Probing physics beyond the TeV scale via nuclear beta decays

Alejandro Garcia
- University of Washington
- Center for Nuclear Physics and Astrophysics

- Acknowledgments: thanks to Oscar Naviliat-Cuncic, Xavier Flechard, Stefan Baessler for some slides

Probing physics beyond the TeV scale via nuclear beta decays

Outline

1. Motivation: the low-energy precision frontier
2. Chirality flip as tool for selecting beyond-SM physics
3. Beta spectroscopy with CRES
4. Beta spectroscopy with Calorimetry, and Si detector
5. Theory needs
6. Summary

Low-energy precision frontier

General idea:

$$H_{total} = H_{SM} + H_{new} = C_{SM}\ \hat{O}_{SM} + \sum C_{new,\,i}\ \hat{O}_i$$

Example: dim-6 operators couplings scaling

$$C \sim \frac{C_0}{M^2 - q^2}$$

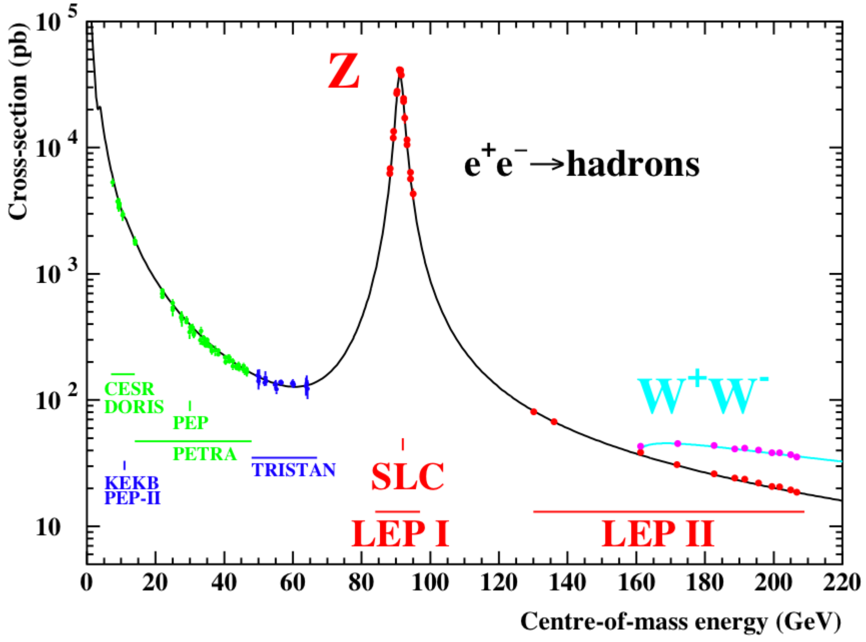
Effects of new physics at $q \approx 0$

$$\delta X \sim \frac{C_{new,\,i}/\Lambda^2}{C_{SM}/(2\ M_W)^2}$$

To reach sensitivity to Λ ~10 TeV need precision at

$$\delta X \sim 3\ \times 10^{-4}$$

High Energy Frontier:
LEP and LHC imply new physics probably beyond 1 TeV scale



Helicity

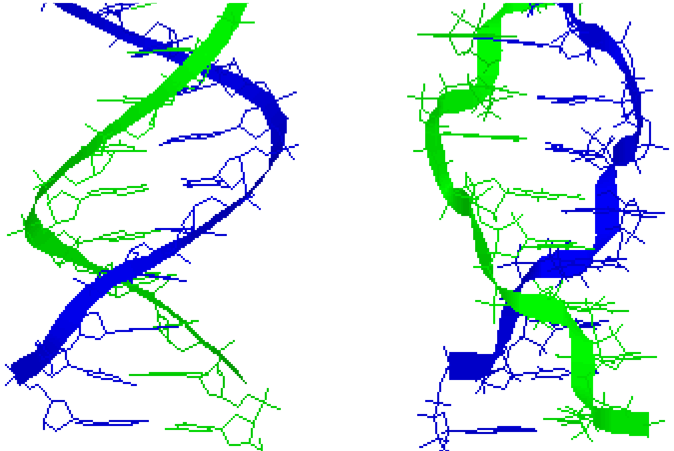
$$\mathcal{H} = \frac{\vec{J} \cdot \vec{p}}{|\vec{J}||\vec{p}|}$$

Projection of spin, $\vec{J}$, along momentum, $\vec{p}$

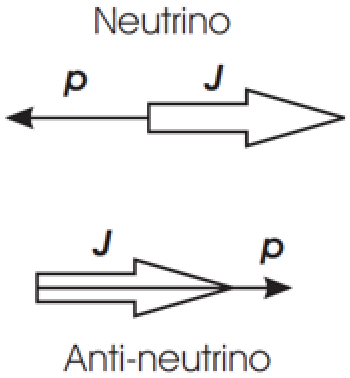
Screws can have *positive* or *negative handedness*.

Surprising: Nature distinguishes helicity, at the **molecular** level.

Many organic molecules (glucose and most biological amino acids) have *handedness*.



Beta decays:
L Neutrinos: $\mathcal{H}$<0
L Anti-neutrinos: $\mathcal{H}$>0

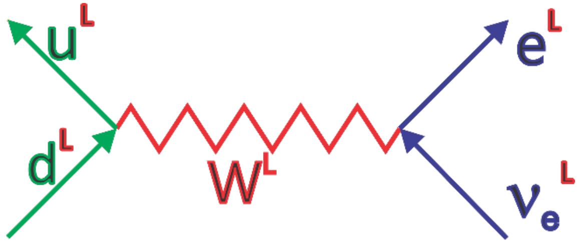


Chirality

Helicity is *not* a relativistic invariant

In relativistic QM → use chirality → can be Left or Right

For beta decay, for example:



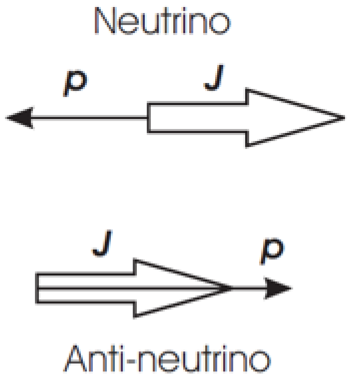
Remarkably → only Left components participate in beta decays

Current-current interaction

$$\left[\bar{e}^{L}\gamma_{\mu}\nu_{e}^{L}\ \cdot\bar{u}^{L}\gamma^{\mu}d^{L}\right]$$

L particles → $\mathcal{H} < 0$
L anti-particles → $\mathcal{H} > 0$

Beta decays:
L Neutrinos: $\mathcal{H}$<0
L Anti-neutrinos: $\mathcal{H}$>0

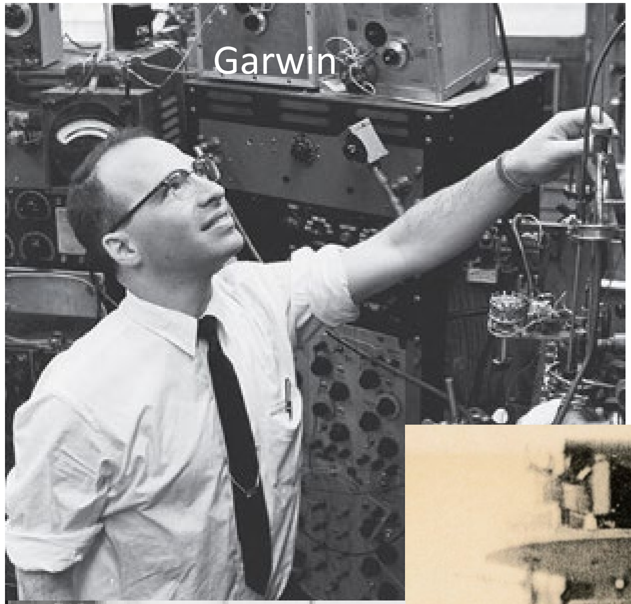


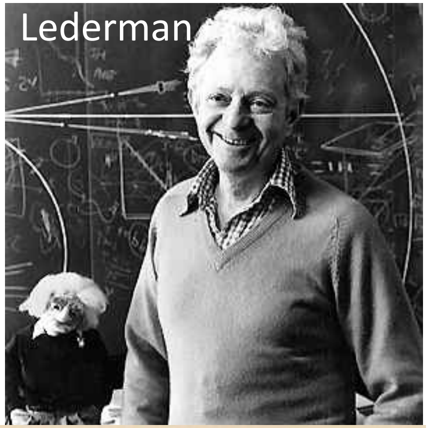
Weak interaction is left handed

Charged weak current in SM has only *L components*

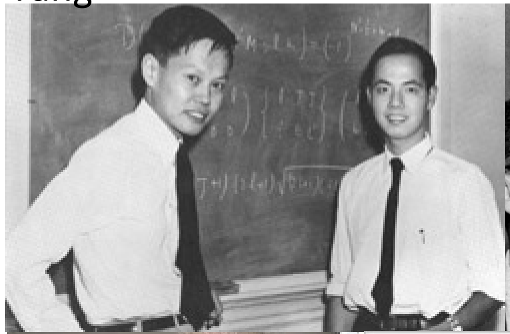
$$\mathcal{L}_{CC} = -\sqrt{2}G_F^0 V_{ud}\left[\bar{e}^{L}\gamma_\mu \nu_e^{L} \cdot \bar{u}^{L}\gamma^\mu d^{L}\right]$$

