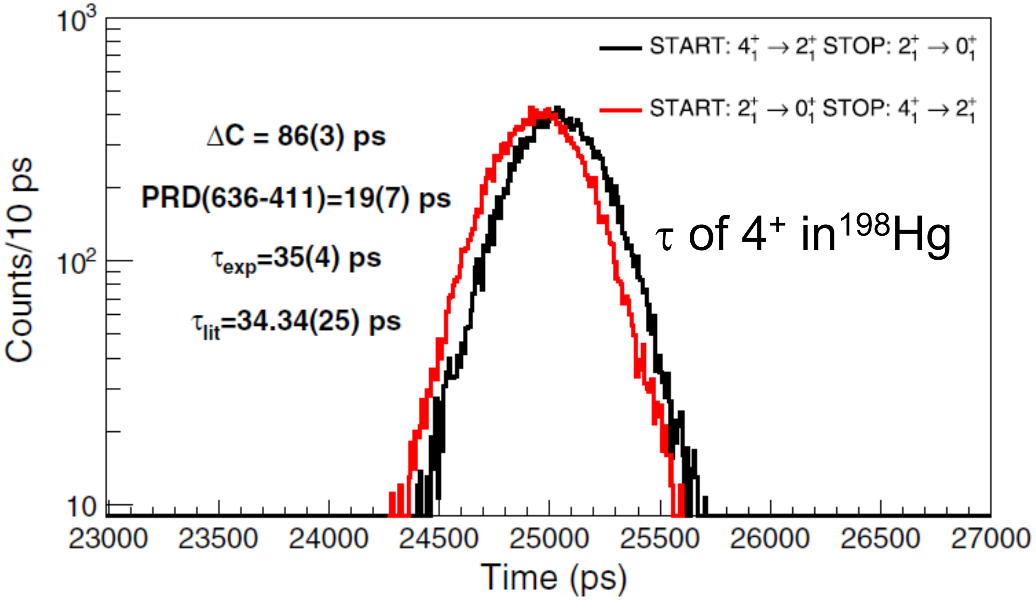


- Eight $LaBr_3$(Ce) 2”x2” cylindrical crystal
- Source-detector distance=12.5 cm. (unshielded) and 13.5 cm (with BGO shield)
- Fast beta scintillator (BC422Q).
- Hybrid analogue + digital electronics, excellent time resolution



BGO shield for each $LaBr_3$(Ce)

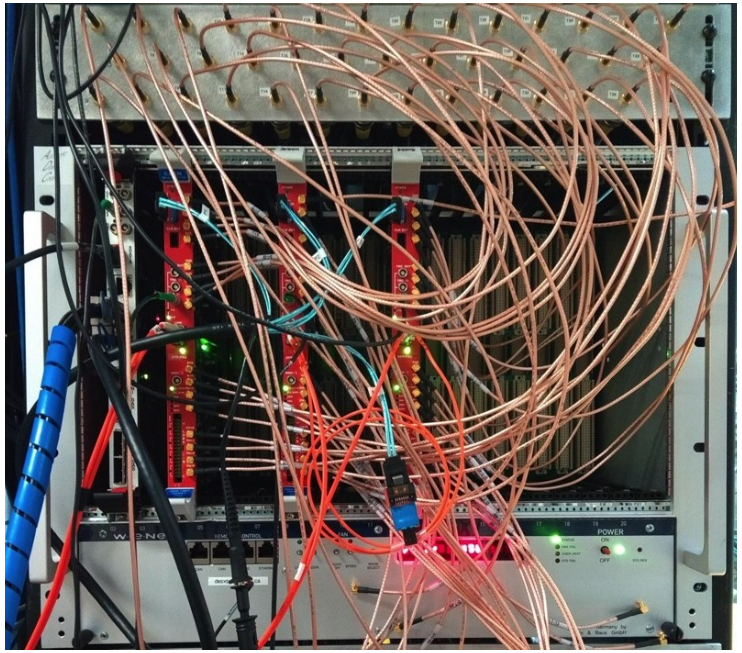


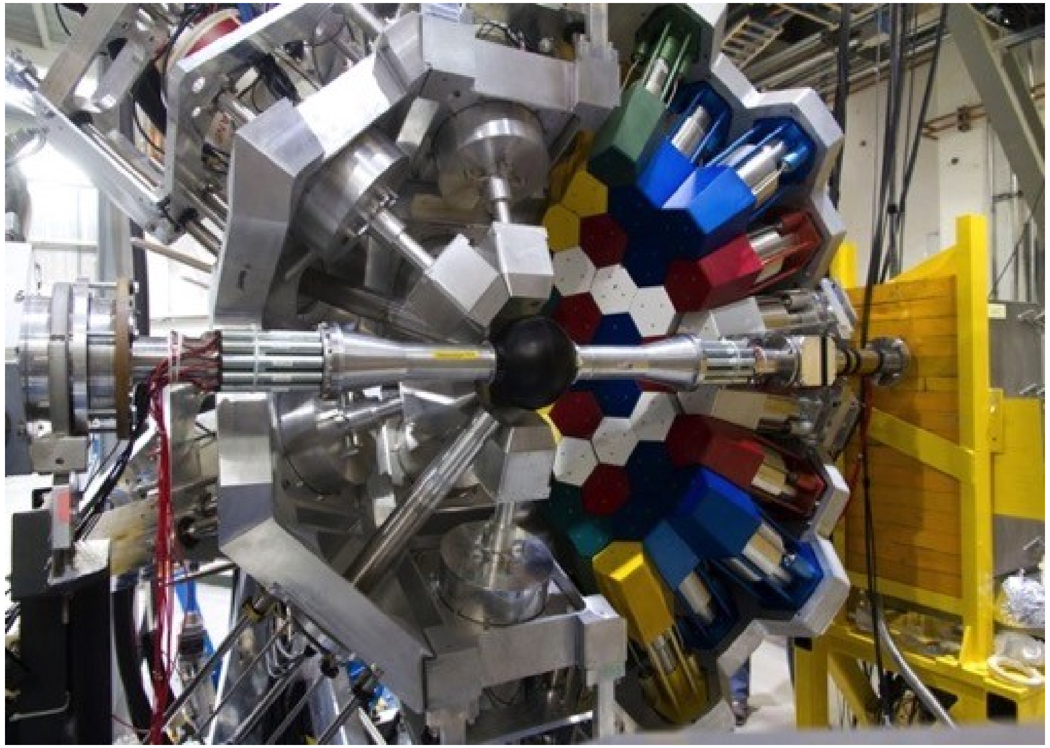


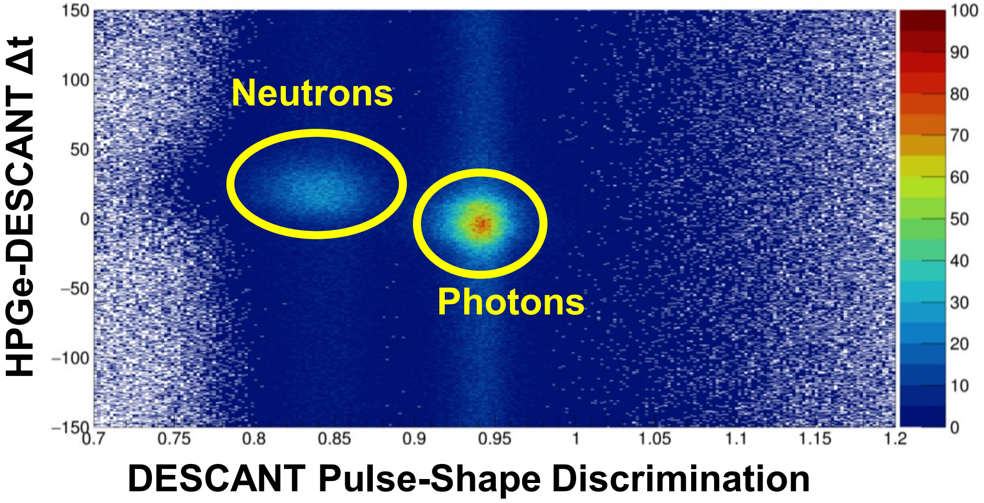
B. Olaizola *et al*. PRC 100,024301 (2019)

GRIFFIN+DESCANT

- 70 element array of deuterated scintillator for neutron detection covering ~1π solid angle, (50cm flight path).
- Enables beta-gamma-ICE-neutron spectroscopy
- Five CAEN VX1730, 500MHz, 14-bit digitizers.
- Neutron-gamma discrimination from pulse shape and TOF
- GRIFFIN and DESCANT read out separately and events combined offline using timestamps. Used in S1602 beamtime in Aug 2019.







GRIFFIN DAQ System

A.B. Garnsworthy *et al*., NIM A 853, 85 (2017).

