TRIUMF

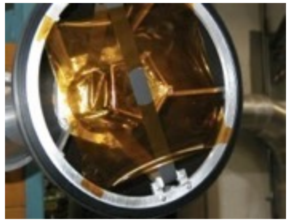
Spin-Polarized beams to the GRIFFIN Spectrometer

Adam Garnsworthy
TRIUMF Senior Scientist

TRIUMF Science Week

20^{th} July 2022

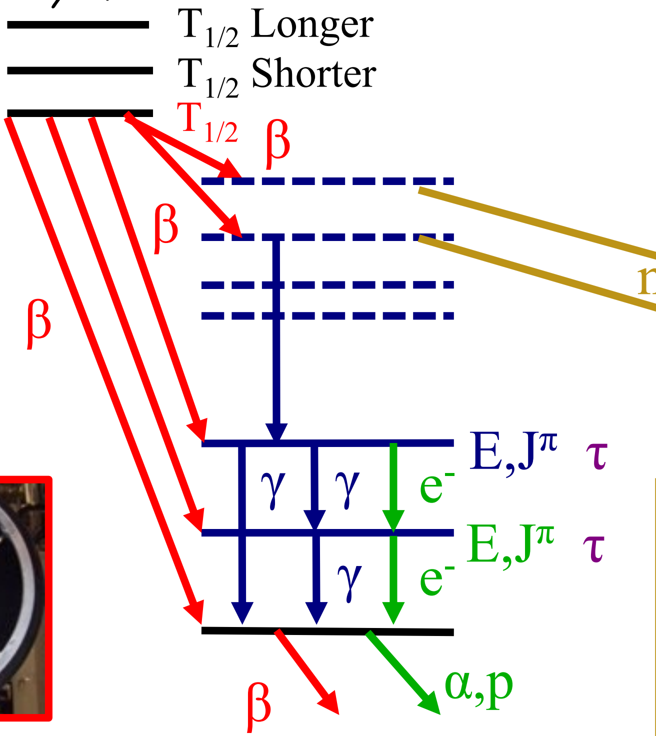
The GRIFFIN Spectrometer for precision decay studies at ISAC

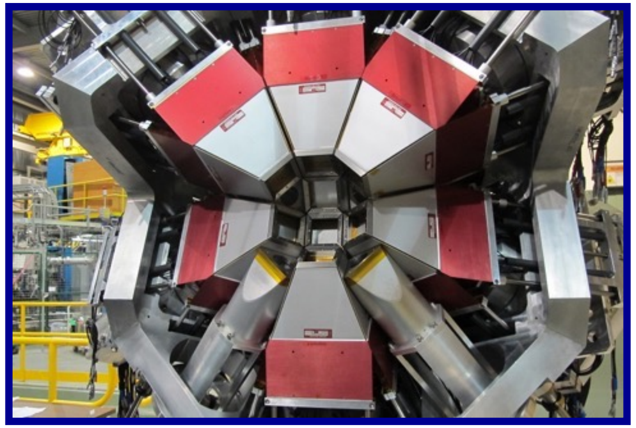



Fast, in-vacuum tape system

Enhances decay of interest

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



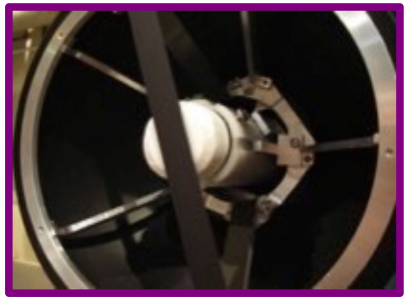


HPGe: 16 Compton-suppressed Clovers

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

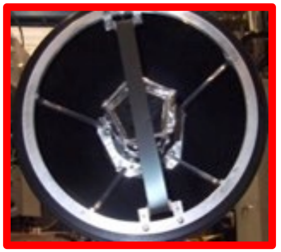
$LaBr_3$: 8 Compton-suppressed $LaBr_3$

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

"The GRIFFIN Facility for Decay-Spectroscopy Studies at TRIUMF-ISAC", A.B. Garnsworthy *et al.*, NIMA 918, 9 (2019). arXiv:1809.07183
"The GRIFFIN data acquisition system", A.B. Garnsworthy *et al.*, NIMA 853, 85 (2017). arXiv:1711.06236
"Characteristics of GRIFFIN high-purity germanium clover detectors", U. Rizwan, *et al.*, NIMA 820, 126 (2016). arXiv:1711.05287

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

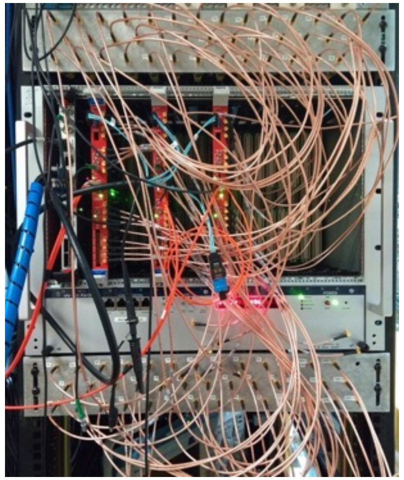
High accountability:
Deadtime, pile-up, event tracing
For precision measurements

GRIF-16 Module

16 chans
100MHz,
14bit

Collector Modules

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

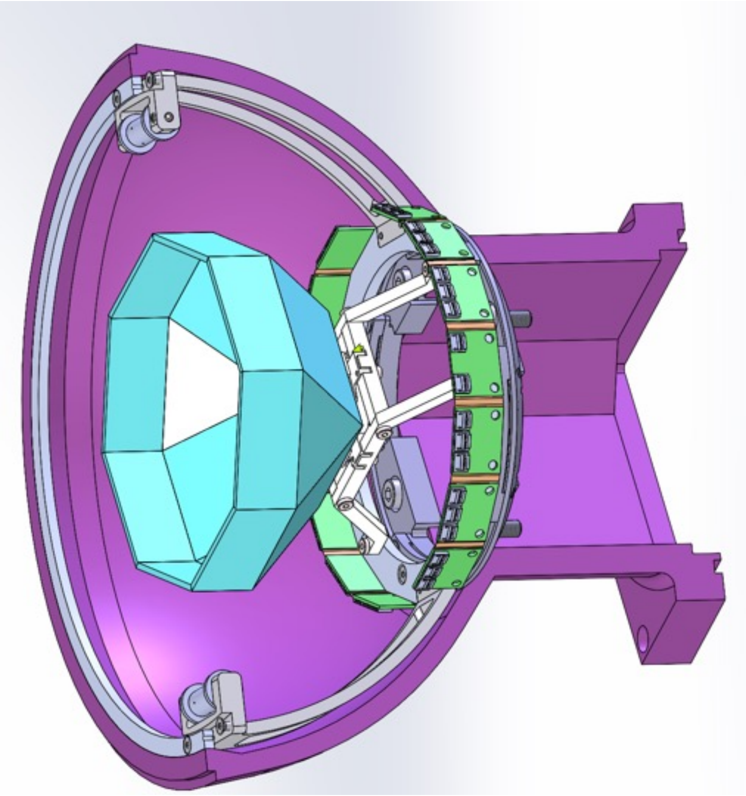


CAEN 500MHz, 14 bit digitizers used for DESCANT.

Ancillary detector for Rare Isotope Event Selection (ARIES)

A major upgrade of the SCEPTAR beta-tagging array for GRIFFIN

Victoria Vedia, R. Umashankar, W. Royer, L. Mantle, S. Rodrigues, M. Spinazze, L. Tomlin *et al.*
Miles Constable, D. Bishop (Electronics design),
Shaun Georges (Mechanical design)



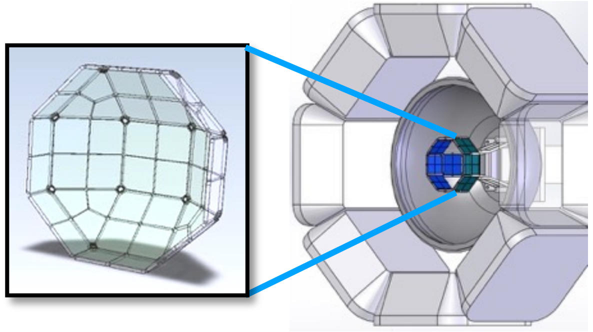
Geometry optimized for GRIFFIN with 1 beta paddle for each HPGe crystal,
+ 8 triangles + 4 downstream = (36 US)+(40 DS) = 76 total channels

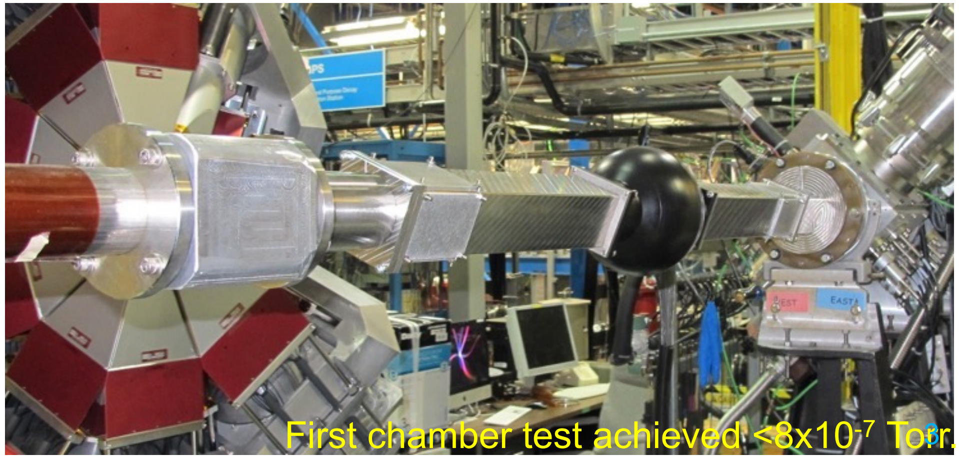
New ARIES beta-tagging array enables:

- Counting of high source activities ~20MBq with ~91.5% 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.

- Self-supporting structure of 1.5mm thick BC422Q ultra-fast plastic scintillator coated with aluminum reflector to improve light collection.
- Light read-out using SiPM sensors printed on flexible circuit board ~50μm thickness will provide energy and fast-timing signal.
- Processing with the GRIFFIN DAQ.