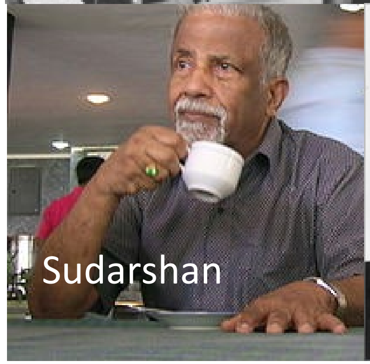
Took much effort and ingenuity to come out of confusing times



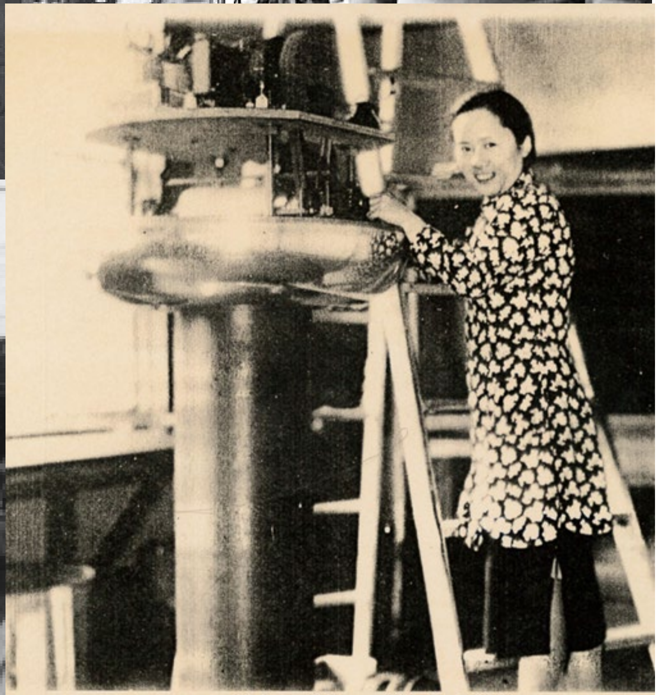


Yang Lee Gell-Mann Feynman





Marshak



Chien-Shiung Wu (b. 1912)
Nuclear Physicist

Chirality flip as tool to distinguish new physics

Low-energy charged weak current in SM:
only *L* components

$$\mathcal{L}_{CC} = -\sqrt{2}G_F^0 V_{ud}\left[\bar{e}^{L}\gamma_\mu \nu_e^{L} \cdot \bar{u}^{L}\gamma^\mu d^{L}\right]$$

Can be used to search for signatures of new physics →

Credit: https://hackernoon.com/finding-a-needle-in-a-haystack-5e024f931dc0

Use "chirality flip" as a signature for new physics

$$\bar{\psi}_e O^\mu \psi_\nu \overset{?}{\rightarrow} \begin{cases} \bar{\psi}_e^{L} O^\mu \psi_\nu^{R} \\ \bar{\psi}_e^{R} O^\mu \psi_\nu^{L} \end{cases}$$

Phenomenology for low-energy

Chirality-flipping interactions in beta decays

$$\mathcal{L}_{CC} = -\sqrt{2} G_F^0 V_{ud} \left[\bar{e}^L \gamma_\mu \nu_e^L \cdot \bar{u}^L \gamma^\mu d^L \right.$$
$$+ \boldsymbol{\epsilon_S}\, \bar{e}^R \nu_e^L \cdot \bar{u} d$$
$$\left. + \boldsymbol{\epsilon_T}\, \bar{e}^R \sigma_{\mu\nu} \nu_e^L \cdot \bar{u}^R \sigma^{\mu\nu} d^L \right]$$

Much recent progress from lattice in calculating nucleon form factors
Bhattacharya et al., Phys. Rev. D **85**, 054512 (2012)
Bhattacharya et al., Phys. Rev. D **94**, 054508 (2016)
Park et al., Phys. Rev. D **105**, 054505 (2022)
…
$g_S \approx g_T \approx 1$ to within 10%

In what follows we will simply assume
$g_S = g_T = 1$

Phenomenology for low-energy

Chirality-flipping interactions in beta decays

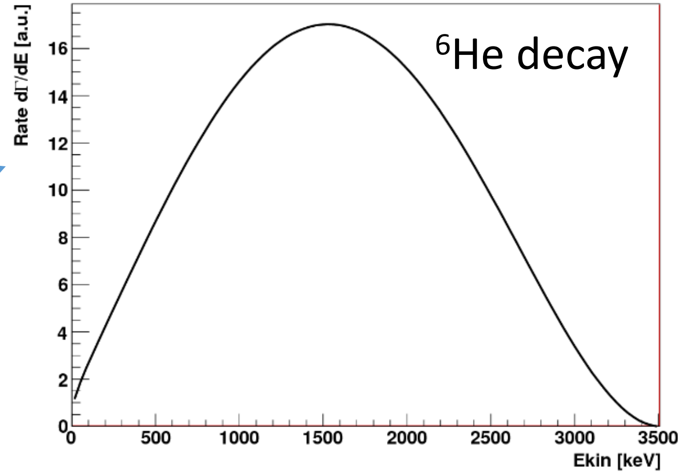
$$\mathcal{L}_{CC} = -\sqrt{2}G_F^0 V_{ud}\ \Big[\bar{e}^L\gamma_\mu\nu_e^L \cdot \bar{u}^L\gamma^\mu d^L$$
$$+\epsilon_S\ \bar{e}^R\nu_e^L \cdot \bar{u}d$$
$$+\epsilon_T\ \bar{e}^R\sigma_{\mu\nu}\nu_e^L \cdot \bar{u}^R\sigma^{\mu\nu}d^L\Big]$$

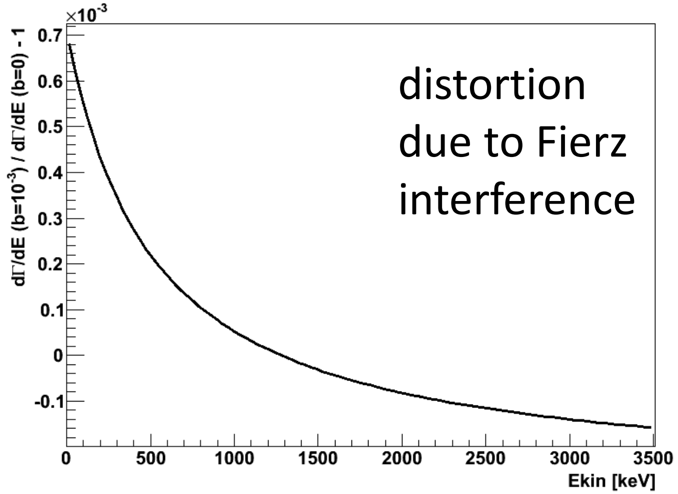
Many models of new physics naturally predict $\epsilon_S, \epsilon_T \neq 0$.

$$\frac{dN}{dE} = \left(\frac{dN}{dE}\right)_{standard}\left(1 + b\,\frac{m}{E}\right)$$