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 precision Clock
Low-jitter fan-out to all modules

High data through-put:
50kHz per crystal, >300MB/s total
For ultra-high-statistics studies

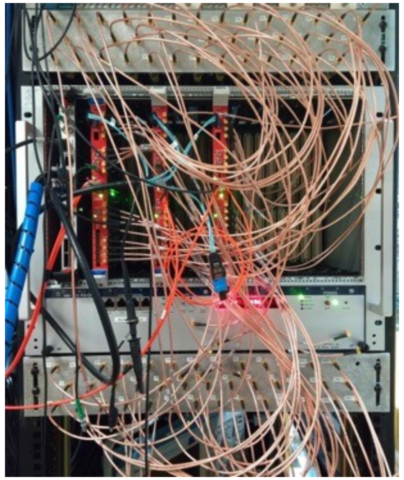
High accountability:
Deadtime, pile-up, event tracing
For precision measurements

GRIF-16 Module

16 chans
100MHz,
14bit

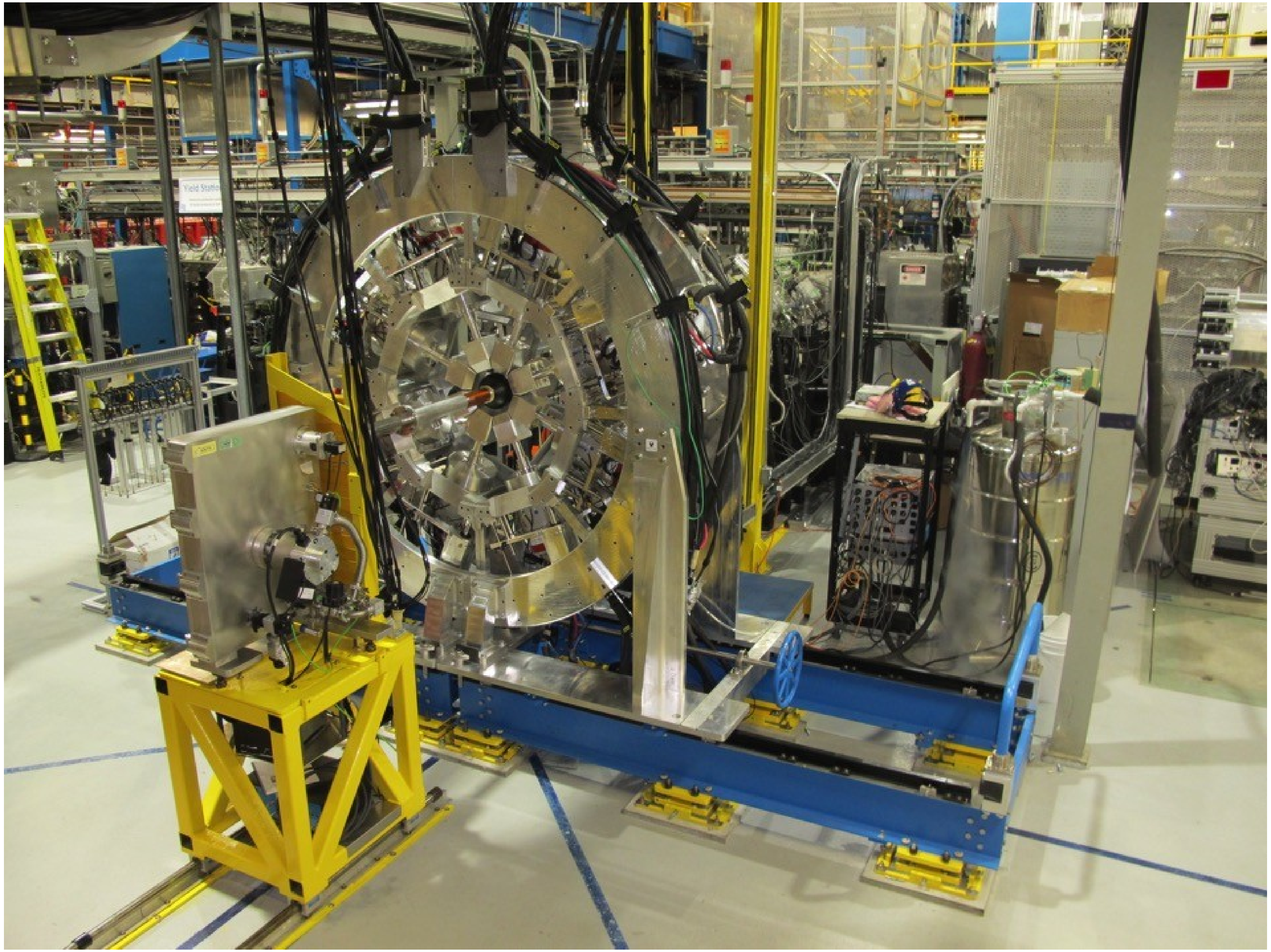
Primary and secondary Collector Modules

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



CAEN 500MHz, 14 bit digitizers used for DESCANT.

The GRIFFIN Spectrometer for precision decay studies at ISAC



Technical publications:

“Characteristics of GRIFFIN high-purity germanium clover detectors”,
U. Rizwan, *et al.*, NIM A 820, 126 (2016).
arXiv:1711.05287

“The GRIFFIN data acquisition system”,
A.B. Garnsworthy *et al.*, NIM A 853, 85 (2017).
arXiv:1711.06236

“The GRIFFIN Facility for Decay-Spectroscopy Studies at TRIUMF-ISAC”,
A.B. Garnsworthy et al., NIM A 918, 9 (2019).
arXiv:1809.07183

“γγ angular correlation analysis techniques with the GRIFFIN spectrometer”,
J.K. Smith *et al.*, NIM A 922, 47 (2019).
arXiv:1807.07570

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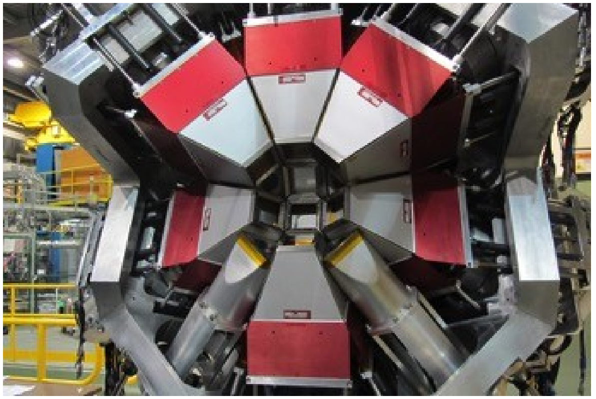
The GRIFFIN Spectrometer for precision decay studies at ISAC



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

$^{188-200}$Tl: Development of collectivity in Hg isotopes
B. Olaizola *et al.*, PRC 100, 024301 (2019).

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

$^{160-166}$Eu, ^{156,158,160,162,166}Tm: Development of collectivity in rare-earth region

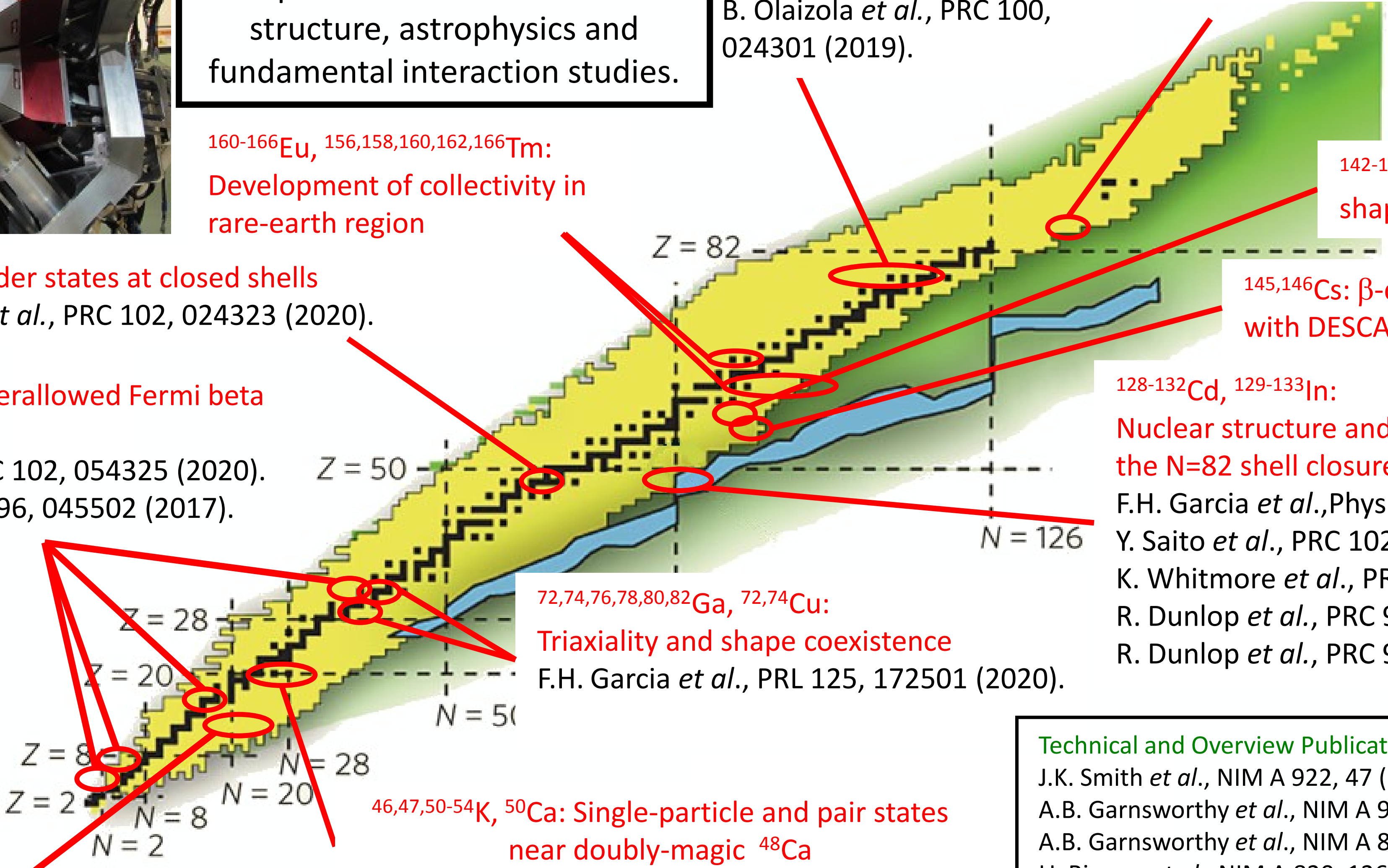
$^{142-152}$La: Octupole collectivity and shape coexistence in Ce isotopes

^{118}In: Intruder states at closed shells
K. Ortner *et al.*, PRC 102, 024323 (2020).