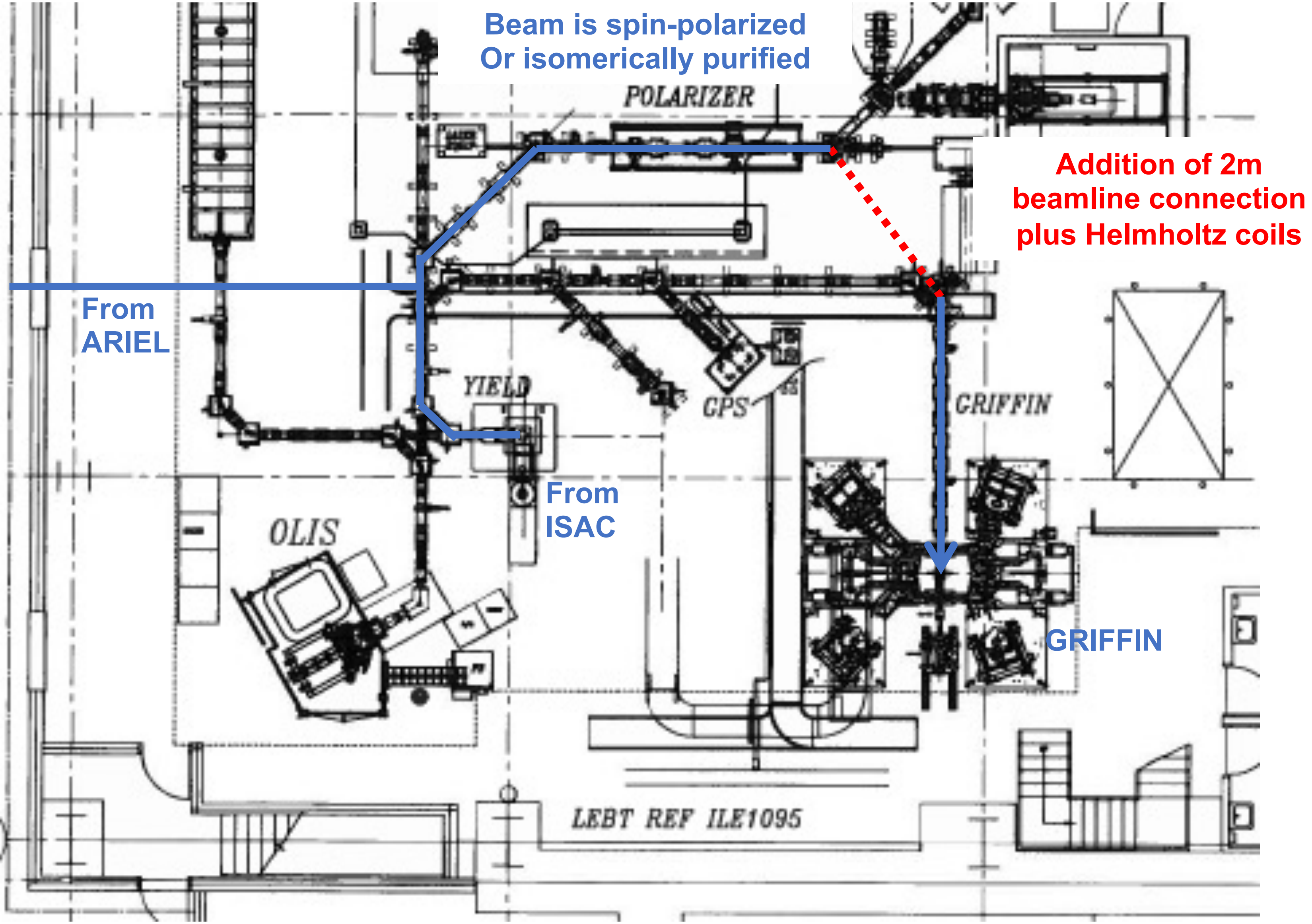
First experiments anticipated in 2023





First chamber test achieved <8x10^{-7} Torr.

Required new infrastructure to deliver spin-polarized beams to GRIFFIN



The Polarizer is operated by the Laser Applications group as a beam-delivery device (Ruohong Li, Jens Lassen).

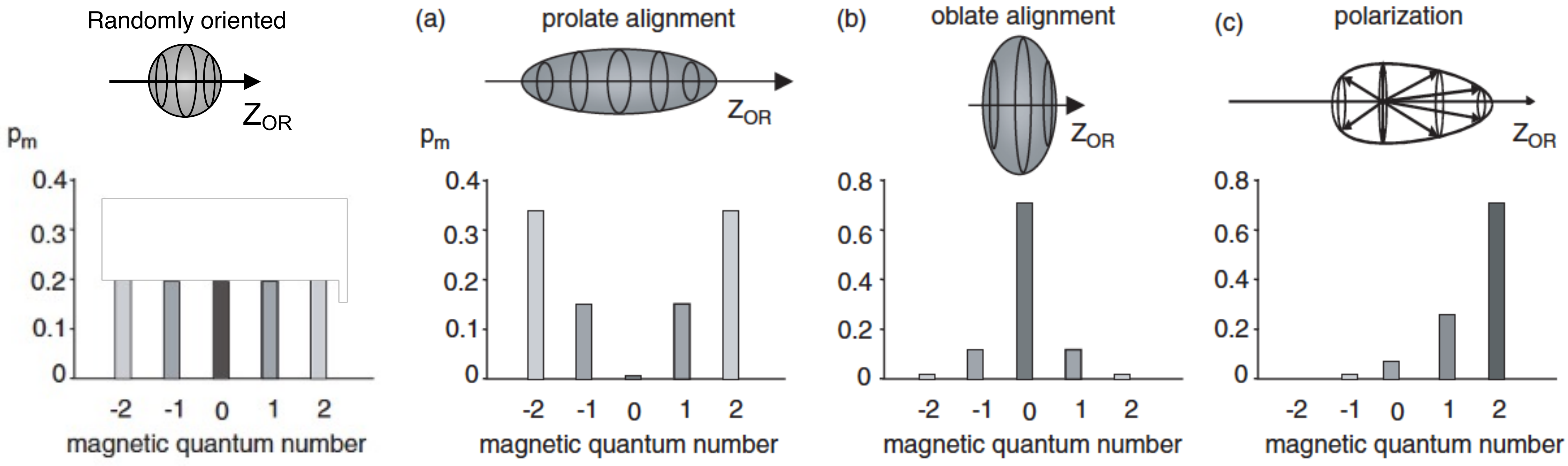
~$200k of new infrastructure:

- 2 meter beamline connection with vacuum and controls etc.
- Helmholtz coils for guiding field
- New beta detector optimized for polarized beams
- Implantation foil with large static magnetic field (permanent magnets)

Plus associated upgrades to the laser infrastructure to increase the range of elements which can be spin-polarized.

Alignment and polarization

- Radioactive source or ISAC beam has an ensemble with **randomly oriented** nuclear spins.
- Define an axial symmetry-axis of the oriented ensemble (Z_{OR}).
- Describe the spin-orientation with respect to Z_{OR} by the probability p_m that the nuclear spin has a projection $|m\rangle$ onto this axis.
- An ensemble of spins is **aligned** if an axially symmetric distribution of the spins has reflection symmetry with respect to a plane perpendicular to the axial symmetry-axis.
- An ensemble of nuclei is **polarized** if the up/down symmetry along the axial symmetry-axis is broken.



G. Neyens, Rep. Prog. Phys. 66, 633 (2003).

Spin-polarization from optical pumping

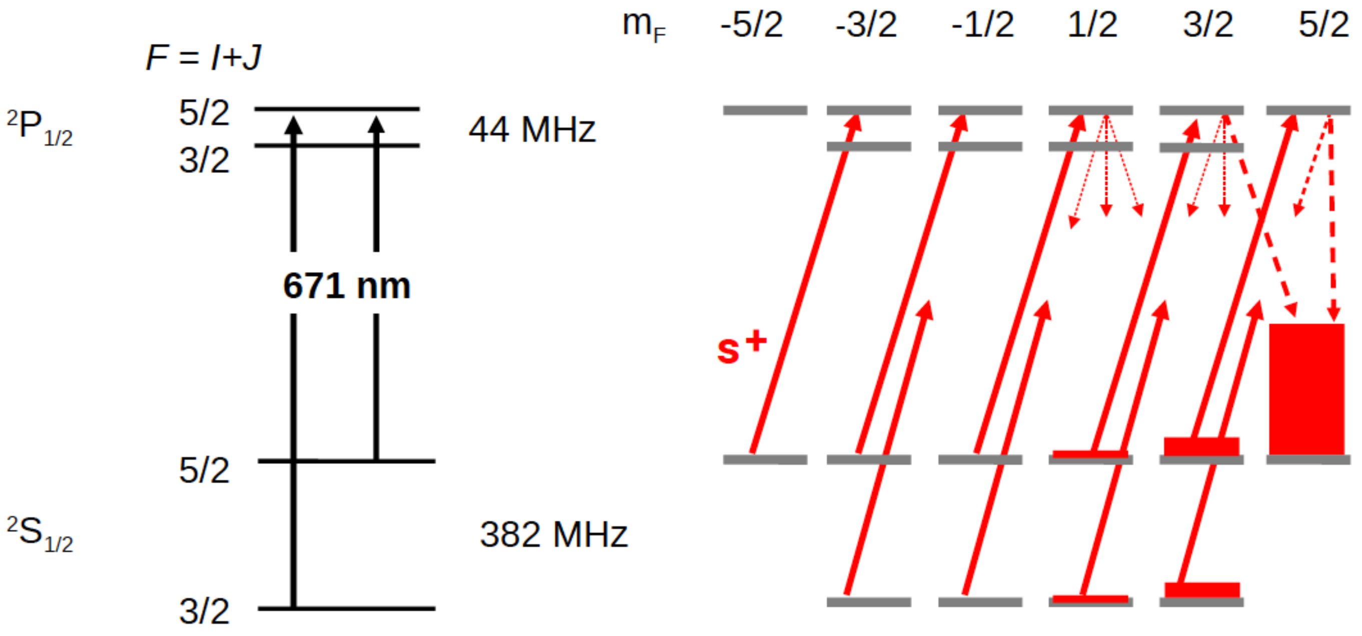
The atomic electrons are polarized by the interaction of the atomic (or ionic) beam with a circularly polarized colinear laser beam.

Repeated for several atomic excitation/decay processes.

The hyperfine interaction between the electron spin J and the nuclear spin transfers the polarization to the nucleus.

Nuclear polarization of typically 30–50% can be obtained.

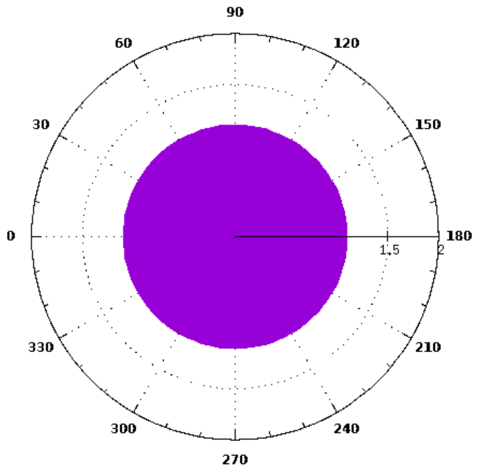
Weak guiding field preserves polarization to experiment.