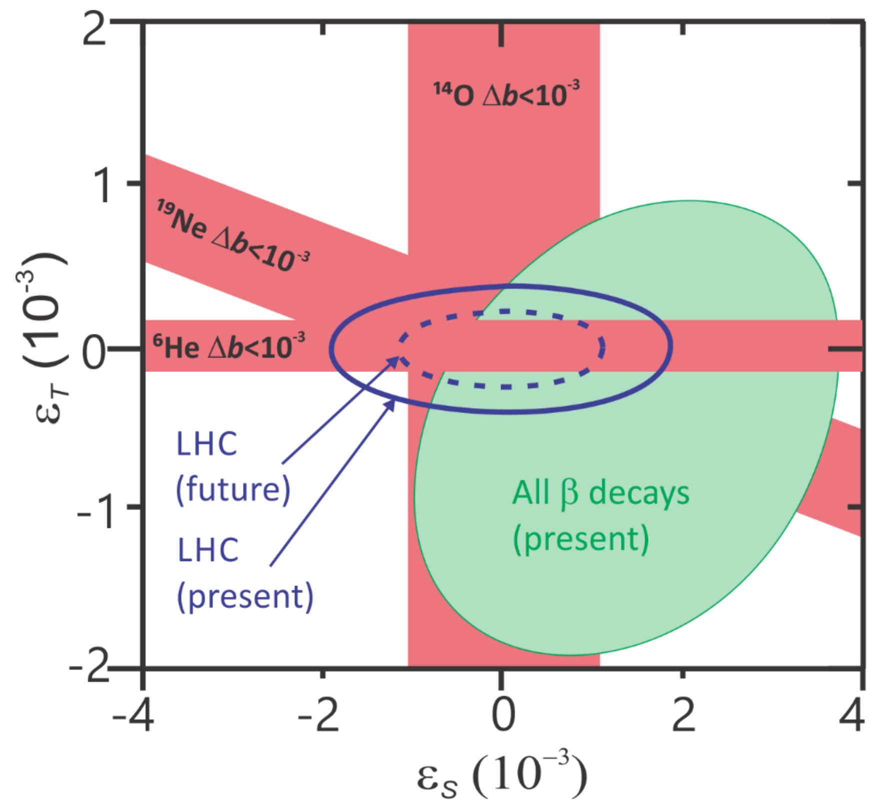
`Fierz interference'

$$b \approx \begin{cases} \pm 8\epsilon_T/\,g_A \text{ for GT} \\ \pm\epsilon_S \text{ for Fermi} \end{cases}$$





Present limits on Scalar and Tensor currents



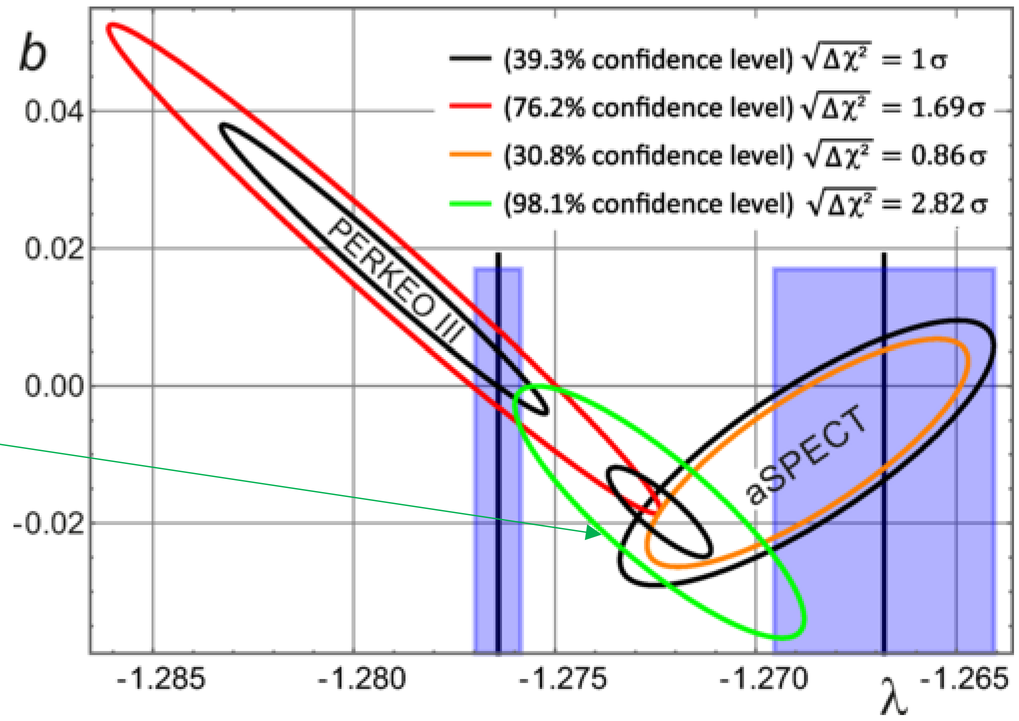
Search for chirality flipping currents beyond the LHC?

Challenging goal:
Measure beta spectra with accuracies 10^{-3} or better across a wide energy range.

$$\mathcal{L}_{CC} = -\sqrt{2} G_F^0 V_{ud} \left[\bar{e}^L \gamma_\mu \nu_e^L \cdot \bar{u}^L \gamma^\mu d^L + \epsilon_S \, \bar{e}^R \nu_e^L \cdot \bar{u} d + \epsilon_T \, \bar{e}^R \sigma_{\mu\nu} \nu_e^L \cdot \bar{u}^R \sigma^{\mu\nu} d^L \right]$$

A positive signal?

Two experiments can be reconciled ***if*** they assume a non-zero Fierz-interference: b = −0.0181 (65).



Unlikely to be real physics: limit from LHC assuming new physics at high energies is 10 times smaller.

Nonetheless, tighter limits on b simplify pinpointing sources of discrepancies in neutron beta decay and may clarify issues with g_A

M. Beck et al.
Phys. Rev. Lett. **132**, 102501 (2024)

Selected experiments searching for $\boldsymbol{b \leq 10^{-3}}$

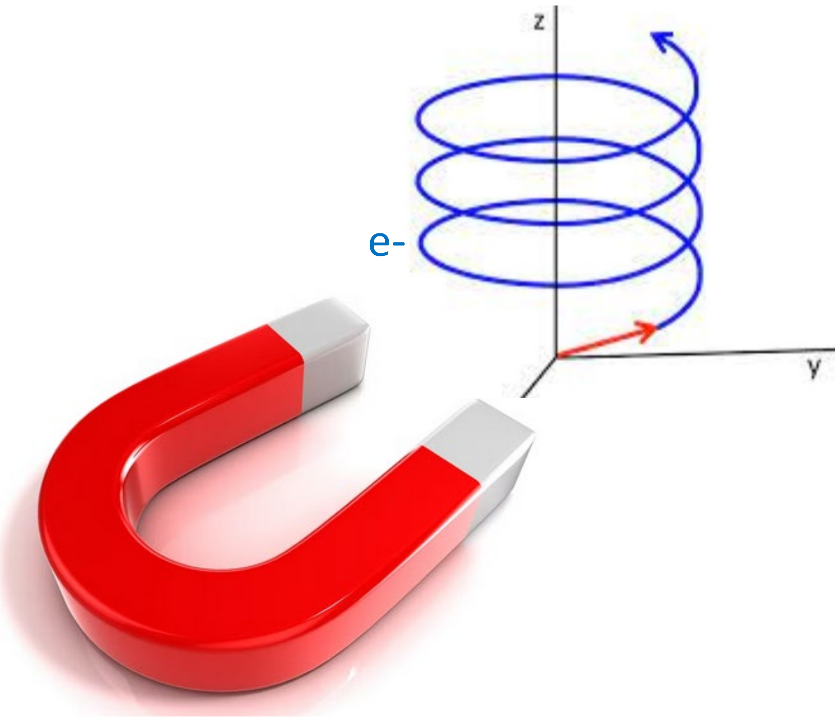
- Cyclotron radiation → He6-CRES
- Calorimetry → Flechard et al.(LPC/CAEN); Naviliat-Cuncic et al. (MSU)
- Si detector → Nab

Cyclotron Radiation Emission Spectroscopy (CRES)

β undergoes cyclotron motion in B field.
radiation frequency → beta energy

$$\omega_{radiation} = \omega_{cycl} = e\, c^2 \frac{B}{E}$$

→ e- energy



Order of magnitude:
For $E = 1$ MeV, $B = 1$ T,
$f_{cycl} = \omega_{cycl}/2\pi \approx 14$ GHz

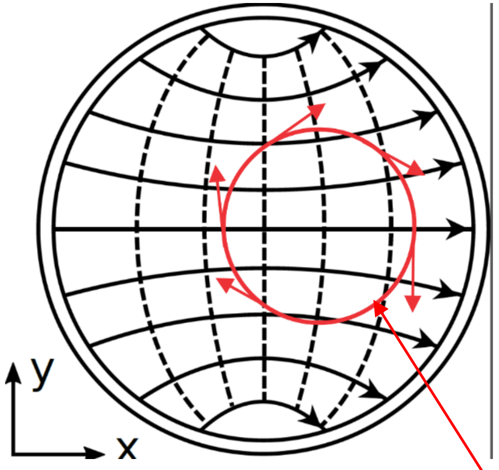
-> `microwaves'

Microwaves for nuclear spectroscopy

Difficulty: power≈femtoWatt

Power ≈ femtoWatt
To detect small signals →
use waveguides

Example: TE_{11}-mode $\vec{E}$ lines



β trajectory

$$\omega_{cycl} = e\, c^2 \frac{B}{E}$$

Radiation amplitude proportional to

$$\int d^3x \; \vec{E}_{11} \cdot \vec{J}$$

Guide mode

β current

CRES proposal and first implementation: Project 8 collaboration

Selected for a Viewpoint in *Physics*
PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