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

^{10}C, ^{14}O, ^{22}Mg, ^{62}Ga: Superallowed Fermi beta decays
A.D. MacLean *et al.*, PRC 102, 054325 (2020).
M.R. Dunlop *et al.*, PRC 96, 045502 (2017).

$^{128-132}$Cd, $^{129-133}$In:
Nuclear structure and r-process nucleosynthesis at the N=82 shell closure
F.H. Garcia *et al*.,Phys.Rev.C103,024310 (2021)
Y. Saito *et al.*, PRC 102, 024337 (2020).
K. Whitmore *et al.*, PRC 102, 024327 (2020).
R. Dunlop *et al.*, PRC 99, 045805 (2019).
R. Dunlop *et al.*, PRC 93, 062801(R) (2016).



^{72,74,76,78,80,82}Ga, ^{72,74}Cu:
Triaxiality and shape coexistence
F.H. Garcia *et al.*, PRL 125, 172501 (2020).

$^{46,47,50-54}$K, ^{50}Ca: Single-particle and pair states near doubly-magic ^{48}Ca
J.K. Smith *et al.*, PRC 102, 054314 (2020).
J. Pore *et al.*, PRC 100, 054327 (2019).
A.B. Garnsworthy *et al.*, PRC 96, 044329 (2017).

^{31,32}Na, $^{33-35}$Mg, ^{34}Al:
Island of inversion

Technical and Overview Publications
J.K. Smith *et al.*, NIM A 922, 47 (2019).
A.B. Garnsworthy *et al.*, NIM A 918, 9 (2019).
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).

Superallowed Fermi β Decay

phase space (Q-value) → $f\,t = \dfrac{K}{|M_{fi}|^2\, g^2}$ ← constants

half-life, branching ratio

Weak coupling strength

matrix element

For the special case of $0^+ \rightarrow 0^+$ (pure Fermi) β decays between isobaric analogue states (superallowed) the matrix element is that of an isospin ladder operator:

$$|M_{fi}|^2 = (T - T_Z)(T + T_Z + 1) = 2 \quad (\text{for } T=1)$$

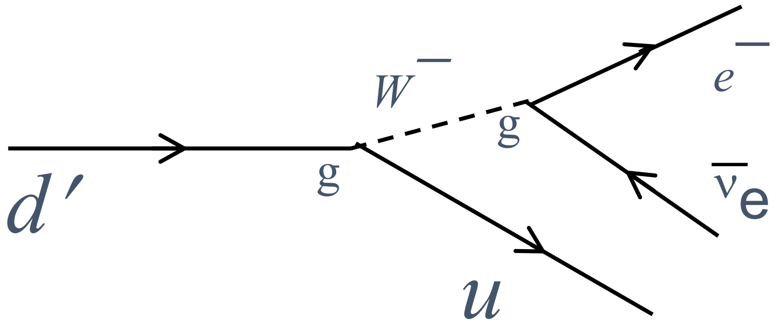
Strategy: Measure superallowed ft-values, deduce G_V and V_{ud}:

Vector coupling constant → $ft = \dfrac{K}{2\, G_V^2}$

$|V_{ud}| = G_V / G_F$ ← Fermi coupling constant

The Standard Model of particle physics

The CKM matrix plays a central role in the Standard Model



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle + V_{ub}|b\rangle$$

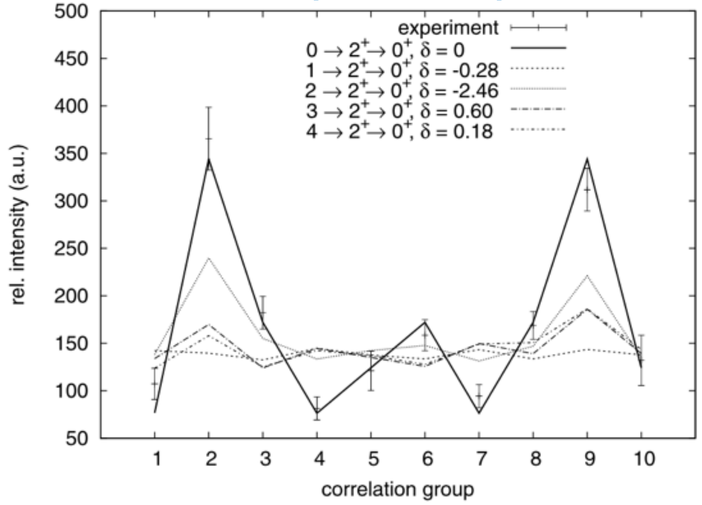
In the Standard Model the CKM matrix describes a unitary transformation:

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

The first row of the CKM matrix provides the most demanding experimental test of the unitarity condition.

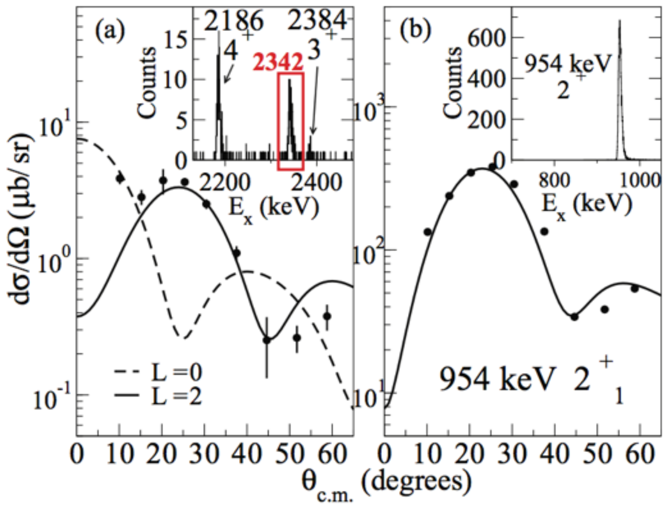
A study of the $^{64}Zn(p,t)^{62}Zn$ reaction disagrees with previous transfer reaction measurements on the spin of the 2.342 keV level in ^{62}Zn

$^{61}Ni(^{3}He,2n\gamma)$



M. Albers *et al.*, Nuc. Phys. 847, 180 (2010).

K. G. Leach *et al.*, Phys. Rev. C. 88, 031306(R) (2013).

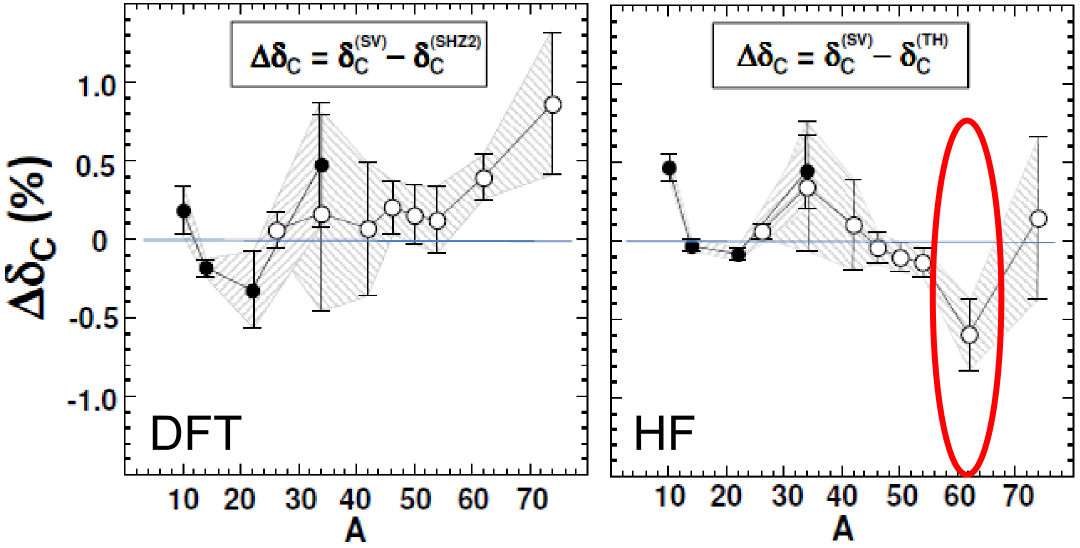


K. G. LEACH *et al.* PHYSICAL REVIEW C **88**, 031306(R) (2013)

TABLE II. A comparison of the unscaled and scaled isospin-mixing correction terms for ^{62}Ga, using both the previous 0_2^+ excitation energy from Ref. [27] and the value presented here. The result of the new energy scaling lowers the δ_{C1} central value by nearly a factor of two. The adopted values in each case are shown in bold and result from the average of the MSDI3 and GXPF1 calculations. The uncertainties used for the adopted values are described further in the text.