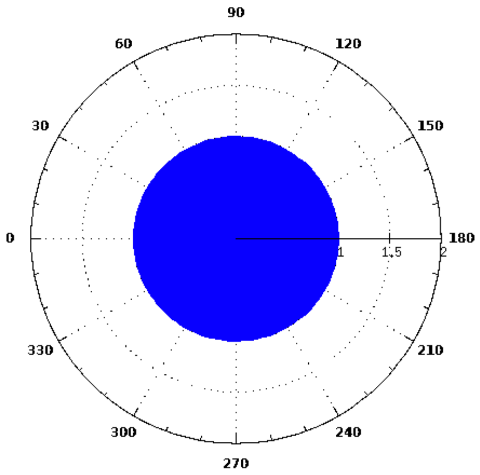
Effect of polarization on emitted radiation

No polarization:

Beta particles



Dipole gamma ray

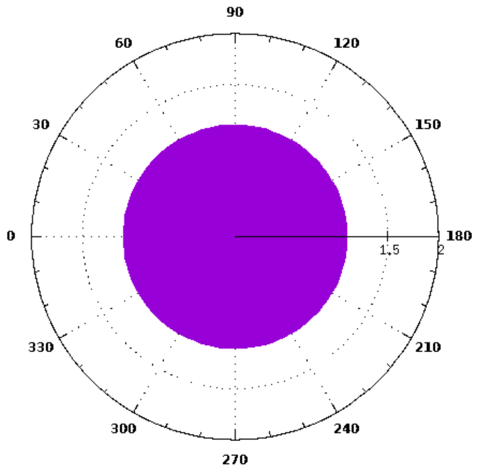


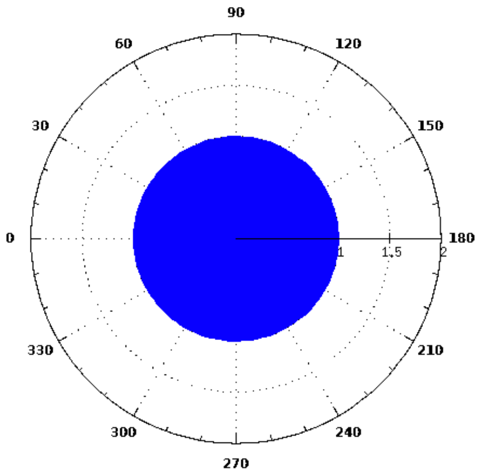
Effect of polarization on emitted radiation

Beta and gamma-ray angular distributions from a polarized source are anisotropic in the lab frame.

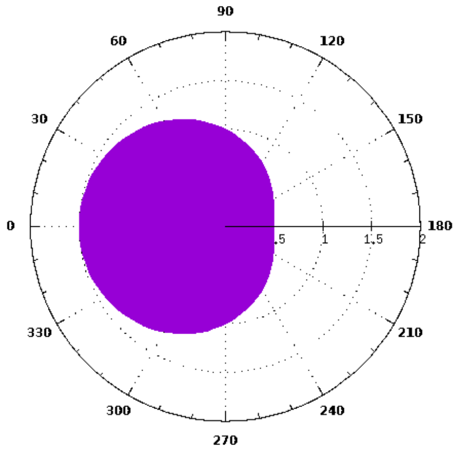
Beta particles | Dipole gamma ray

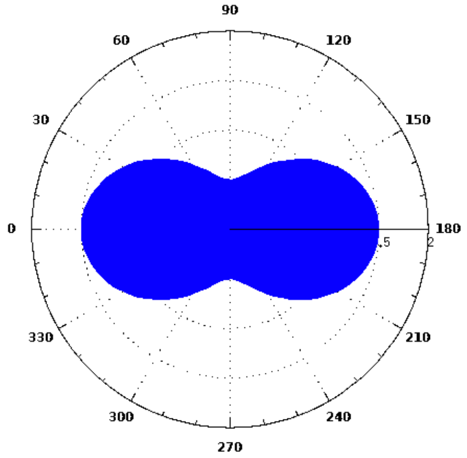
No polarization:





50% polarization:





$$W(\theta_r) = 1 + Pa_\beta \cos(\theta_r)$$

$$W(\theta_r) = a_0 + Pa_2 \cos(2\theta_r) + Pa_4 \cos(4\theta_r) + \ldots$$

Asymmetry increases with degree of polarization.

The *a* parameters depend on the details of the transitions (initial and final spins, mixing ratio of multipoles, etc.)

Measurements of the angular distributions provide information on the nuclear or environmental properties.

Similar effect on all emitted radiation; **α**, **β**, **γ**, ICE, p

Studies using spin-polarized nuclear decays

Nuclear structure and astrophysics:
(gamma-tagged) Beta particle angular distribution
Gamma ray angular distribution

}

- Assign spins/parities to daughter states,
- measure moments,
- measure F/GT mixing ratios of β transitions,
- measure multipole mixing ratios of γ-ray transitions

Fundamental interactions:
Beta-gamma angular correlations
Gamma-gamma angular correlations
Linear polarization of gamma rays

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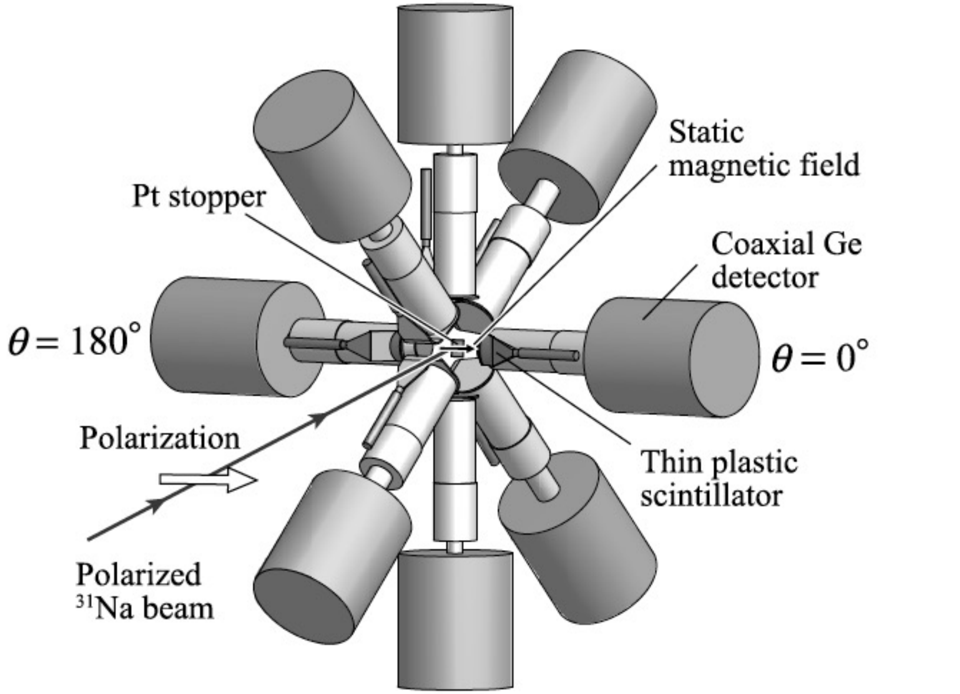
- CPT violation
- Searches for new physics

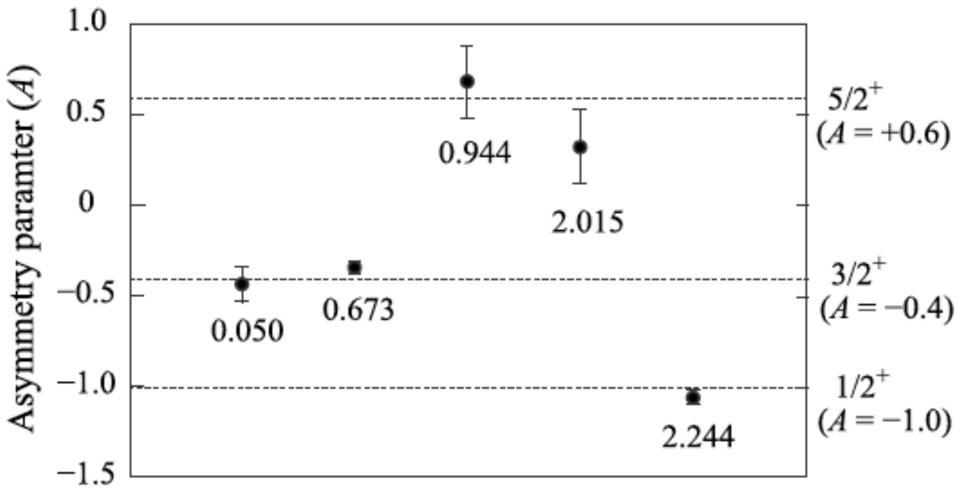
Other things too…

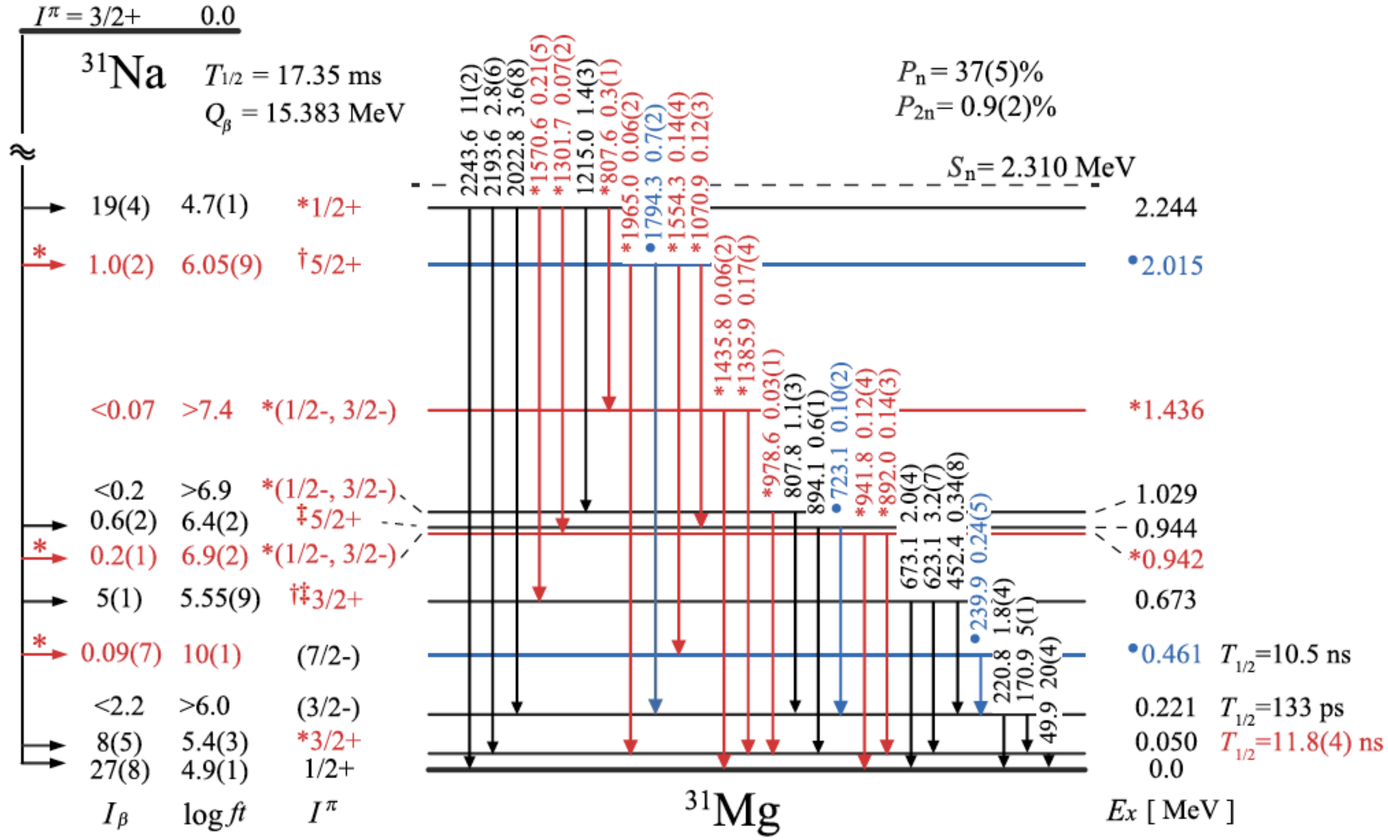
OSAKA @ TRIUMF: Spin/parity from γ-tagged β asymmetry