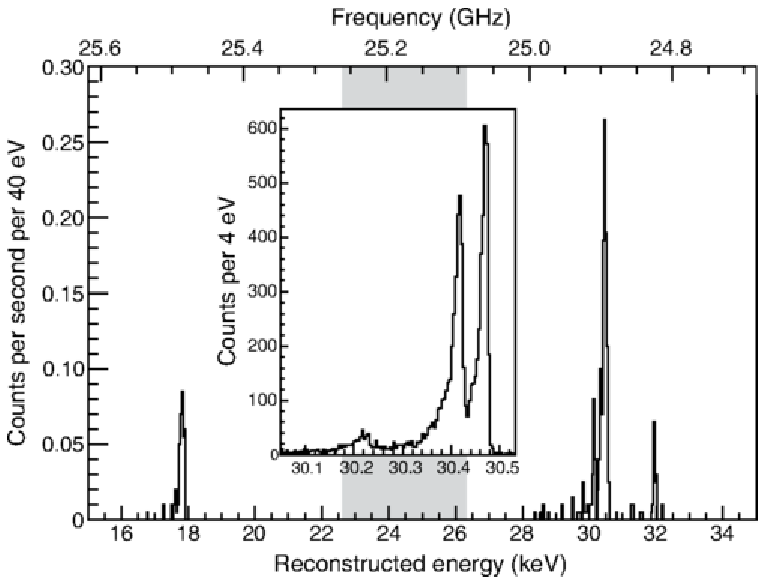
Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. G. H. Robertson,[4] L. J Rosenberg,[4] G. Rybka,[4] D. Rysewyk,[5] M. G. Sternberg,[4] J. R. Tedeschi,[1] T. Thümmler,[6] B. A. VanDevender,[1] and N. L. Woods[4]

(Project 8 Collaboration)

Aimed at m_ν from ^{3}H
$Kmax$ ≈18 keV.

Project 8 collaboration
$\Delta K/K$ ≈10^{-3} resolution for ^{83}Kr conversion electrons of 18-32 keV.



He6-CRES – Collaboration

N. Buzinsky[1], A. Garcia[1], S. Gopal[1], H. Harrington[1], P. Kolbeck[1], L. Malavasi[1], D. Melconian[4], P. Mueller[5], E. Noviskti[1], N. Oblath[6], R.G.H. Robertson[1], G. Rybka[1], G. Savard[5], D. Stancil[3], D. Storm[1], H.E. Swanson[1], R.J. Taylor[3], B.A. Vandeevender[6], F. Wietfeldt[7], C. Wiseman[1], A. Young[3]

He6-CRES phases

Phase I: proof of principle
- Observe ^{83}Kr lines
- Understand RF issues and spectra
- Study power distribution
- Show detection of cycl. radiation from ^{6}He

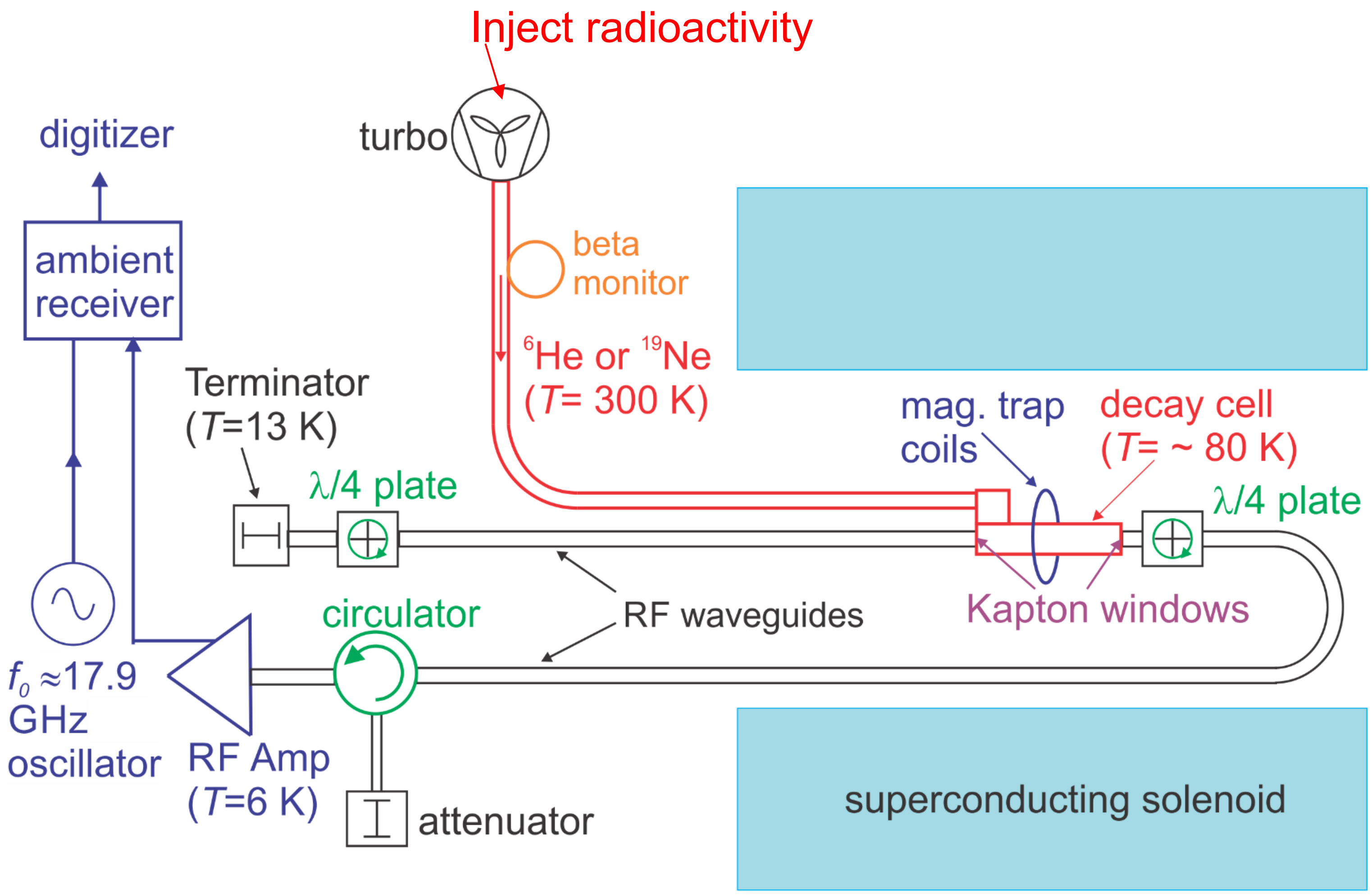
Done

Phase II: first measurement
- ^{6}He and ^{19}Ne measurements: ($b < 10^{-2}$)
- Develop ^{79}Kr and ^{14}O sources.
- Develop next beta monitor.
- Analysis of uncertainties and improvements.
- ^{6}He and ^{19}Ne measurements: ($b < 10^{-3}$)

Next 3 years:
- Phase II

Phase III: ultimate measurement ($b < 10^{-4}$)
- ^{14}O measurements.
- Ion-trap system.

He6-CRES – sketch of setup and RF



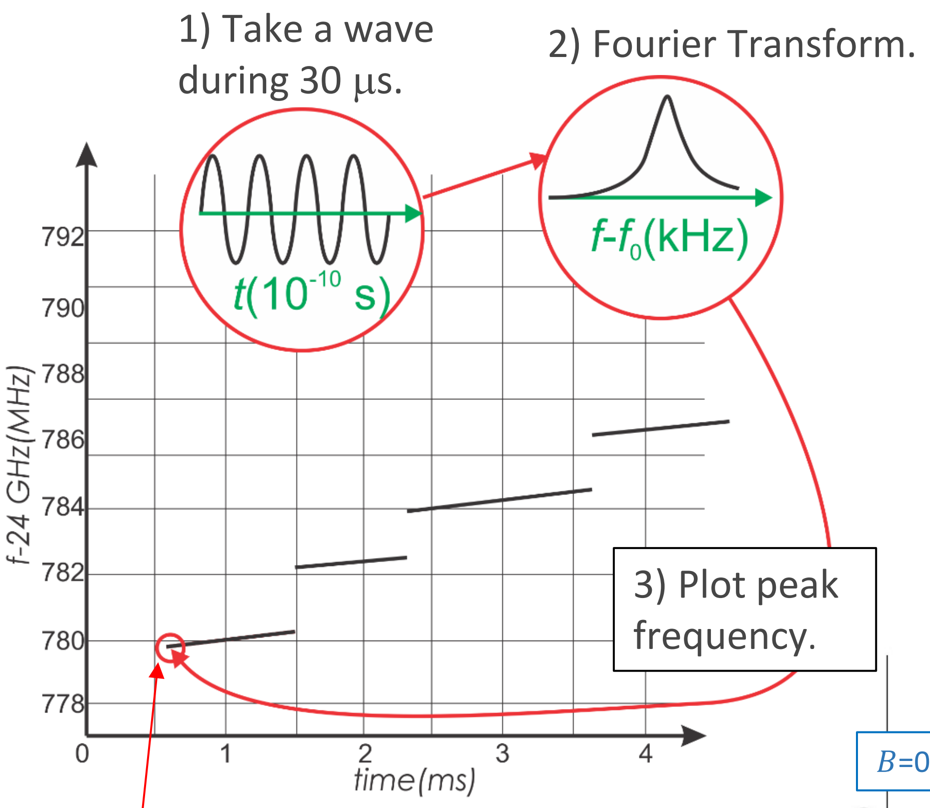
The $e^{\pm}$ cyclotron motion excites RF waves with