Shell model		Unscaled		Ref. [27]	Previous scaling		This work	New scaling	
Interaction	$E_x(0_2^+)$ (MeV)	δ_{C1}^1 (%)	δ_{C1} (%)	$E_x(0_2^+)$ (MeV)	δ_{C1}^1 (%)	δ_{C1} (%)	$E_x(0_2^+)$ (MeV)	δ_{C1}^1 (%)	δ_{C1} (%)
MSDI3	2.263	0.089	0.350	2.342	0.084	0.329	3.045	0.049	0.193
GXPF1	2.320	0.160	0.221		0.159	0.219		0.093	0.128
		Adopted value			**0.120(40)**	**0.275(55)**		**0.070(35)**	**0.160(70)**

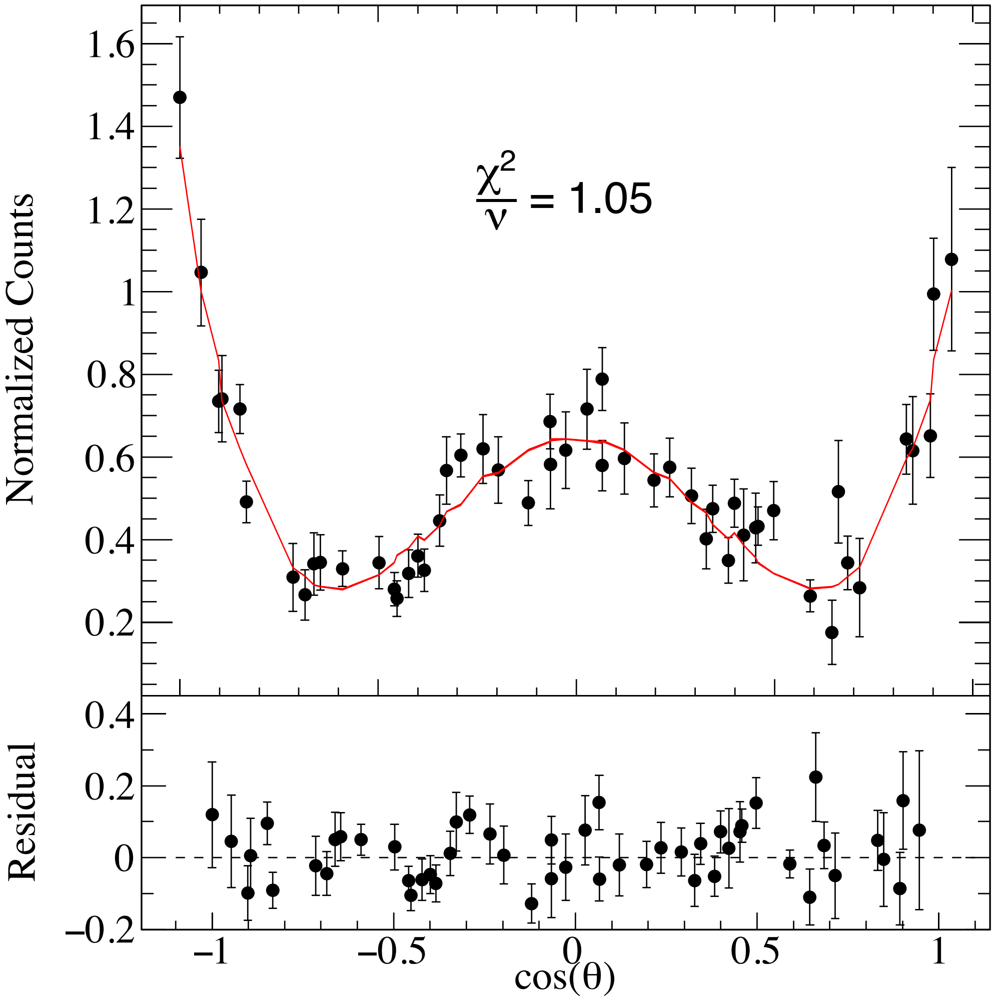
2σ shift in TH δ_{C1}

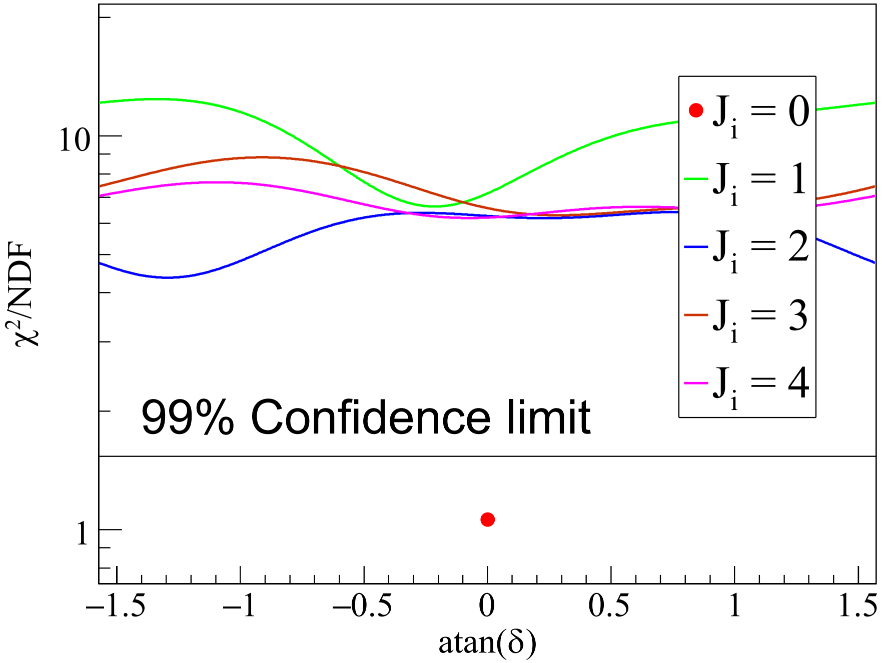


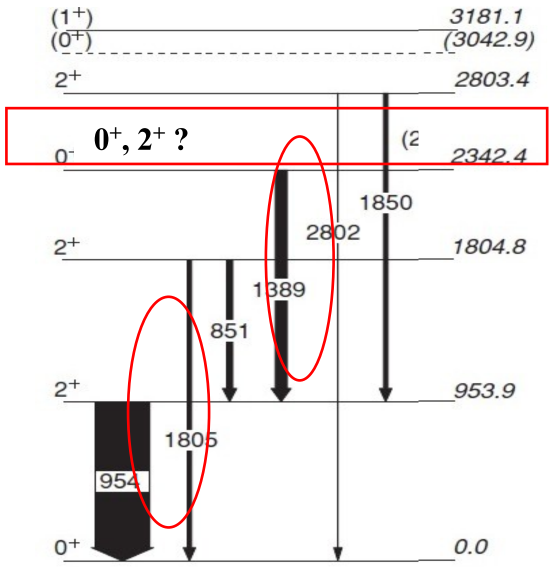
W. Satula *et al.*, Phys. Rev. C **86**, 054316 (2012)

GRIFFIN result is definitive

A. MacLean, University of Guelph







- Definitive measurement with GRIFFIN assigns 0^+ to the 2342keV state in ^{62}Zn.

- Important nuclear data for refining the isospin-symmetry-breaking corrections

A.D. MacLean *et al.*, PRC 102, 054325 (2020).

GRIFFIN studies around doubly-magic ^{132}Sn

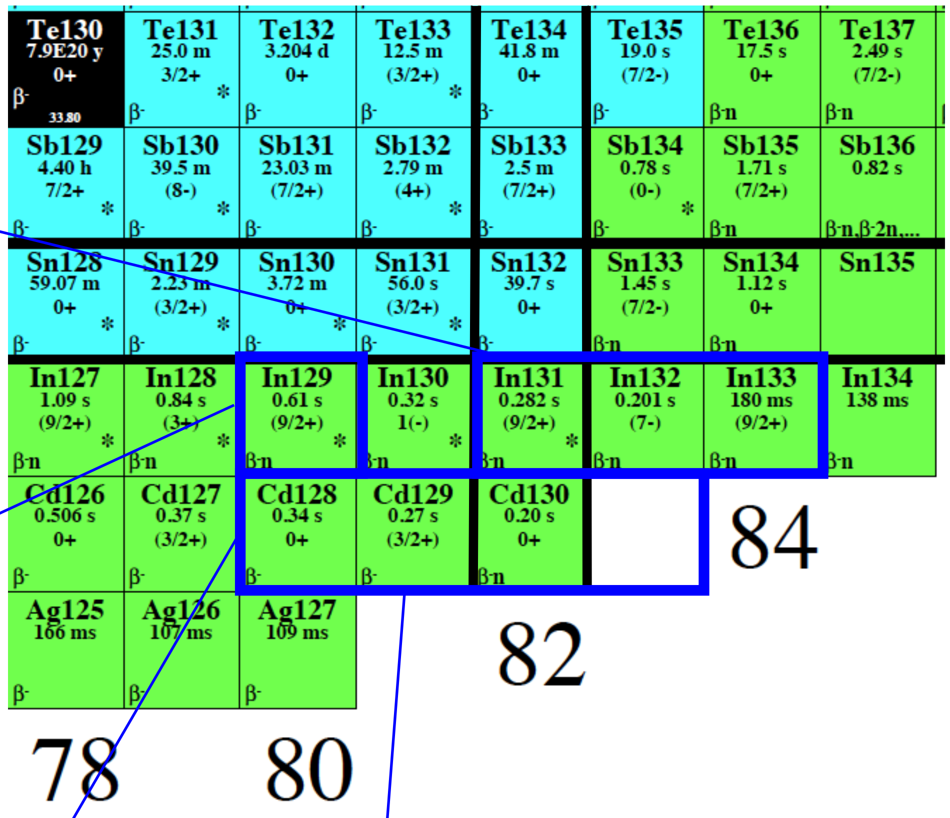
Two beamtime periods with GRIFFIN
2 publications, 4 in preparation
- **2 PhD thesis, 1 Masters thesis**
- **1 PhD thesis in progress**

"Beta-decay and beta-delayed neutron decay of the *N*=*82* nucleus ^{131}In",
R. Dunlop *et al.*, PRC 99, 045805 (2019).