200pps of ^{31}Na ($T_{1/2}$=17.35ms) with 32(1)% polarization.
8 plastic scintillator + HPGe telescopes.
- 2 at 0/180° to polarization for **β** asymmetry (ε_β≈16%)
- 6 perpendicular to polarization (ε_β≈32%, ε_γ≈2.9%@1.3MeV)

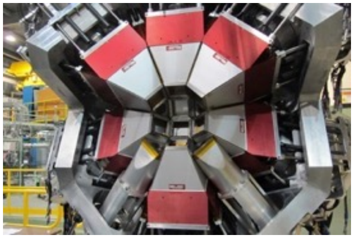
GRIFFIN+ARIES: ε_β≈90%, ε_γ≈16%@1.3MeV





H. Nishibata *et al*. Physics Letters B 767, 81 (2017).

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.
Under analysis at Uni. of the West of Scotland

^{156,158,160,162,166}Tm: Shape coexistence around *N*=90
Under analysis at JAEA and TRIUMF

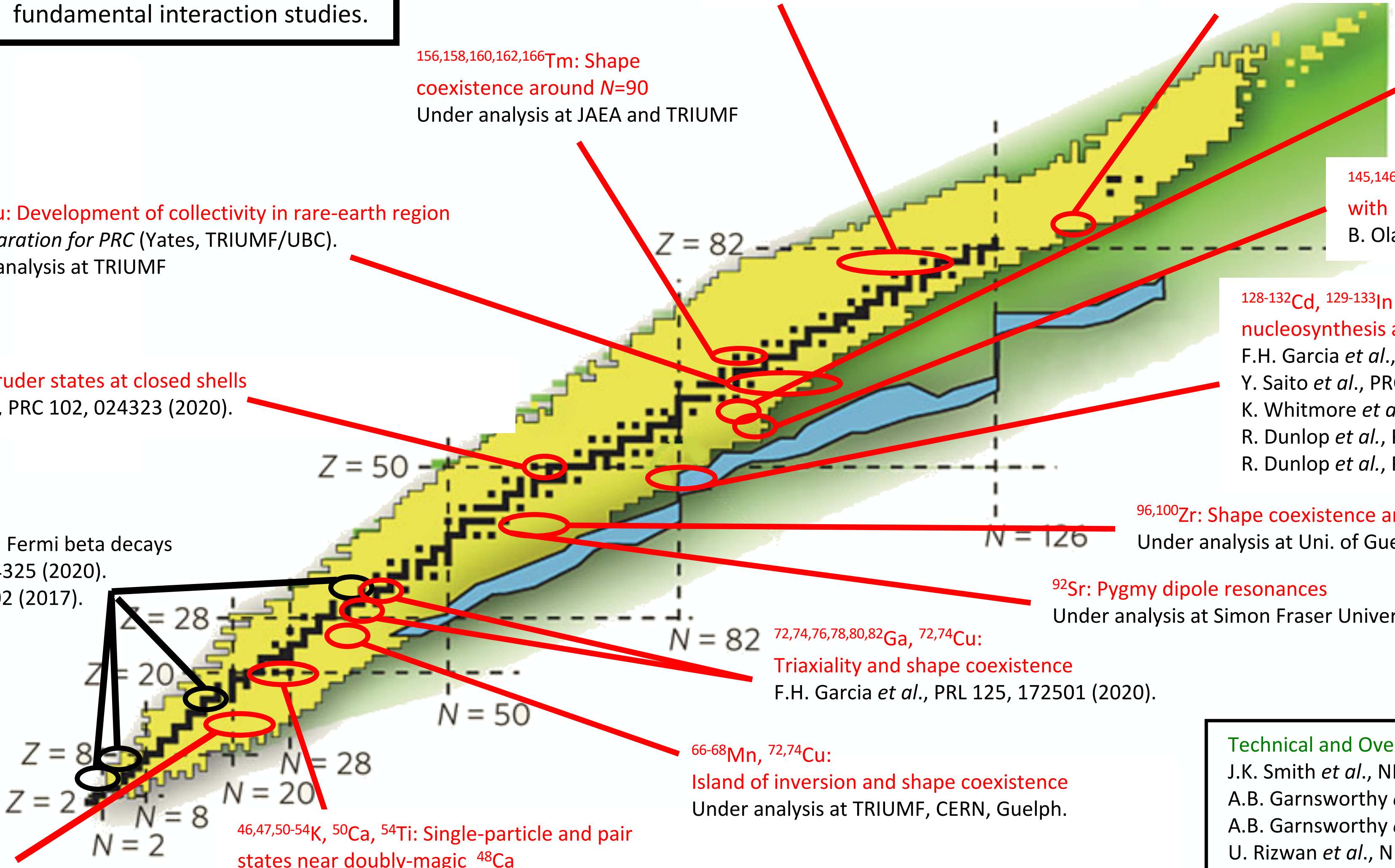
$^{142-152}$La: Octupole collectivity and shape coexistence in Ce isotopes
Under analysis at Uni. of Liverpool

$^{160-166}$Eu: Development of collectivity in rare-earth region
In preparation for PRC (Yates, TRIUMF/UBC).
Under analysis at TRIUMF

^{145,146,148,150}Cs: β-delay neutron measurements with DESCANT, fast-timing with $LaBr_3$
B. Olaizola *et al.*, PRC 104, 034307 (2021).

$^{128-132}$Cd, $^{129-133}$In: Nuclear structure and r-process nucleosynthesis at the N=82 shell closure
F.H. Garcia *et al.*, PRC 103, 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).

^{118}In, ^{114}Sb: Intruder states at closed shells
K. Ortner *et al.*, PRC 102, 024323 (2020).



^{96,100}Zr: Shape coexistence around *N*=60
Under analysis at Uni. of Guelph

^{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).

^{92}Sr: Pygmy dipole resonances
Under analysis at Simon Fraser University

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

$^{66-68}$Mn, ^{72,74}Cu: Island of inversion and shape coexistence
Under analysis at TRIUMF, CERN, Guelph.

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

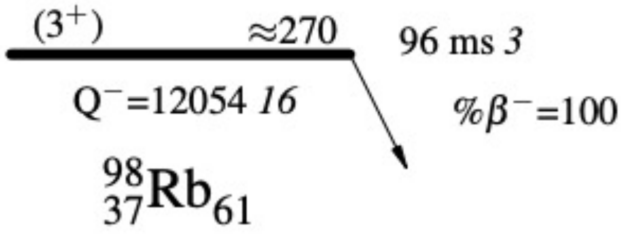
$^{46,47,50-54}$K, ^{50}Ca, ^{54}Ti: Single-particle and pair states near doubly-magic ^{48}Ca
M. Bowry *et al.*, PRC 104, 024314 (2021).
J.K. Smith *et al.*, PRC 102, 054314 (2020).
J. Pore *et al.*, PRC 100, 054327 (2019).
A.B. Garnsworthy *et al.*, PRC 96, 044329 (2017).

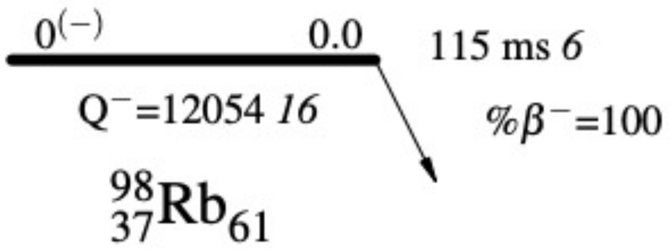
Technical and Overview Publications
J.K. Smith *et al.*, NIM A 922, 47 (2019).
A.B. Garnsworthy *et al.*, NIM A 918, 9 (2019).
A.B. Garnsworthy *et al.*, NIM A 853, 85 (2017).
U. Rizwan *et al.*, NIM A 820, 126 (2016).
A.B. Garnsworthy, Acta Phys.Pol. B, 47, 713 (2016).
C.E. Svensson and A.B. Garnsworthy, Hyp. Int. 225, 127 (2014).

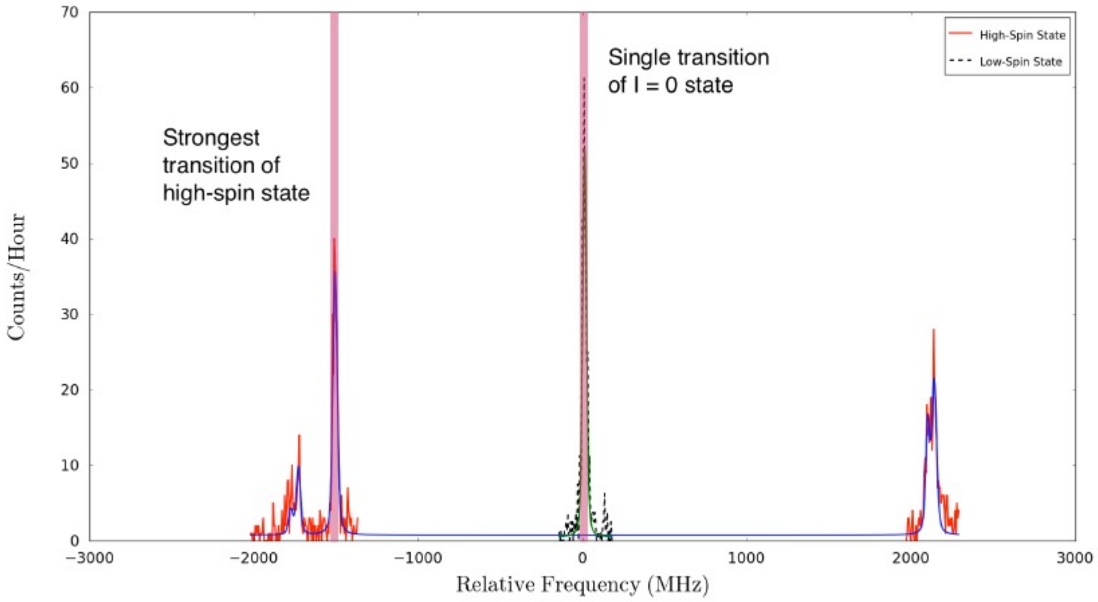
Isomer-selected beam

S1475 (M. Rajabali, Tennessee Tech Uni.) is a demonstration of the technique:

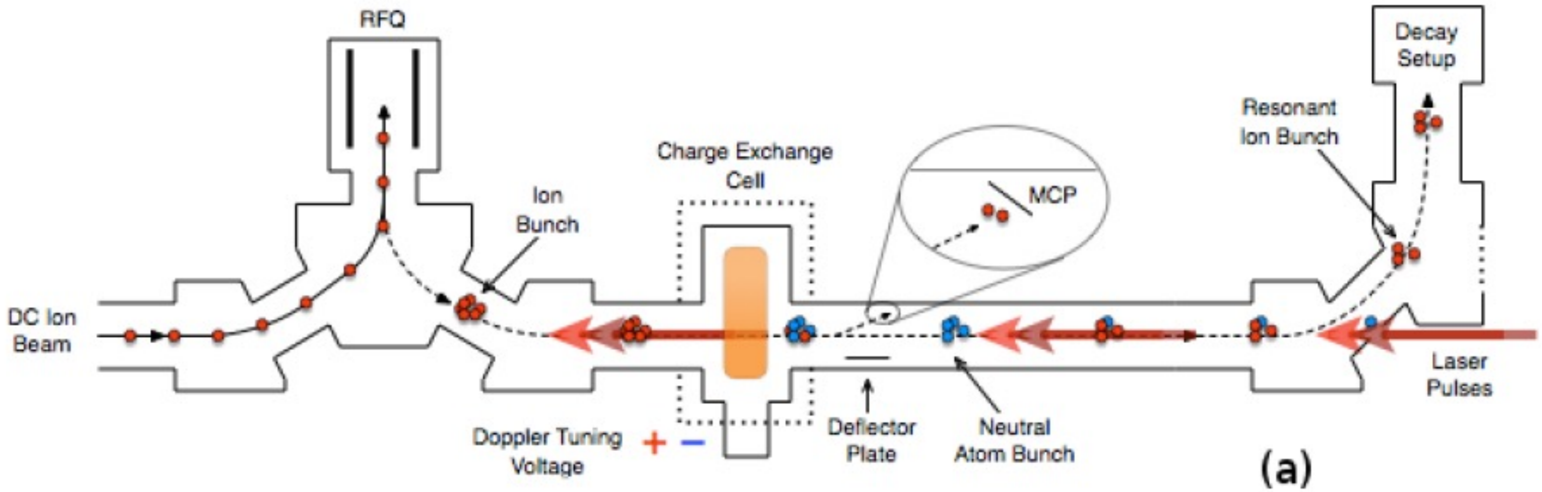
^{98}Rb has two beta-decaying states that decay to ^{98}Sr with similar half life.