$$\omega_{cycl} = e\, c^2 \frac{B}{E}$$

→extract *E*
==energy

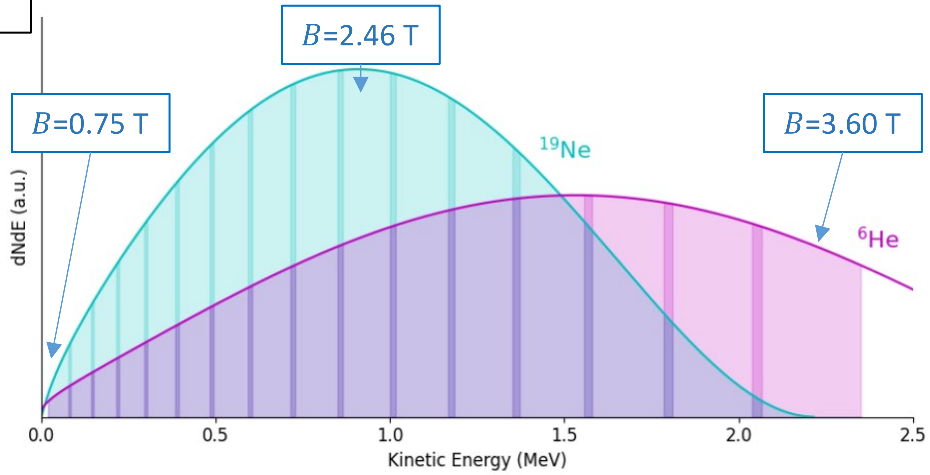
He6-CRES – technique basics

- **Measures beta energy at creation, before complicated energy-loss mechanisms.**
- No background from room photon or e scattering.
- High resolution: allows debugging of systematic uncertainties.
- 6He/19Ne in gaseous form works well with the technique.



Initial frequency $\omega_c = \frac{qB}{E/c^2} \rightarrow E$

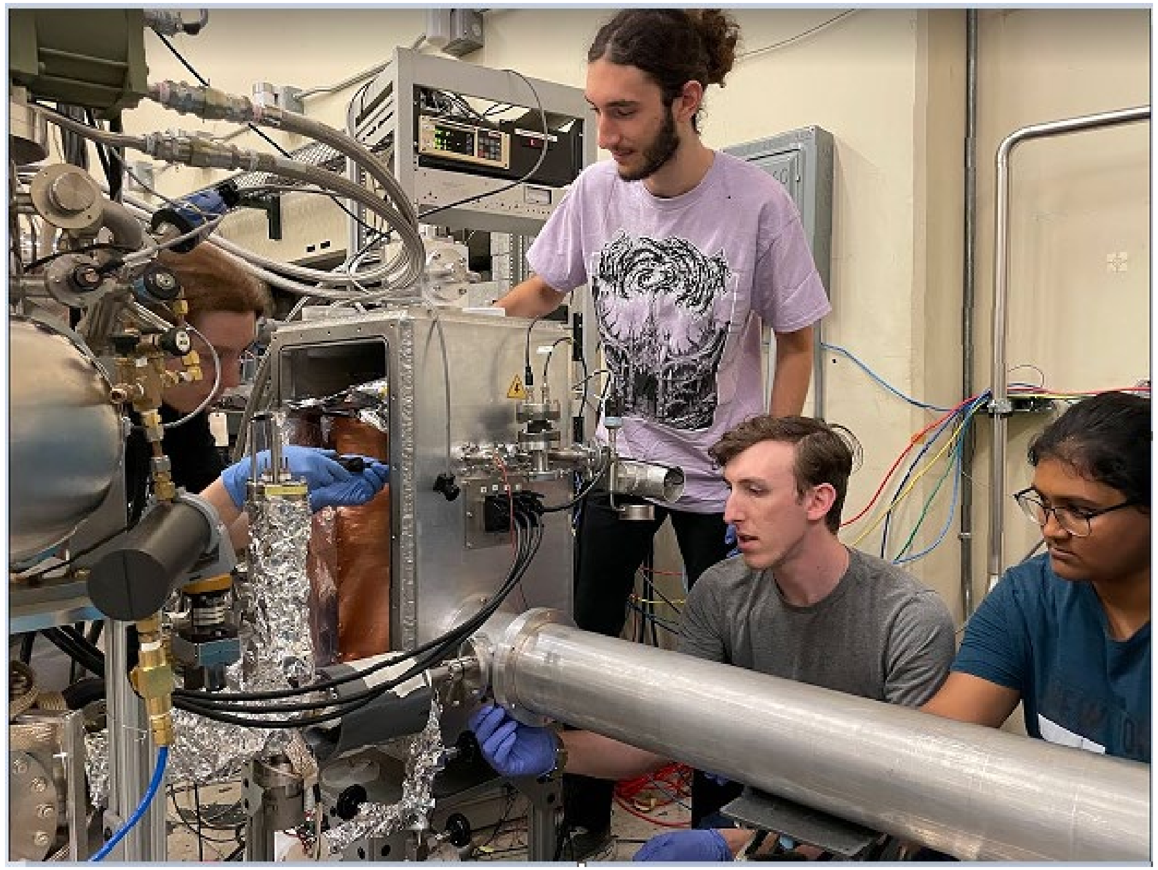
Frequency band: 18-20.4 GHz
Scanning B field yields spectrum



He6-CRES – experimental setup

Cryo-box insides

Assembly

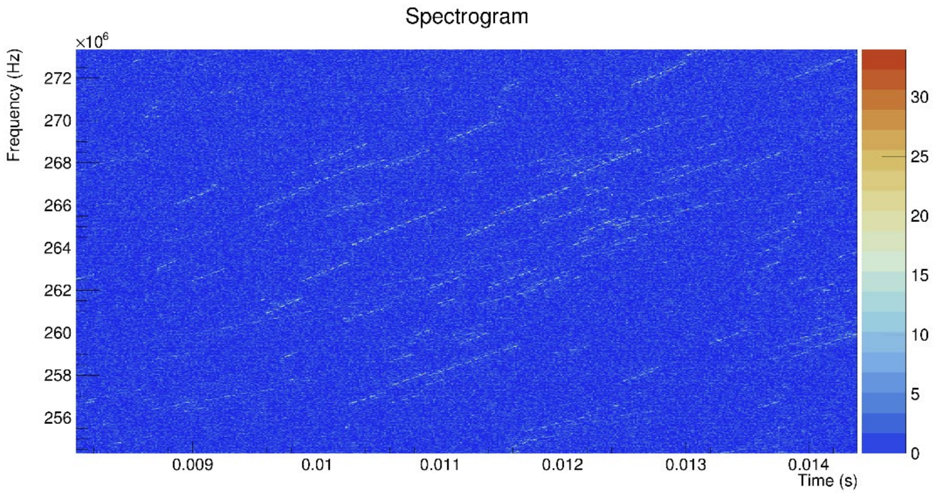


Decay cell and trap coils

He6-CRES – FN Tandem at Seattle

Presently:
^{6}He ($t_{1/2} \approx 0.8$ s) via ^{7}Li(d,^{3}He) $E_d = 18$ MeV
^{19}Ne ($t_{1/2} \approx 17$ s) via ^{19}F(p,n) $E_p = 12$ MeV