^{129}In July 2016, ~600pps, 2.7hrs
^{131}In July 2016, ~600pps, 2hrs
^{132}In July 2016, ~70pps, 63hrs
^{133}In July 2016, ~1pps, 18hrs

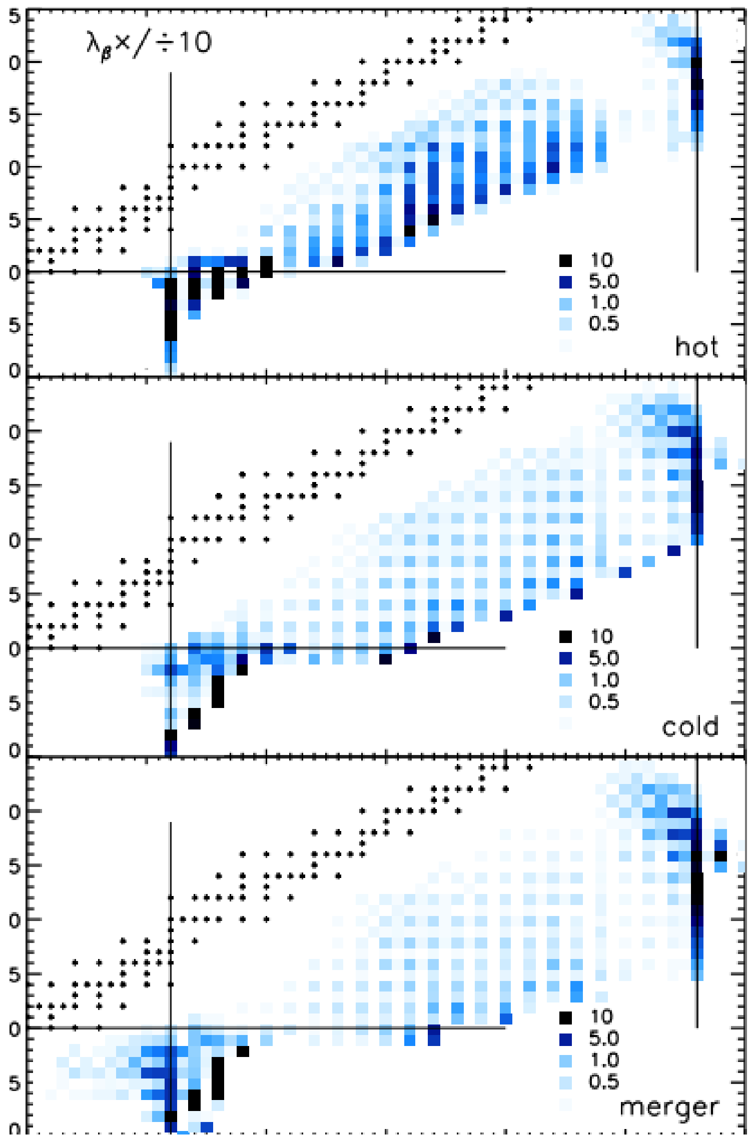
Led by Corina Andreoiu
F. Garcia, PhD thesis in progress (SFU)
K. Whitmore *et al*., PRC 102, 024327 (2020).
F.H. Garcia *et al*.,Phys.Rev.C103,024310 (2021)

^{128}Cd Aug 2015, ~1000pps, 6.5hrs
^{129}Cd Aug 2015, ~150pps, 13hrs
^{130}Cd Aug 2015, ~25pps, 38hrs
^{131}Cd Aug 2015, ~1pps, 32hrs
Led by Iris Dillmann and Reiner Kruecken
N.Bernier, **PhD thesis (2018) UBC**
Y. Saito, **MSc thesis (2018) UBC**
R. Dunlop, **PhD thesis (2019) Uni. Of Guelph**
Y. Saito *et al*., PRC 102, 024337 (2020)
1 manuscripts in preparation



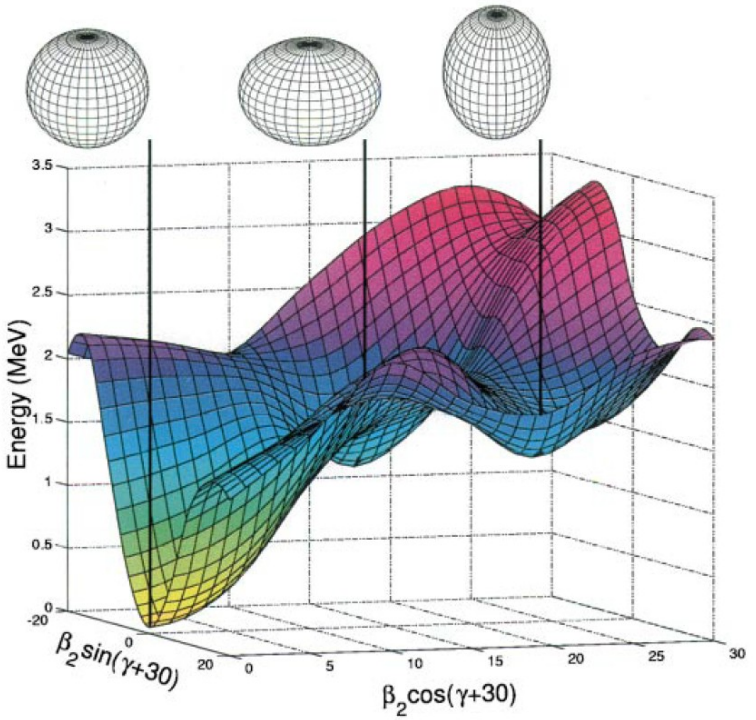
"Half-Lives of Neutron-Rich $^{128\text{-}130}$Cd",
R. Dunlop *et al.*, PRC 93, 062801(R) (2016).

Key nuclear data for r-process

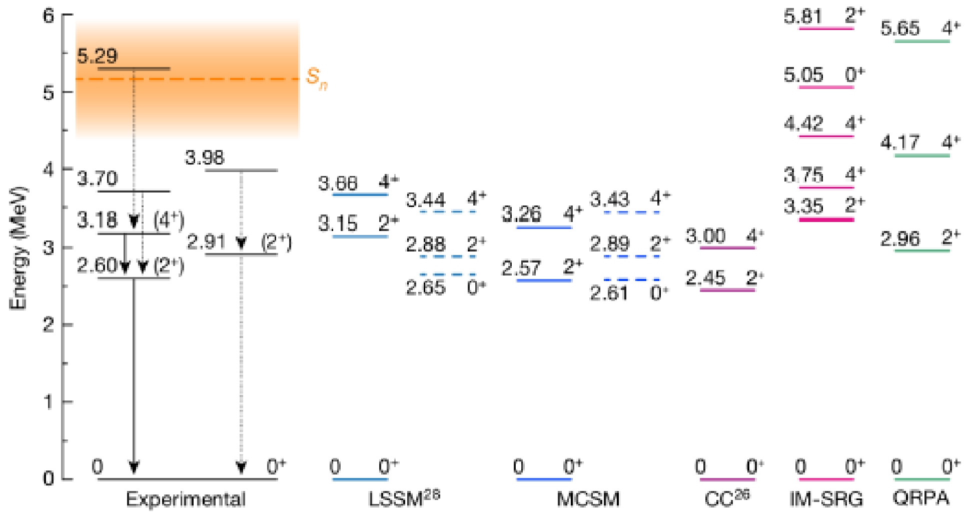


M. Mumpower et al., Prog. Part. Nucl. Phys. 86, 86 (2016)

Shape Coexistence in ^{80}Ge



A recent experiment probed the structure of doubly magic ^{78}Ni.



- ^{186}Pb with three low-lying 0^+ states
  - Z=82 closed shell, N=104 mid-shell
  - Ground, oblate, prolate
  - 2p-2h and 4p-4h proton excitations out of Z=82 spherical closed shell into $h_{9/2}$, e.g.
  - Excitations interact with open neutron shell

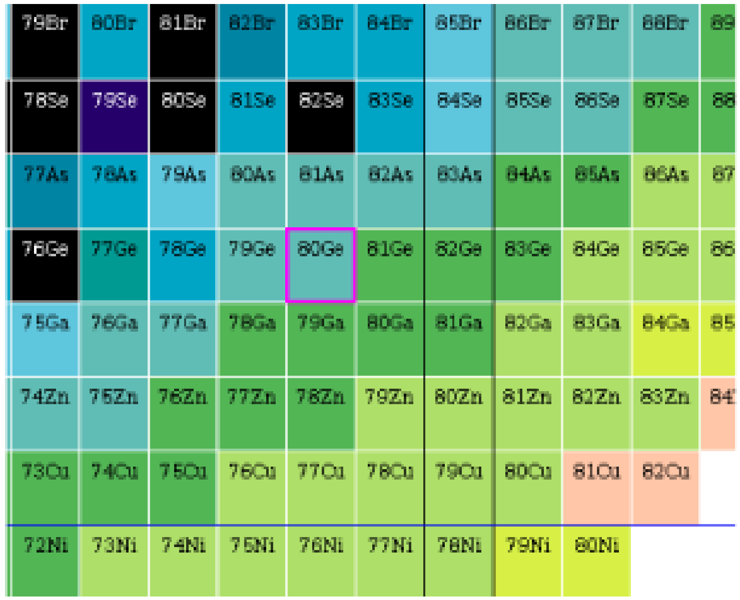
An excited 2^+ state was observed at only 0.31 MeV above the 2^+_1, suggesting shape coexistence in this nucleus.