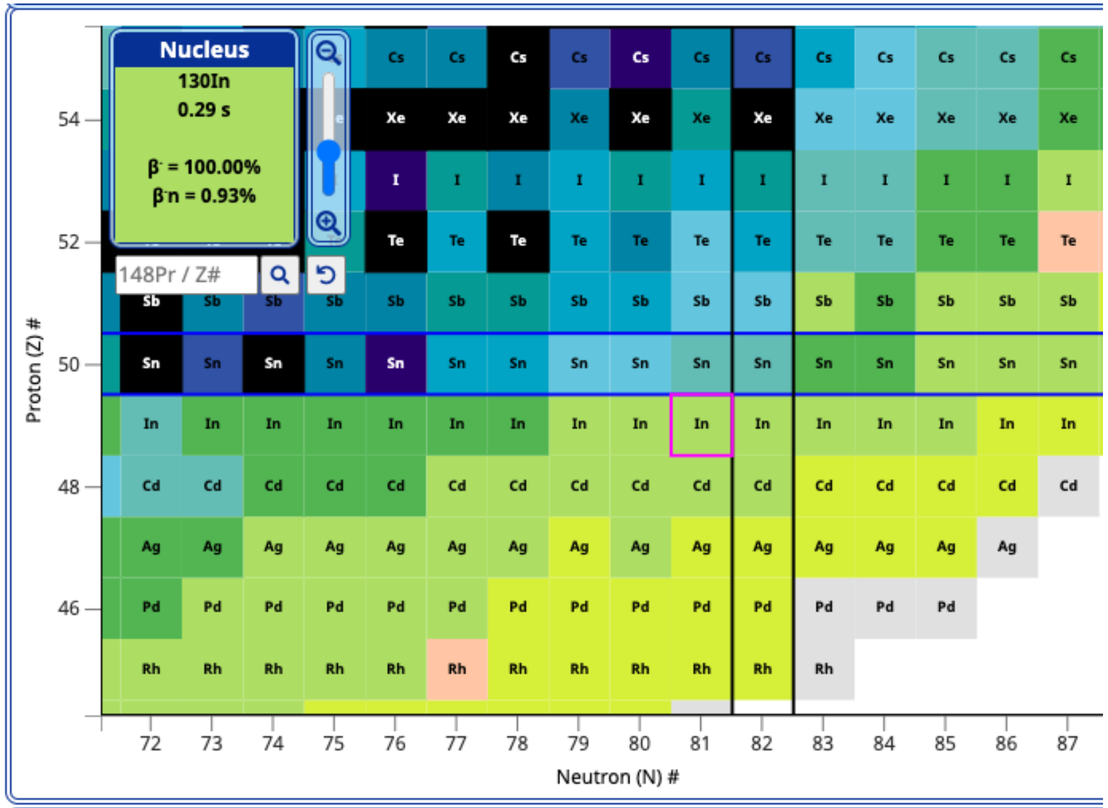




Using resonant laser ionization we can selectively deliver one of the isomers at a time very cleanly and study the decay.



Isomer-selected beam



Ground and isomeric state information for $^{130}_{49}$In

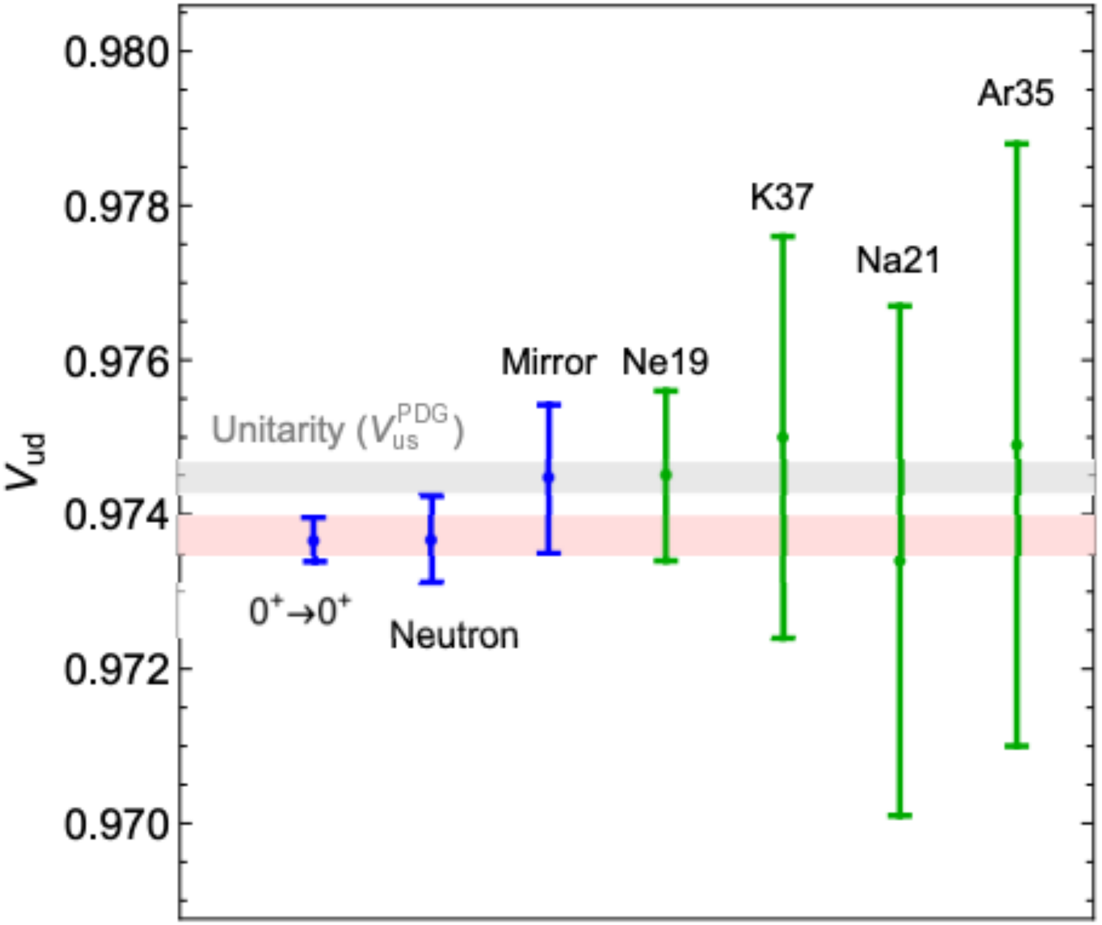
E(level) (MeV)	Jπ	Mass Excess (keV)	$T_{1/2}$	Decay Modes
0.0	1(-)	-69906.5 *18*	0.29 s *2*	β^- = 100.00% β^-n = 0.93%
0.0500	(10-)	-69856.5 *18*	0.54 s *1*	β^- = 100.00% β^-n = 1.65%
0.4000	(5+)	-69506.5 *18*	0.54 s *1*	β^- = 100.00% β^-n = 1.65%

The nuclear structure around doubly-magic ^{132}Sn is very influential on the astrophysical rapid neutron capture process.

Beta-decay isomeric states play an important role, and can have completely different half-lives or decay properties compared to the ground state.

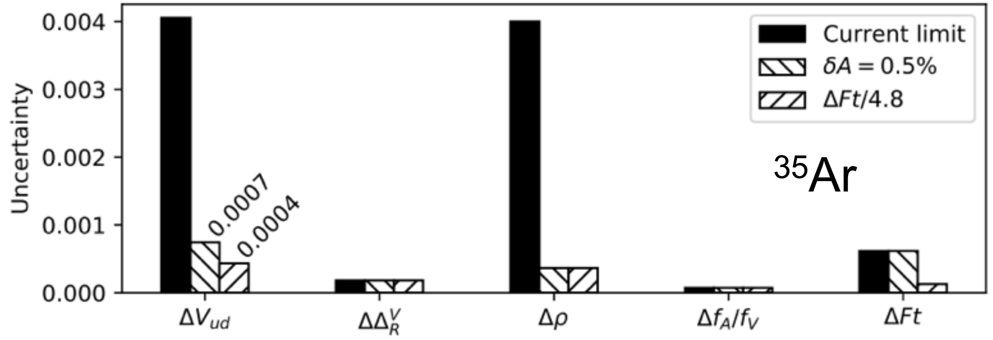
Isomer-selected beam delivery will allow their detailed study by eliminating the main challenges of mixed sources.