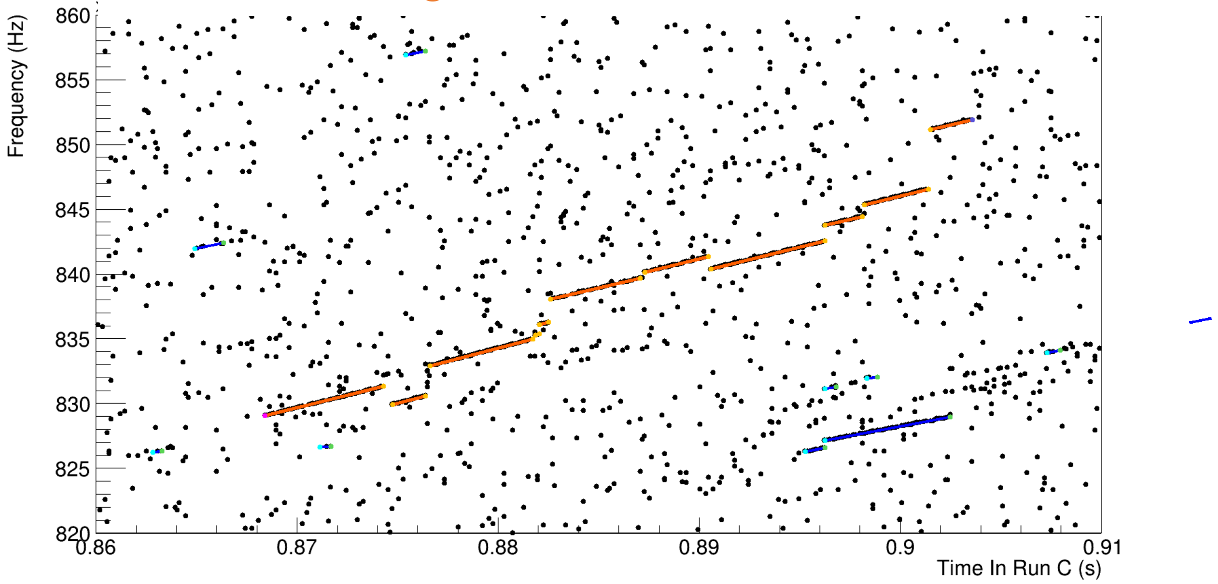
He6-CRES – First ^{83}Kr Conv. e's detection

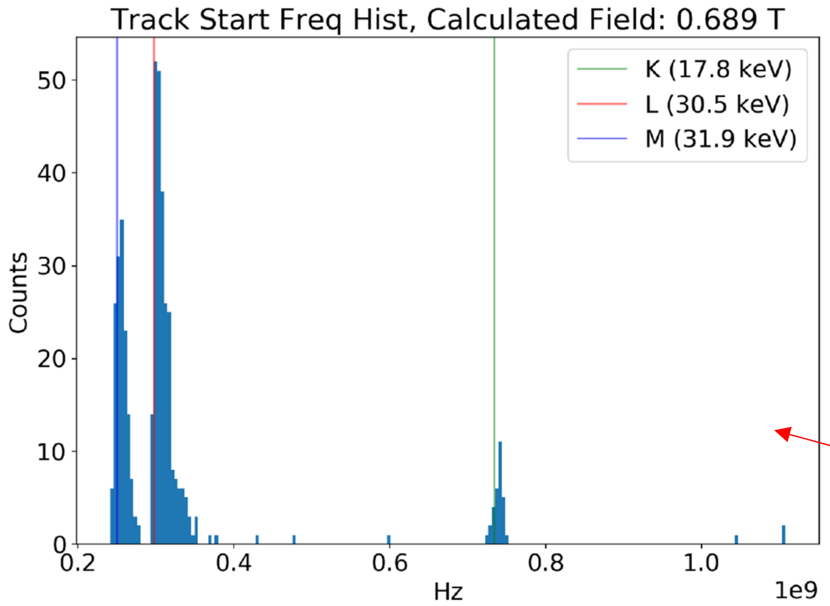


Events from ^{83}Kr:

Identification software working

Blue: tracks; Orange: tracks into events.

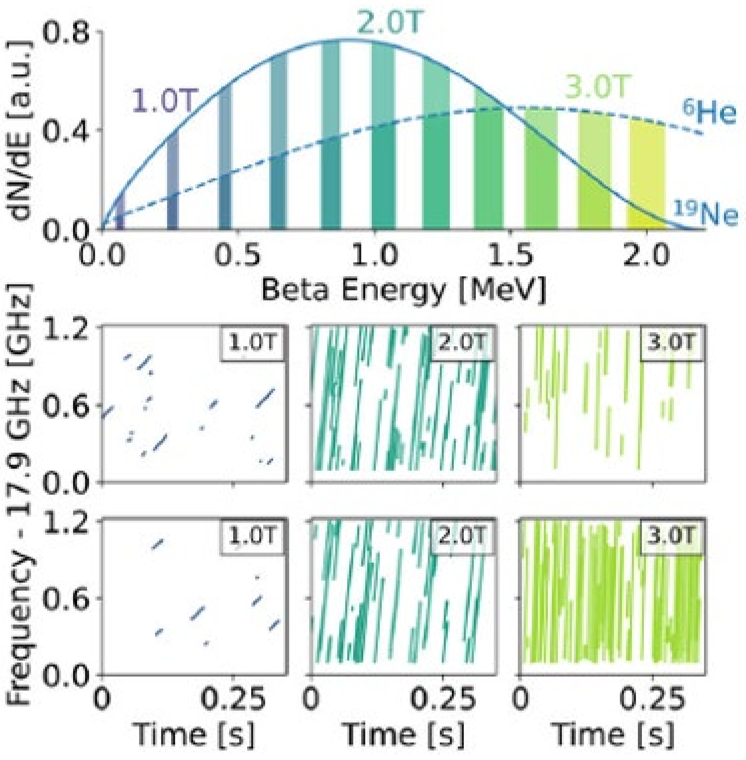




Bandwidth: 1.2 GHz
First time CRES measurement with this bandwidth.

He6-CRES – recent results

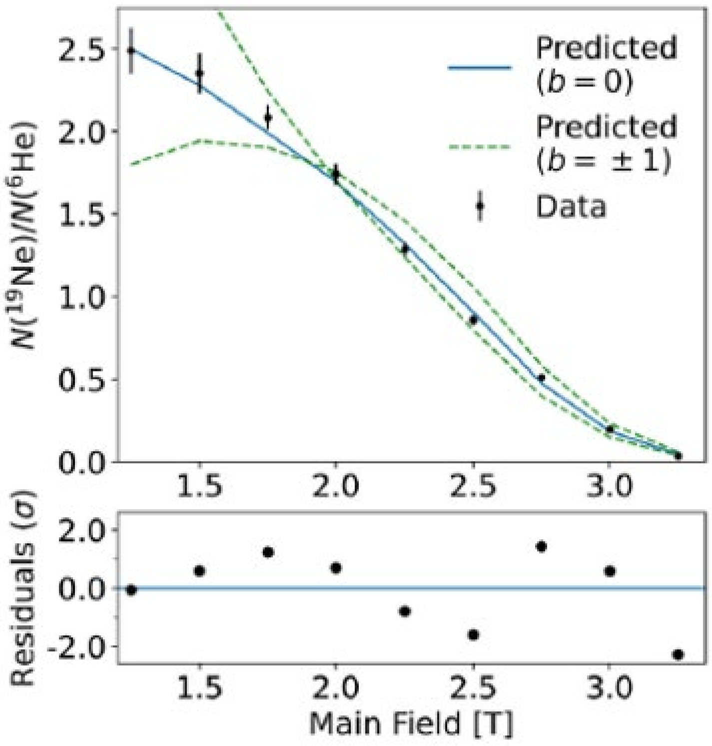
- Demonstration of all components working: Phys. Rev. Lett. **131**, 082502 (2023)



Ratios of counts enhance signal, cancel RF distortions:

$$N(^{19}\text{Ne}) \propto 1 - k\ \varepsilon_T$$
$$N(^{6}\text{He}) \propto 1 + k\ \varepsilon_T$$

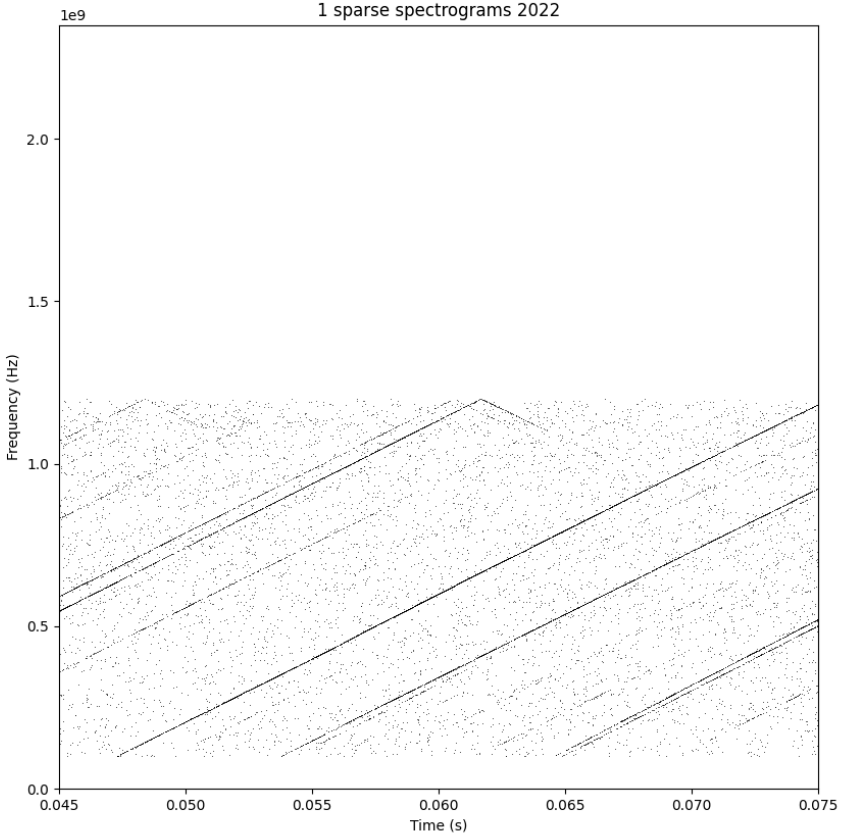
Thanks to charge-symmetry properties of currents