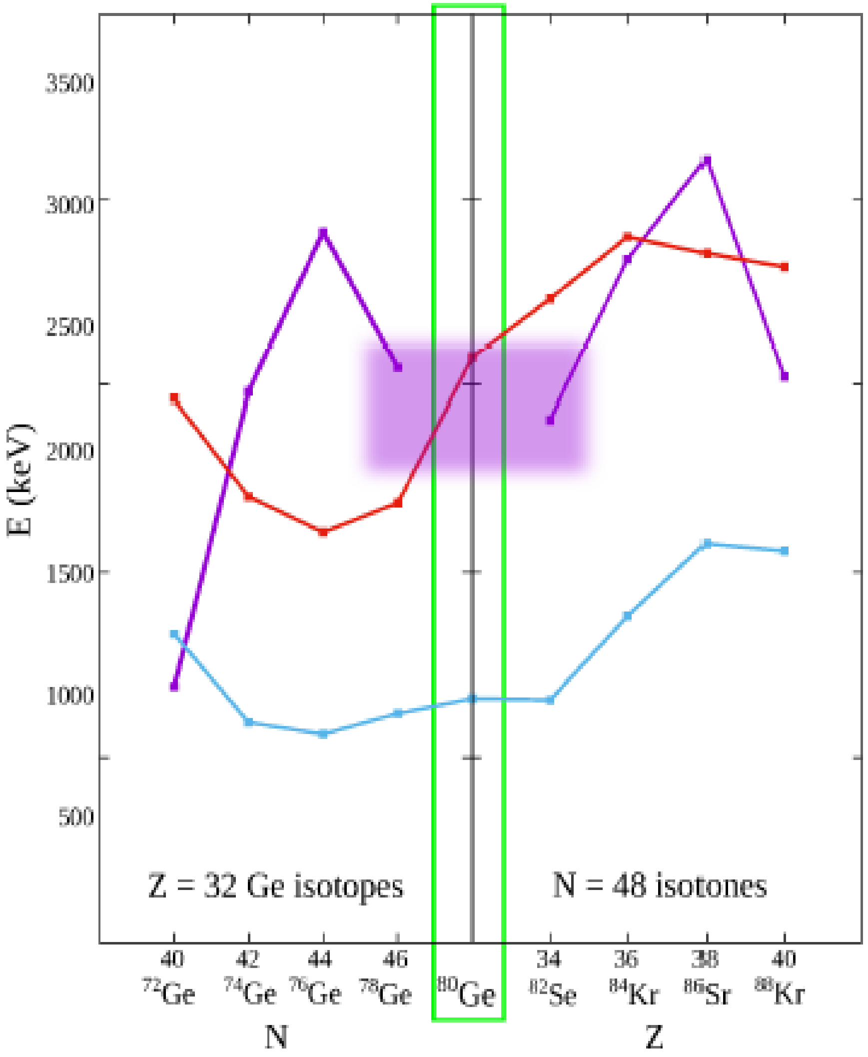
Taniuchi, R *et al.*, Nature 569 (2019) 53

Andreyev et al., Nature 405 (2000) 430
Duguet et al., PLB 559 (2003) 201

Shape Coexistence in ^{80}Ge

Nowacki *et al.** proposed ^{78}Ni to be a portal to the fifth island of inversion.





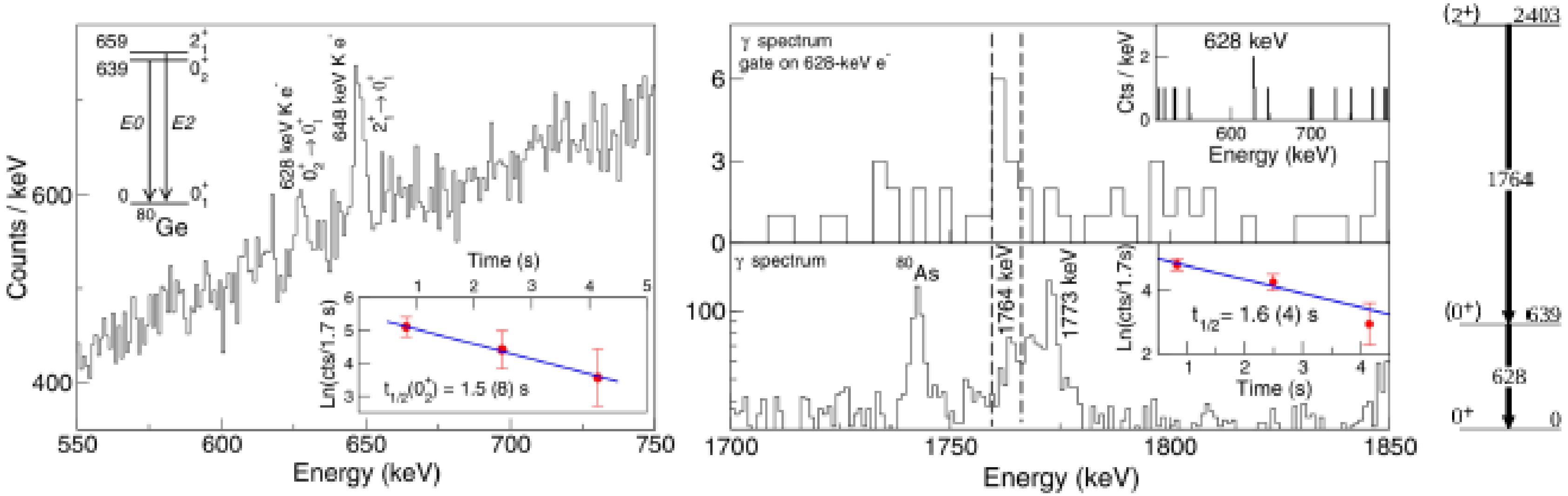
NNDC, Brookhaven National Laboratory

*Nowacki, F., Poves, A., Caurier, E. and Bounthong, B., *PRL* 117, 272501 (2016)

Shape Coexistence in ^{80}Ge

An experiment at ALTO reported a new state 0^+ state in ^{80}Ge at 639 keV, from observation of a conversion electron peak at 628 keV.

A coincidence was also observed between the 628-keV conversion electron and a 1764-keV γ-ray from a new state at 2403 keV.

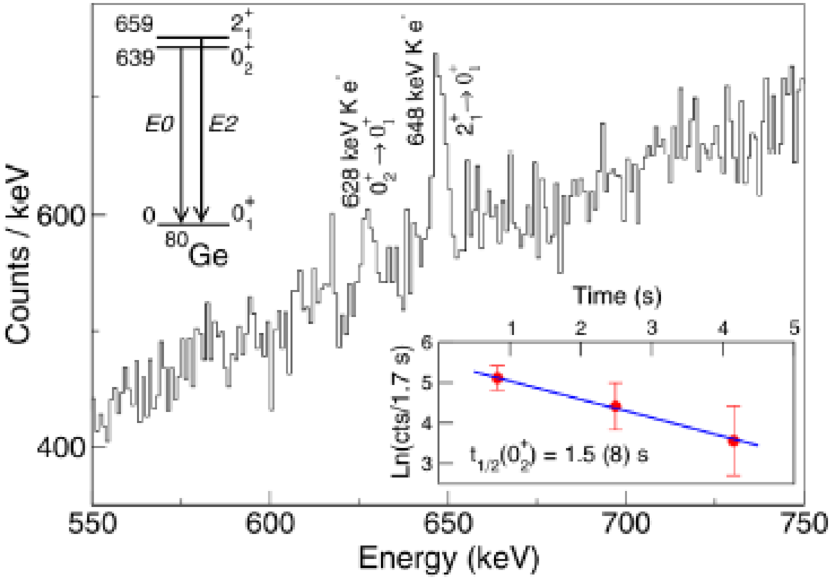


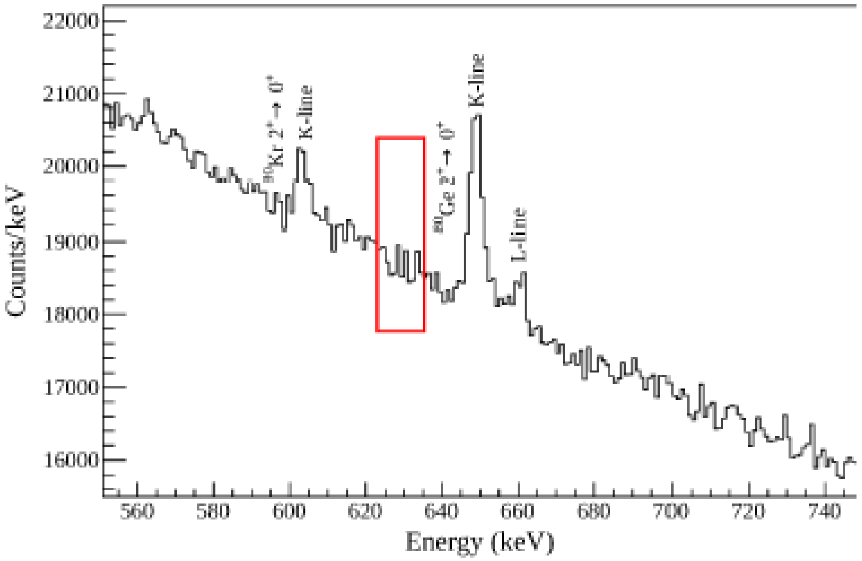
The binding electron of the K-shell electron in ^{80}Ge is 11 keV

Gottardo, A. *et al.*, *PRL* 116, 182501 (2016)

Shape Coexistence in ^{80}Ge

The GRIFFIN experiment used PACES, but did not detect the 628-keV conversion electron peak.