Test of the CVC hypothesis and determination of $|V_{ud}|$



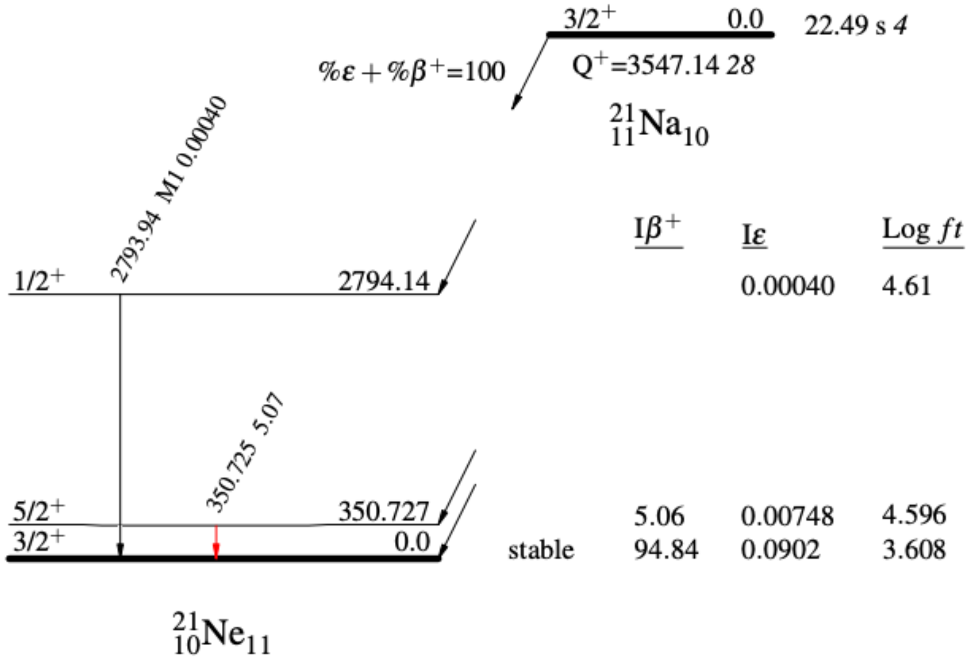
Parent	Spin	Δ [MeV]	$\langle m_e/E_e \rangle$	f_A/f_V	$\mathcal{F}t$ [s]	Correlation
^{17}F	5/2	2.24947(25)	0.447	1.0007(1)	2292.4(2.7) [48]	$\tilde{A} = 0.960(82)$ [12, 49]
^{19}Ne	1/2	2.72849(16)	0.386	1.0012(2)	1721.44(92) [45]	$\tilde{A}_0 = -0.0391(14)$ [50]
						$\tilde{A}_0 = -0.03871(91)$ [43]
^{21}Na	3/2	3.035920(18)	0.355	1.0019(4)	4071(4) [46]	$\tilde{a} = 0.5502(60)$ [40]
^{29}P	1/2	4.4312(4)	0.258	0.9992(1)	4764.6(7.9) [51]	$\tilde{A} = 0.681(86)$ [52]
^{35}Ar	3/2	5.4552(7)	0.215	0.9930(14)	5688.6(7.2) [13]	$\tilde{A} = 0.430(22)$ [14, 53, 54]
^{37}K	3/2	5.63647(23)	0.209	0.9957(9)	4605.4(8.2) [44]	$\tilde{A} = -0.5707(19)$ [39]
						$\tilde{B} = -0.755(24)$ [42]

Table 1. Mirror beta decays used in this analysis. The quantity $\langle m_e/E_e \rangle$ is calculated via eq. (2.6), using the endpoint energy listed in the table. The latter are taken from AME2016 [47], except that of ^{21}Na [46]. The values of f_A/f_V come from refs. [33, 41]. We also used the notation $\tilde{A}_0 \equiv \tilde{A}(m_e)$.



"Comprehensive analysis of beta decays within and beyond the Standard Model",
A. Falkowski, M. González-Alonso, and O. Naviliat-Cuncic, J. High Energ. Phys. 2021 126 (2021).
V. Gins, PhD thesis, KU Leuven (2019).
"Test of the Conserved Vector Current Hypothesis in T=1/2 Mirror Transitions and New Determination of $|V_{ud}|$",
O. Naviliat-Cuncic and N. Severijns, Phys. Rev. Lett. 102, 142302 (2009).

Measure Fermi/Gamow-Teller mixing ratio in Mirror decays



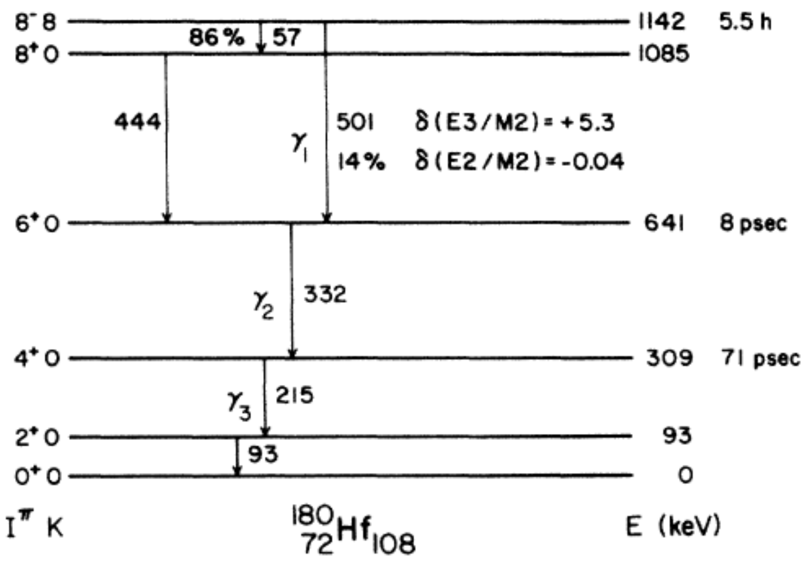
Example of $^{21}Na \rightarrow {}^{21}Ne$ beta decay.
$3/2^+ \rightarrow 3/2^+$ = pure Fermi
$3/2^+ \rightarrow 5/2^+$ = mixed Fermi+GT

Measure beta asymmetry of both branches, then ratio provides Fermi+GT mixing ratio, **ρ**, for GS decay

$$\rho = \frac{C_A M_{GT}}{C_V M_F}$$

where:
C_A = axial-vector coupling constant
C_V = vector coupling constant
M_F = Fermi matrix element
M_{GT} = Gamov-Teller matrix element

Tests of Parity violation in (γ-tagged)-β and γ decay



In the case of ^{180}Hf, the 501keV transition shows strong *P*-violating effects which in turn might show enhanced *T*-violating effects.

^{178}Hf atoms formed ferromagnet with Zr and Fe.
^{180}Hf isomer populated in neutron capture.
Cooled to 20-35mK.
Magnetic field applied to polarize sample.

Only possible for long-lived isomers $T_{1/2}$>hrs.

^{180}Hf 501keV from 8^- to 6^+ has allowed multipolarities of *M2, E3, M4, E5…*

But the Hamiltonian is the sum of parity-conserving, $\mathcal{H}_0$, and a small parity-violating, $\mathcal{H}_{PV}$, part;
$\mathcal{H}=\mathcal{H}_0+\mathcal{H}_{PV}$

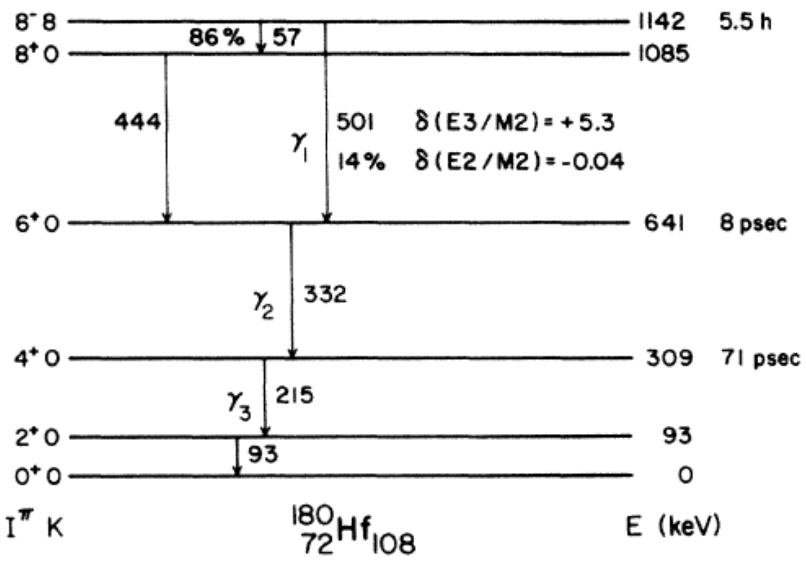
An *E2* component is parity violating and can be detected by a perturbation of the angular distribution of the 501keV gamma rays.

This experiment placed a limit of 10^{-4} on the expected 10^{-5} effect in this case. This 10% measurement was made in 30 hrs using two NaI detectors with a low-temperature oriented source in 1971.

Certainly opportunities to make impactful measurements with Spin-polarized beams to GRIFFIN.

K.S. Krane *et al.*, Phys. Rev. C 4, 1906 (1971).

Tests of Time-reversal violation in γ decay



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Measure **γγ** angular correlations of polarized source.

The effect of *T* violation leads to the mixing ratio of the (*L*+1) and *L* components becoming complex, with phase angle **η**, such that $\delta = |\delta| e^{i\eta}$.

$$W = W_0 + W_T + W' \qquad \mathcal{A} = \frac{W(\uparrow) - W(\downarrow)}{W(\uparrow) + W(\downarrow)} . \qquad \mathcal{A} \approx \frac{W_T + W'}{W_0} .$$

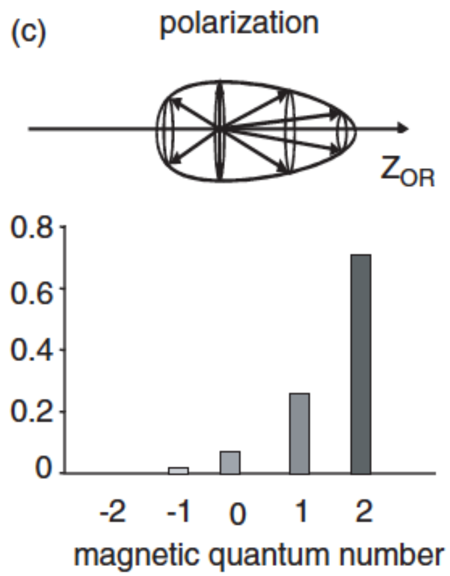
Set of K isomers where there is hindrance of *T*-conserving multipoles but not for *T*-violating multipoles. Allowing for sensitive tests to be performed.

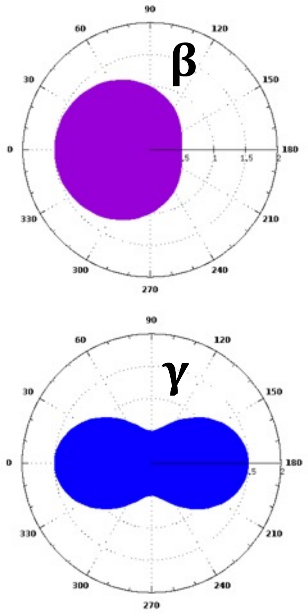
Two review articles from a 1988 workshop:
P. Herczeg, Hyperfine Interactions 43, 77 (1988).
F. Boehm, Hyperfine Interactions 43, 95 (1988).
With discussion and suggestions on how to improve the sensitivity levels by a few orders of magnitude. But does not seem like additional measurements have been made since then.