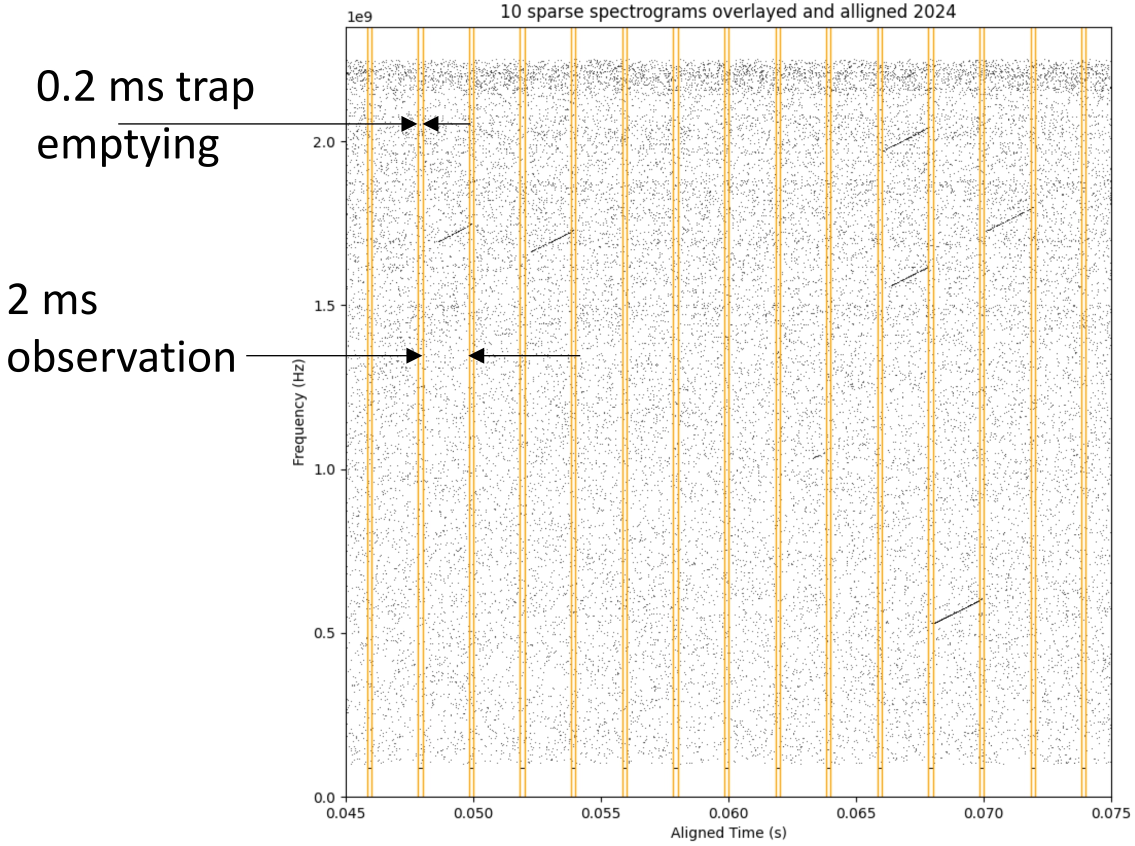
He6-CRES – updates

- With better SNR and ExB trap emptying easy to get individual events

Then: beginning days



Now: ready for a data campaign for $b \sim 0.01$.
Heather Harrington's PhD thesis.



He6-CRES – Future applications

- Can do SPECTACULAR resolution for Auger and Conversion Electron spectroscopy

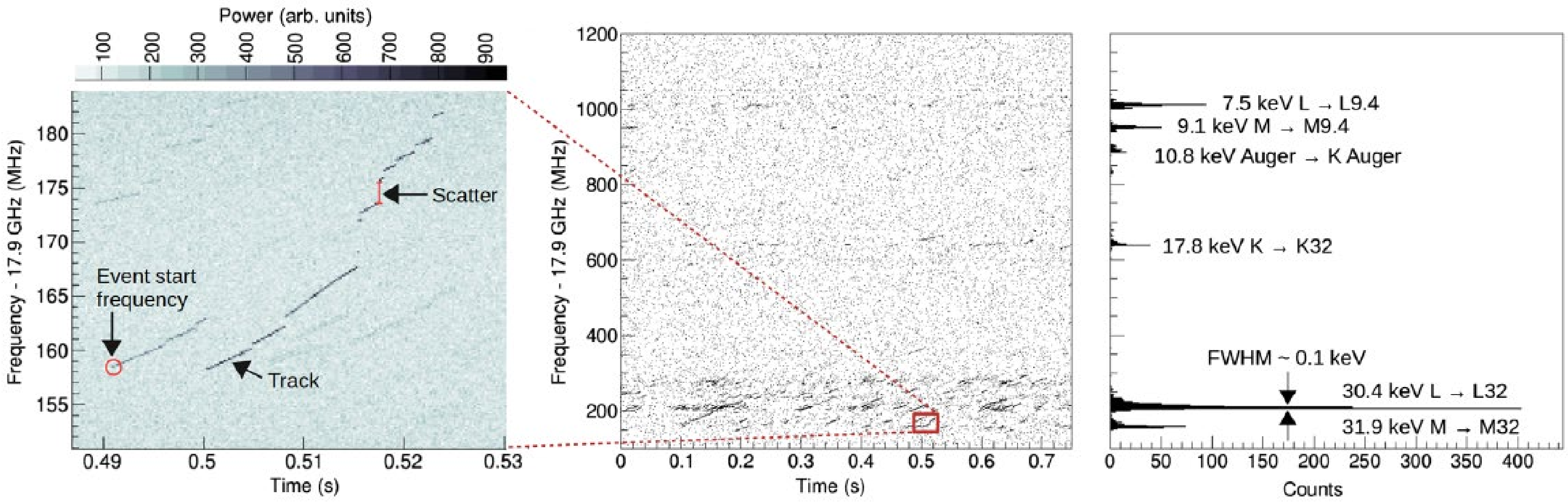


FIG. 3. ^{83m}Kr data taken with $B = 0.68$ T. Center: spectrogram with Fourier bin threshold SNR > 6 (black), demonstrating the full 1.1 GHz bandwidth. Left: enlarged region exemplifying an event composed of multiple tracks. Right: reconstructed event start frequency histogram, showing simultaneous observation of the 7–32 keV lines.