ALTO I^{628}: $\sim$0.08%

GRIFFIN 2σ limit: <0.02%

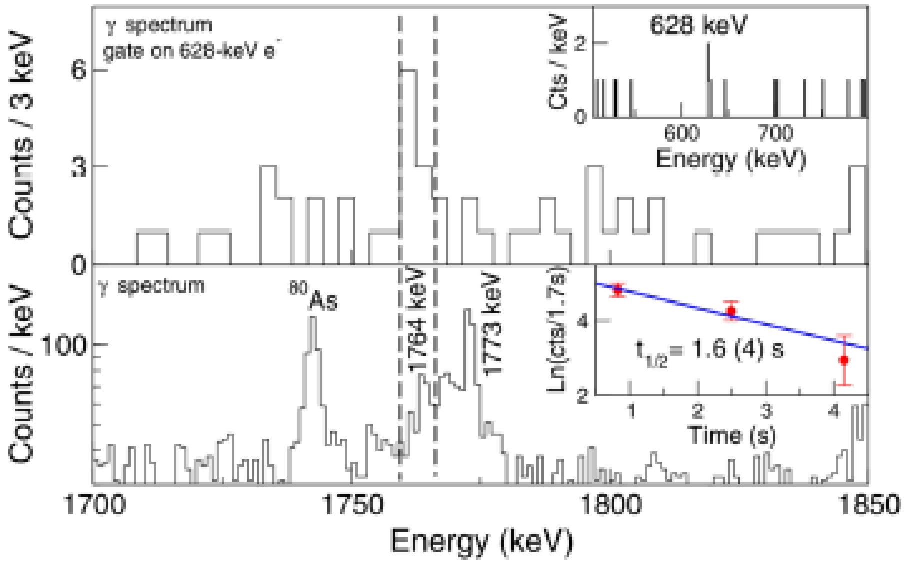
Gottardo, A. *et al.*, *PRL* 116, 182501 (2016)

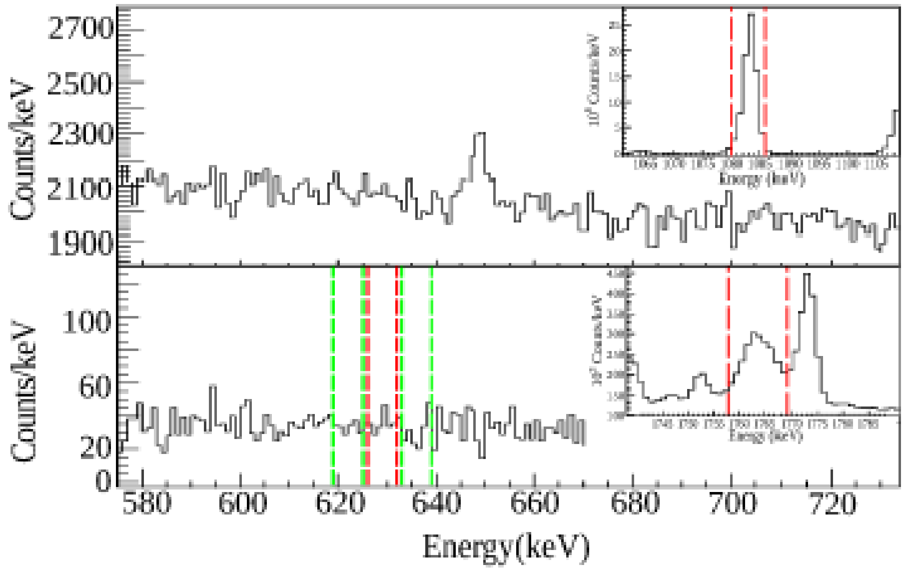
Garcia, F. H. *et al.*, *PRL* 125, 172501 (2020)

F.H. Garcia *et al*., PRL 125, 172501 (2020).

Shape Coexistence in ^{80}Ge

Detection limits were calculated to verify non-observation.





ALTO I_{1764}/I_{1772}: 0.3

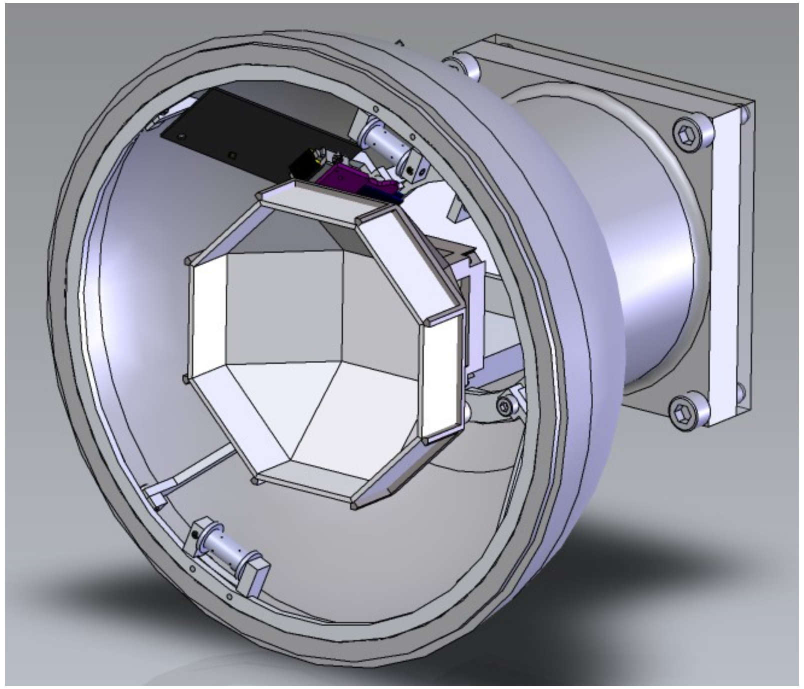
GRIFFIN I_{1764}/I_{1772} 2σ limit: 0.003

F.H. Garcia *et al.*, PRL 125, 172501 (2020).

Gottardo, A. *et al.*, *PRL* 116, 182501 (2016)
Garcia, F. H. *et al.*, *PRL* 125, 172501 (2020)

Future developments and Physics opportunities

Ancillary detector for Rare Isotope Event Selection (ARIES)
A major upgrade of the SCEPTAR beta-tagging array for GRIFFIN

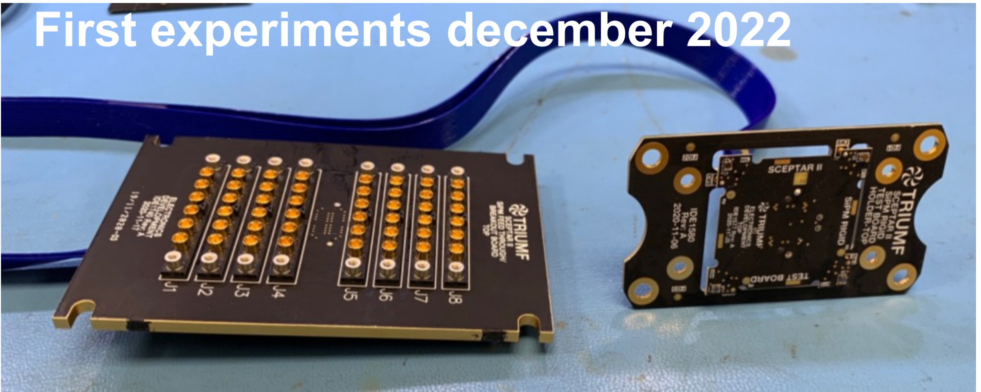


New ARIES beta-tagging array enables:

- Counting of high source activities ~20MBq with ~90% solid-angle coverage.
- Beta-gamma angular correlations with >50 unique angles.
- Beta-gamma fast coinc. timing (few ps) with $LaBr_3$(Ce) detectors (x2 eff. increase over ZDS).
- Easy and economical replacement of detectors contaminated with long-lived activity.

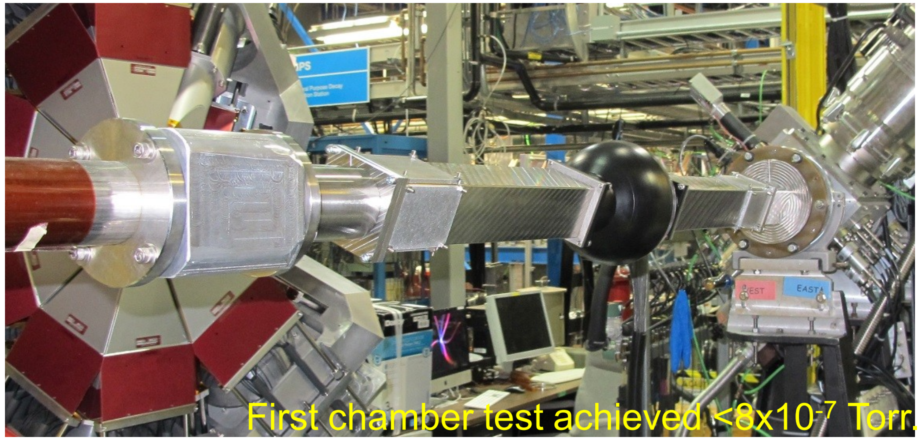
Geometry optimized for GRIFFIN with 1 beta paddle for each HPGe crystal,
+ 8 triangles + 4 downstream = (36 US)+(40 DS) = 76 total channels

- 1.5mm thick BC422Q ultra-fast plastic scintillator.
- Light read-out using SiPM sensors printed on flexible circuit board ~50µm thickness and held in place with a 3D-printed support structure will provide energy and fast-timing signal.
- Processing the GRIFFIN DAQ.