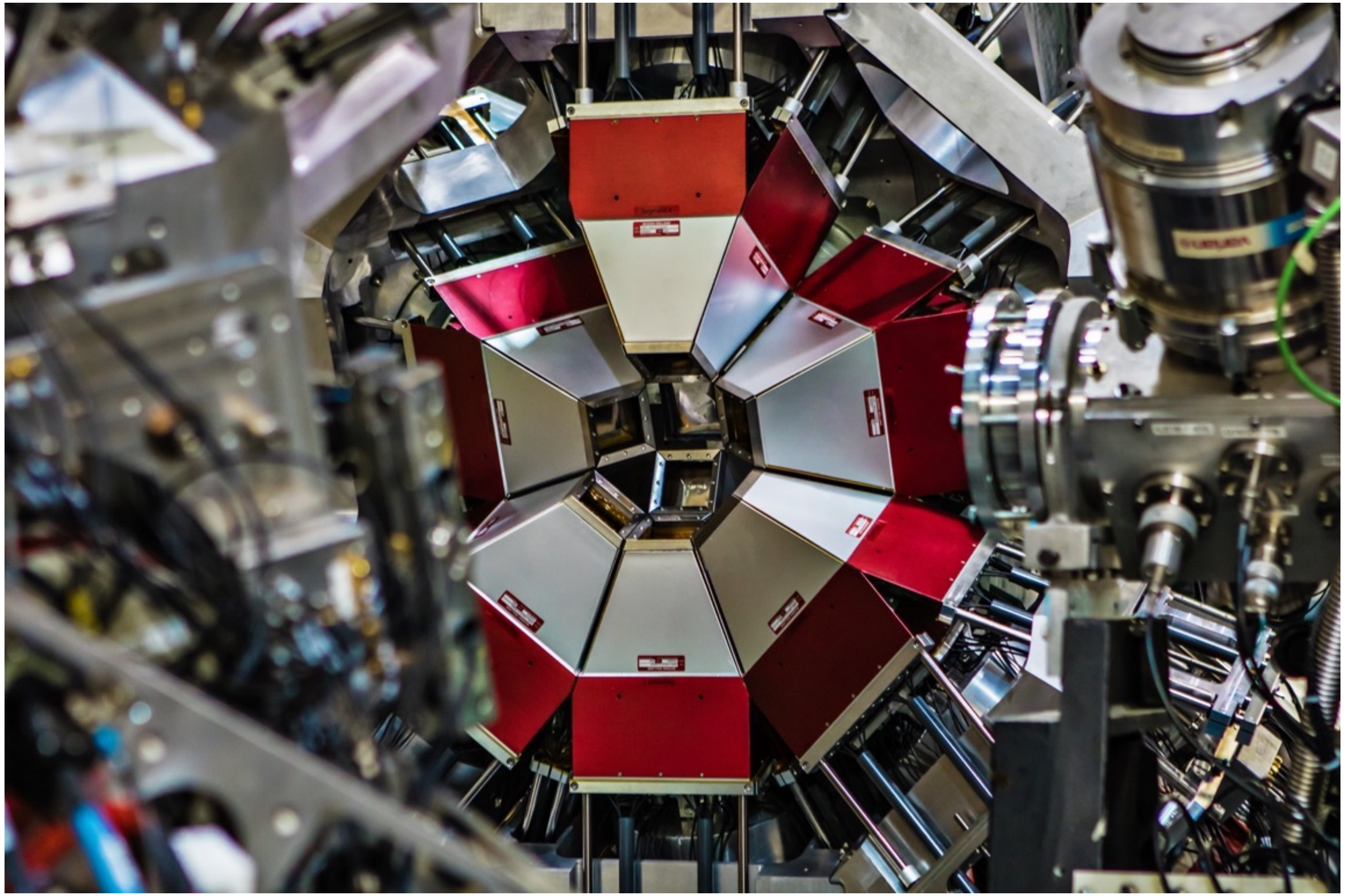
Spin-polarized beams to GRIFFIN would allow such tests in a range of short-lived isomers that was not possible before.

K.S. Krane *et al*., Phys. Rev. C 10, 840 (1974).

New opportunities with spin-polarized beams to GRIFFIN







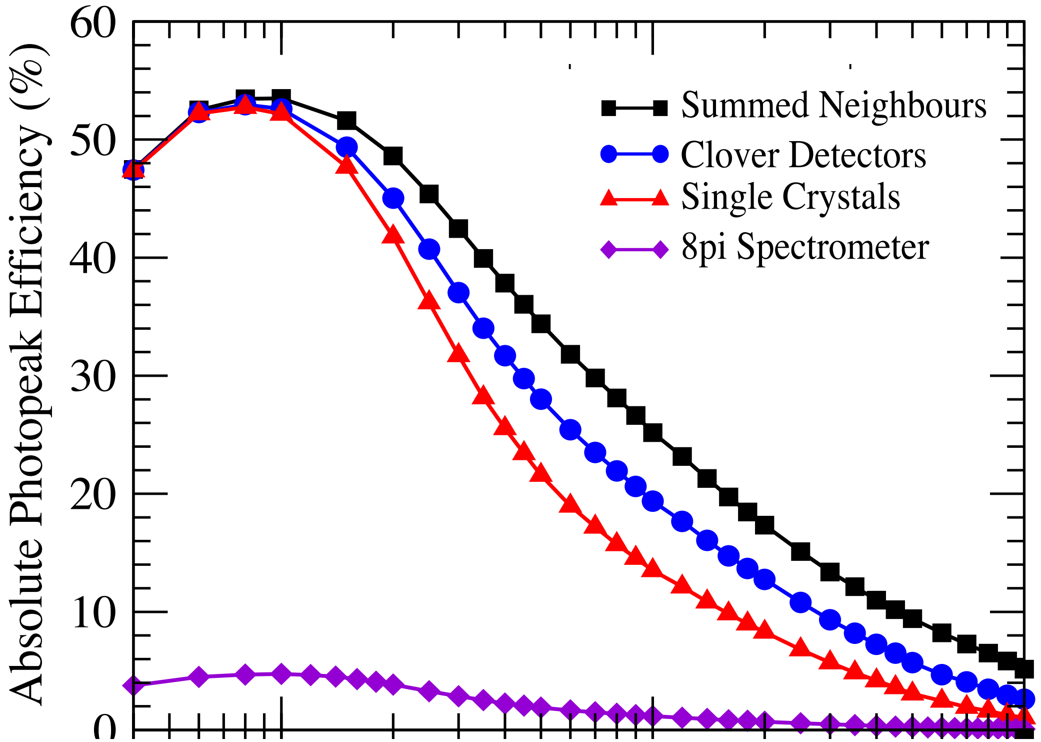
- Assign spins/parities to daughter states,
- measure moments,
- measure F/GT mixing ratios of **β** transitions,
- measure multipole mixing ratios of **γ**-ray transitions
- Tests of CPT violation
- Searches for new physics

Other things too…

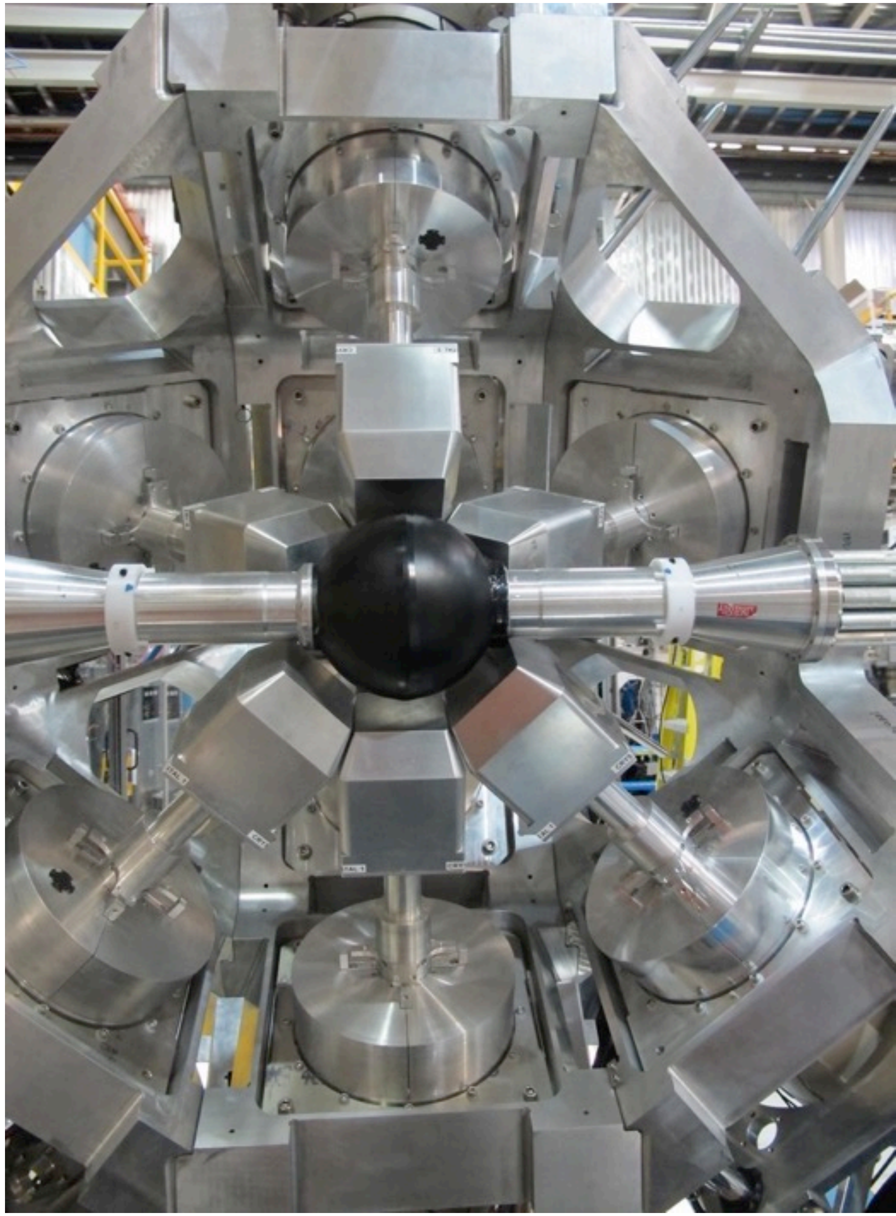
New collaborators are very welcome!

GRIFFIN HPGe Clover Detectors

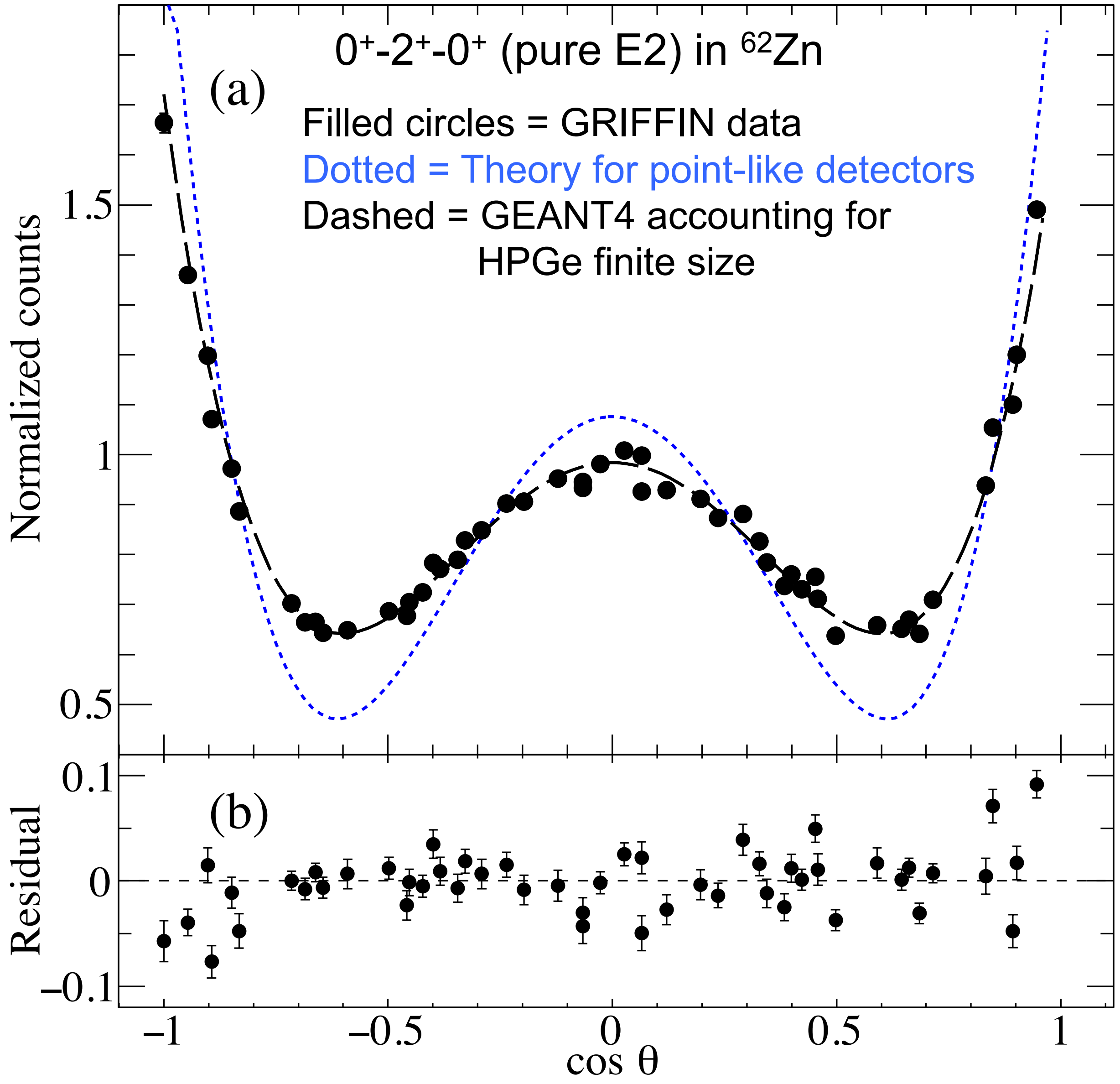
A close-packed array of 16 large-volume HPGe Clover detectors, 64 crystals



4032 crystal pairs at 51 unique angles for γ-γ angular correlations



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.

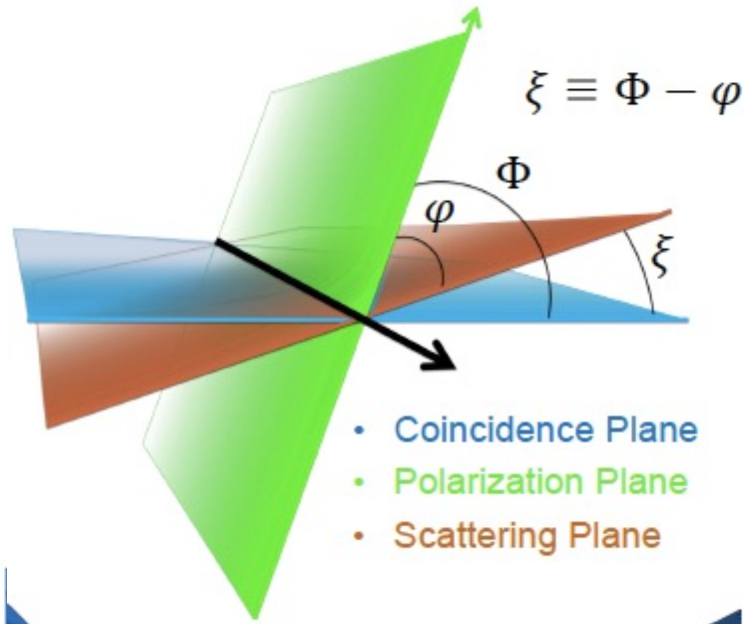
- Finite size and shape of crystals means theoretical distribution is attenuated.
- Obtain 'template' from high-statistics GEANT4 simulation
- Fit template to experimental data.

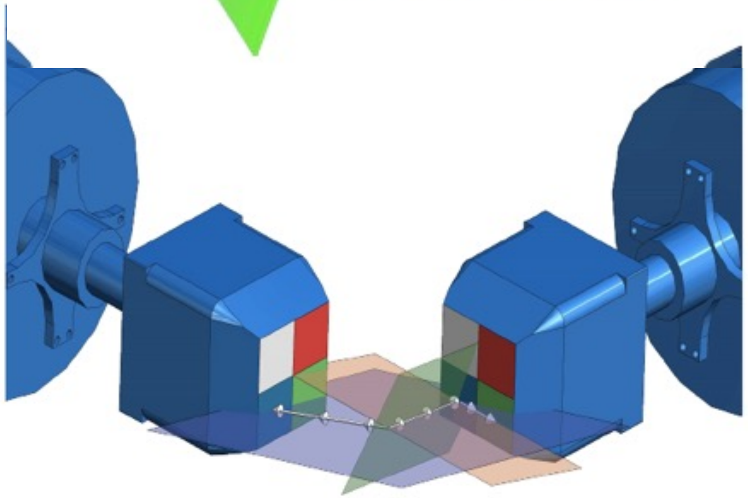
Ideally:

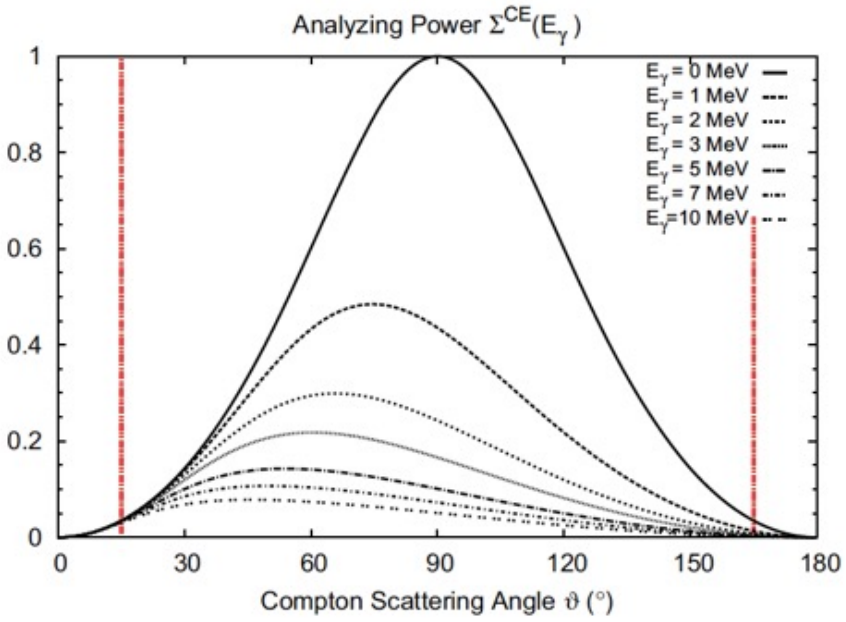
- Fit experimental data
- Plug coefficients into simple equations
- Obtain corrected 'true' coefficients

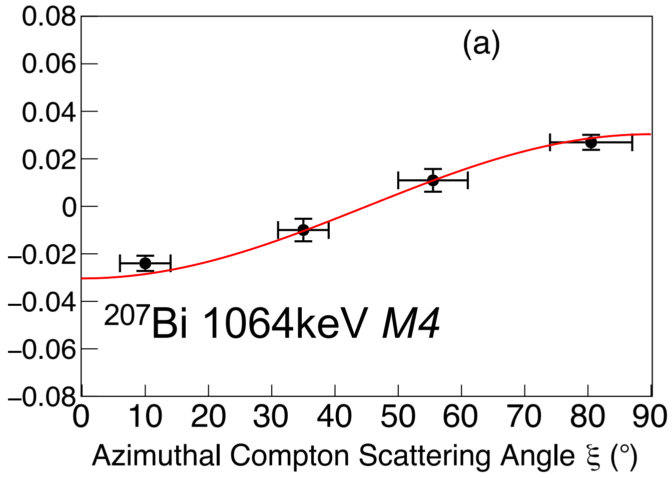
Compton Polarimetry using GRIFFIN

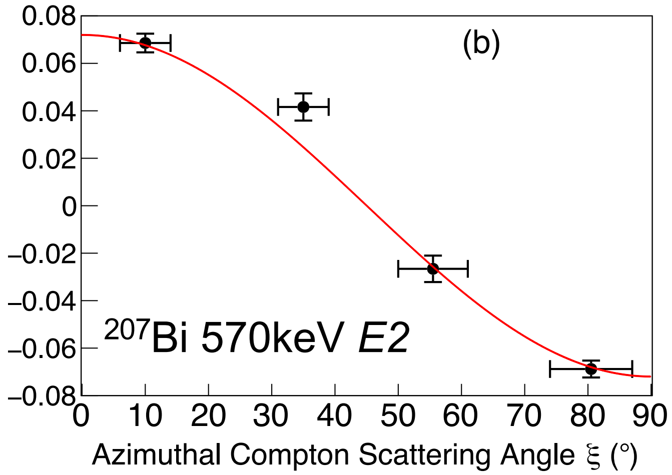
Define Polarization plane from γ–γ coincidence detection. Then examine azimuthal scattering angle to determine electric or magnetic nature of the radiation.









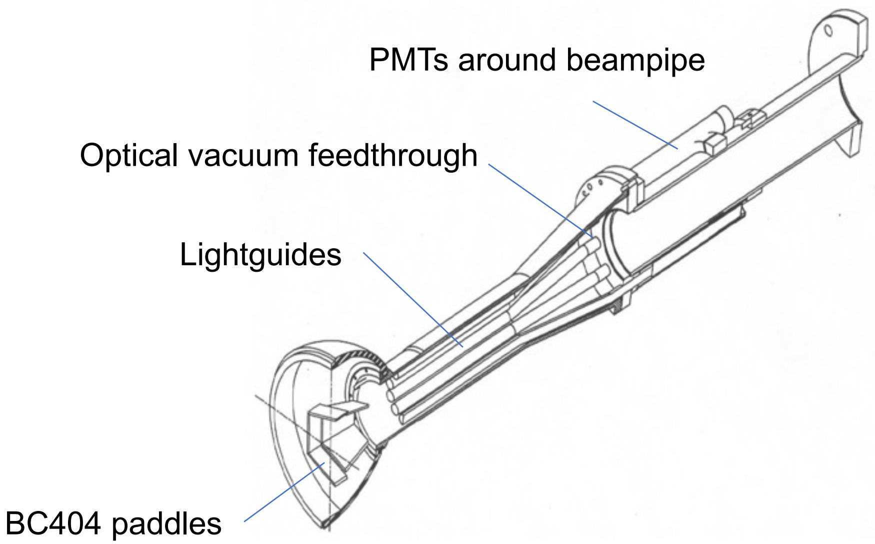


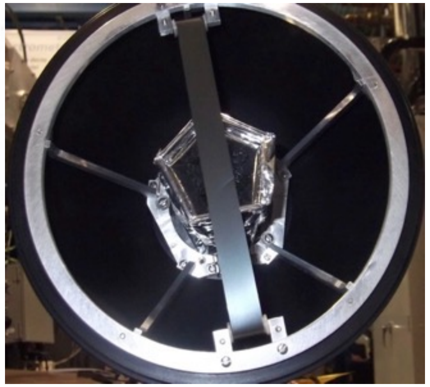
Dan Southall, TRIUMF research student, 2016

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

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

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