Physics opportunities

- ➢ Lifetime measurements
- ➢ $\beta-\gamma$ angular correlations
- ➢ POLARIS: Spin polarized beams to GRIFFIN



Future developments and Physics opportunities

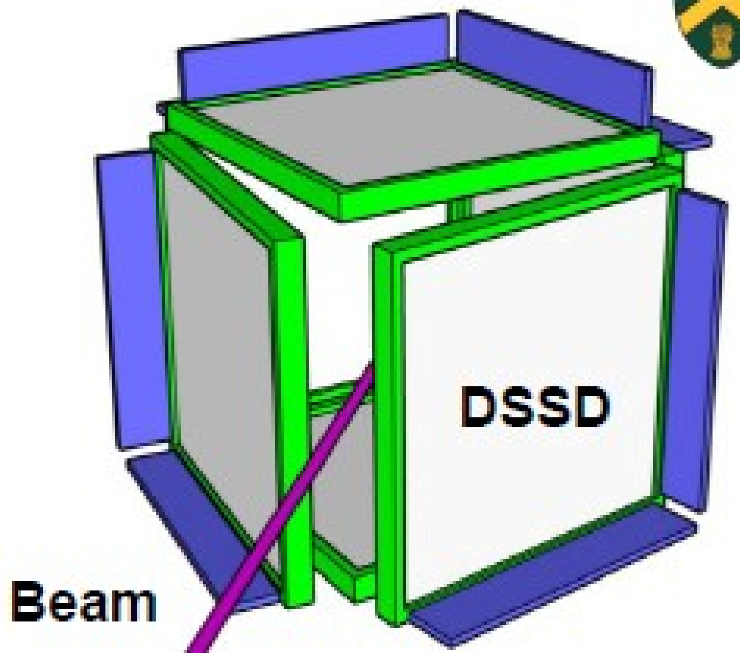
RCMP: Regina Cube for Multiple Particles

University of Regina

- Auxiliary detector for GRIFFIN
  - Charged particle detector
  - α decay and β delayed particles
  - Multiple particles (β2p, βαp, ...)

- 6 DSSD detectors (micron BB7)
  - Active area: 64 x 64 mm^2
  - 6x(32+32) strips = 384 channels
  - Thickness: 1mm (~12 MeV protons)
  - Resolution ≤ 50 keV (FWHM)

- Preliminary design study
  - Compatibility with GRIFFIN
  - Optimized physical geometry
  - Estimated overall efficiency
  - Quantified transparency to γ rays
  - Michael Hladun (Regina)*



DAEMON:
Detector Array for Energy Measurements Of Neutrons

TRIUMF

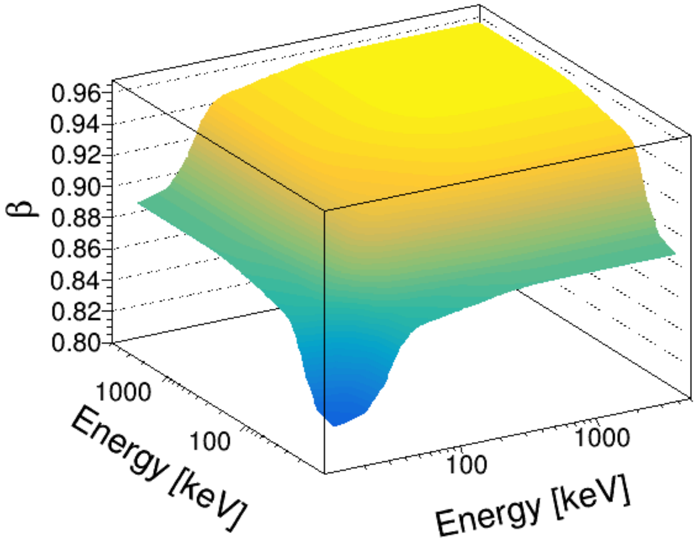
Thank you!!!

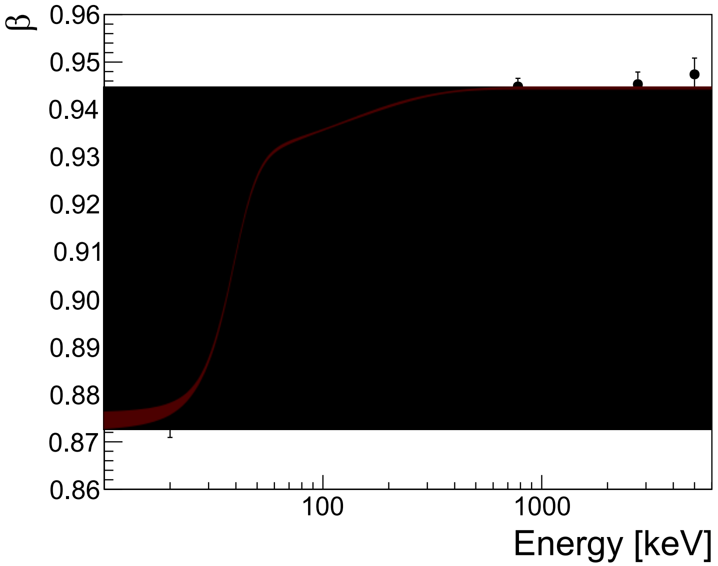
Also many thanks for the plots slides or material to A.B. Garnsworthy, F.H. Garcia, A.D. MacLean, C.Andreoiu and G. Hackman

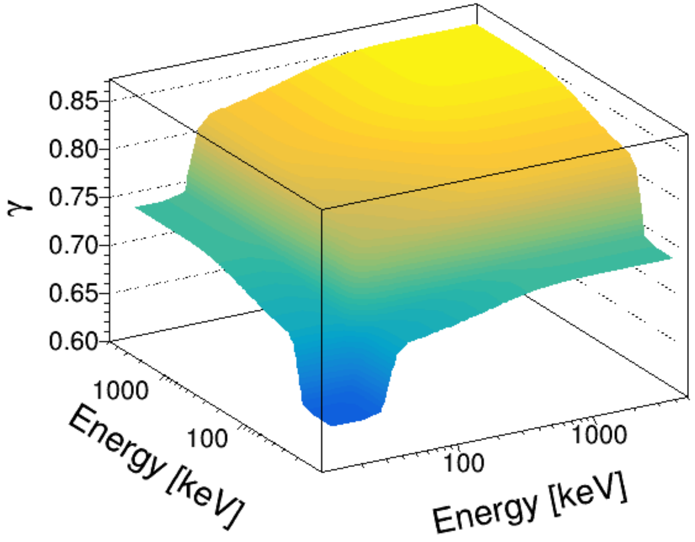
vvedia@triumf.ca

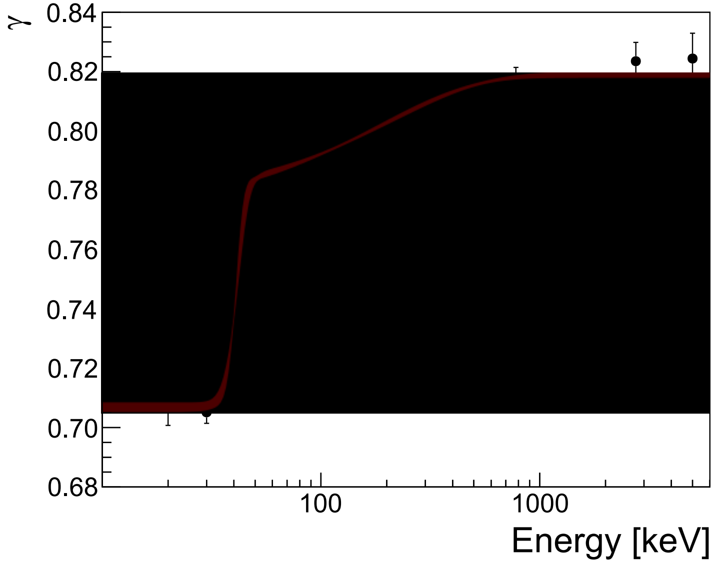
GRIFFIN

Gamma-Gamma Angular Correlation Analysis









J.K. Smith, A.C. MacLean *et al.*
NIM A 922, 47 (2019).
https://arxiv.org/abs/1807.07570

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

- Map the attenuation coefficients over the full γ–γ energy surface.

$$W(\theta) = A_{00}[1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)]$$

where

$$a_i = A_{ii}/A_{00}.$$

$a_2 = \beta c_2$, and $a_4 = \gamma c_4$
where c is fitted coefficient, and a is true coefficient

β and γ coefficients are available for the 110mm distance here:
https://griffincollaboration.github.io/AngularCorrelationCoefficients/

Connor Natzke (CSM/TRIUMF) working on 145mm surface simulations in 2021.