- Can do accurate measurements of beta spectra
- Coupled to ion trap at radioactive beam facility (FRIB) can do both above for a large variety of nuclei

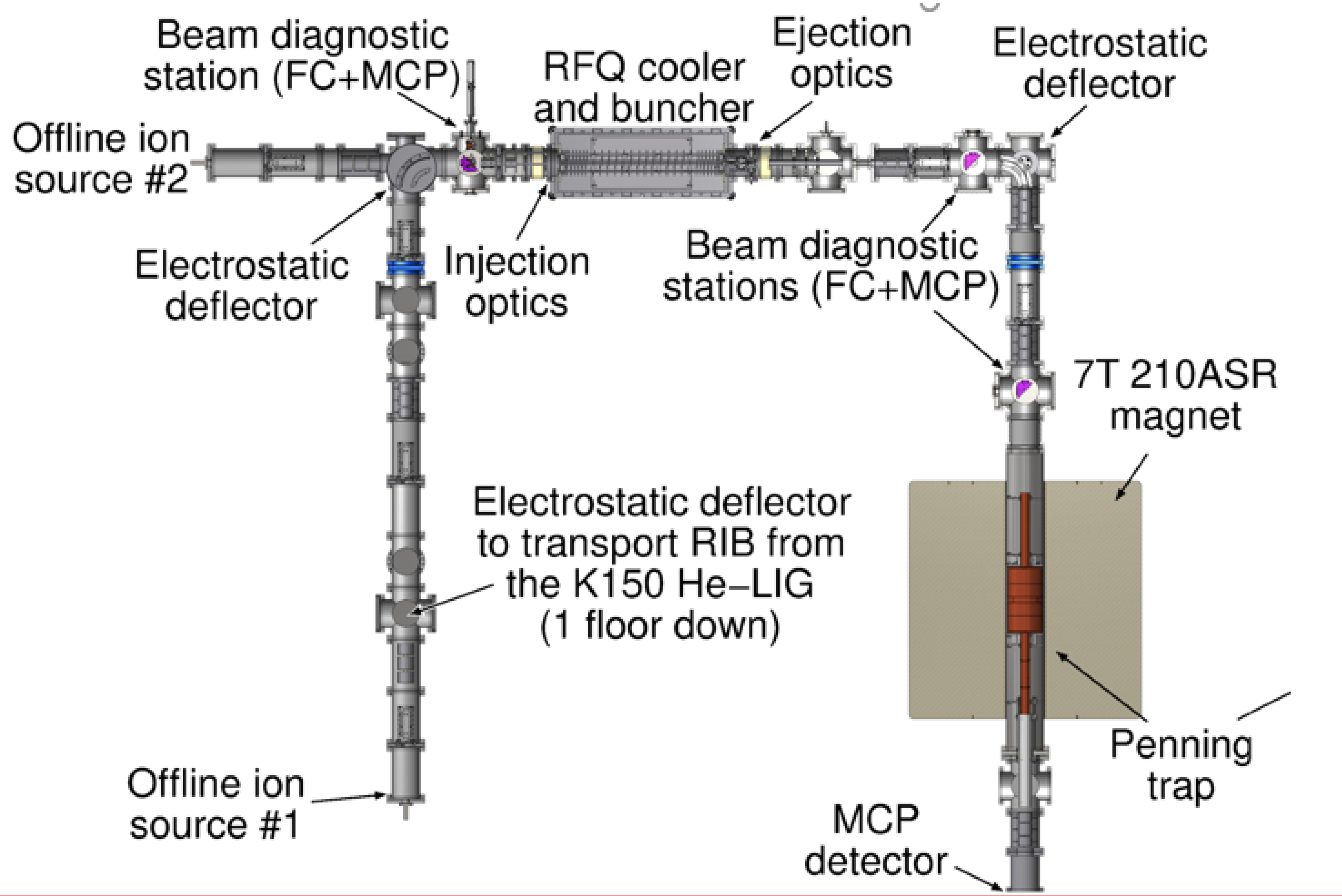
He6-CRES – Ion trap

Ion-trap setup at **Texas A&M**
Dan Melconian et al.

- ECR Ion source (Argonne National Lab)
- Ion trap (Texas A&M)

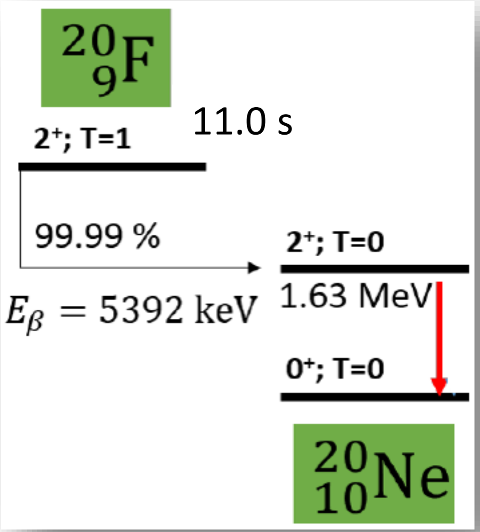
Once working could be coupled to radioactive beam.

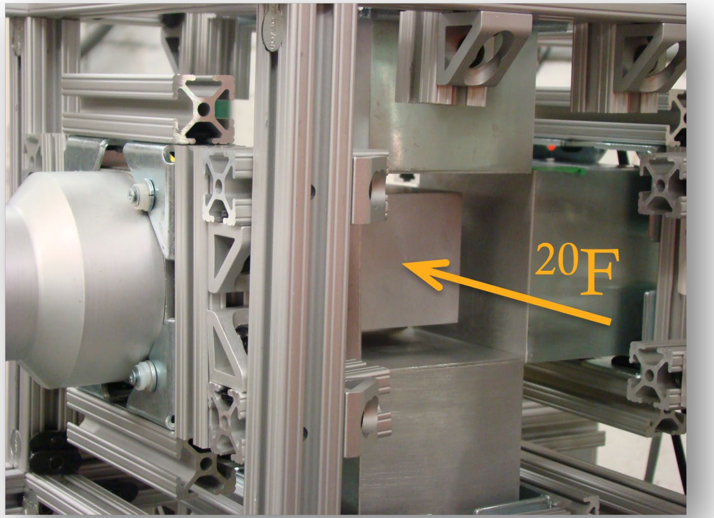
Example applications:
--8B beta spectrum with high precision (solar neutrinos, hep…)
--Beta spectra of typical sources of reactor neutrinos
--Electron Capture spectroscopy
--Auger spectroscopy



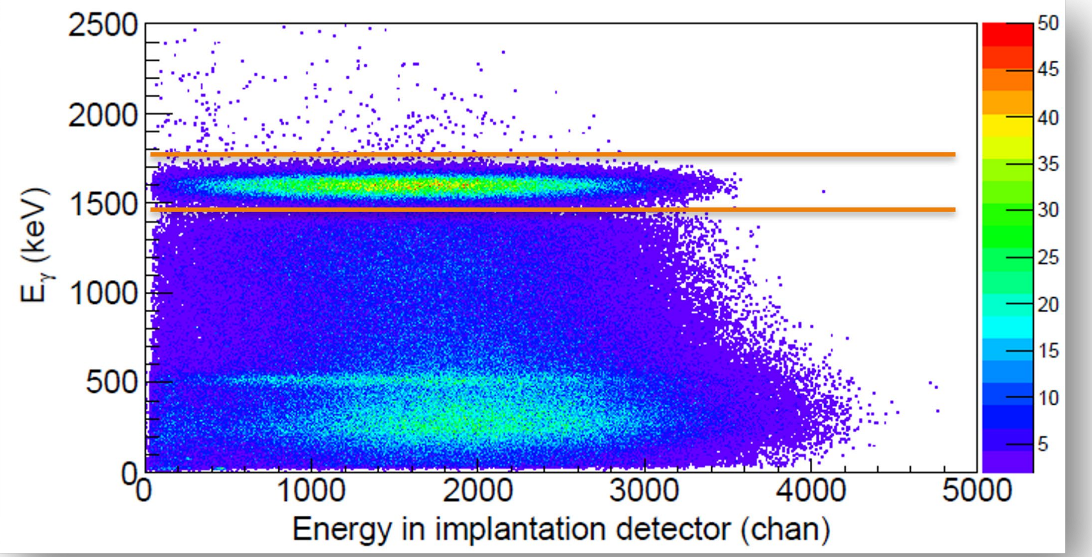
Calorimetry:
ongoing effort at LPC(CAEN) and MSU

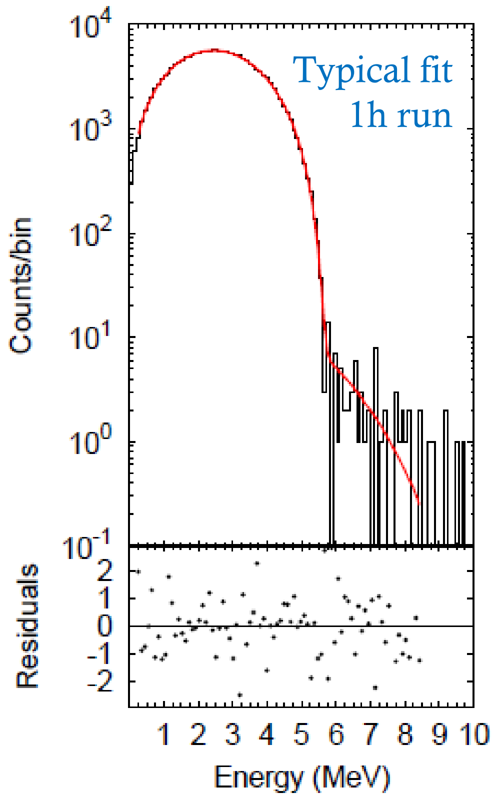
Calorimetry technique with ^{20}F at NSCL





- 132 MeV/nucleon ^{20}F beam implanted at (12±2mm) into a CsI(Na) detector (range of beta particles is 6mm)
- Beta particles detected in coincidence with 1.63 MeV γ ray.



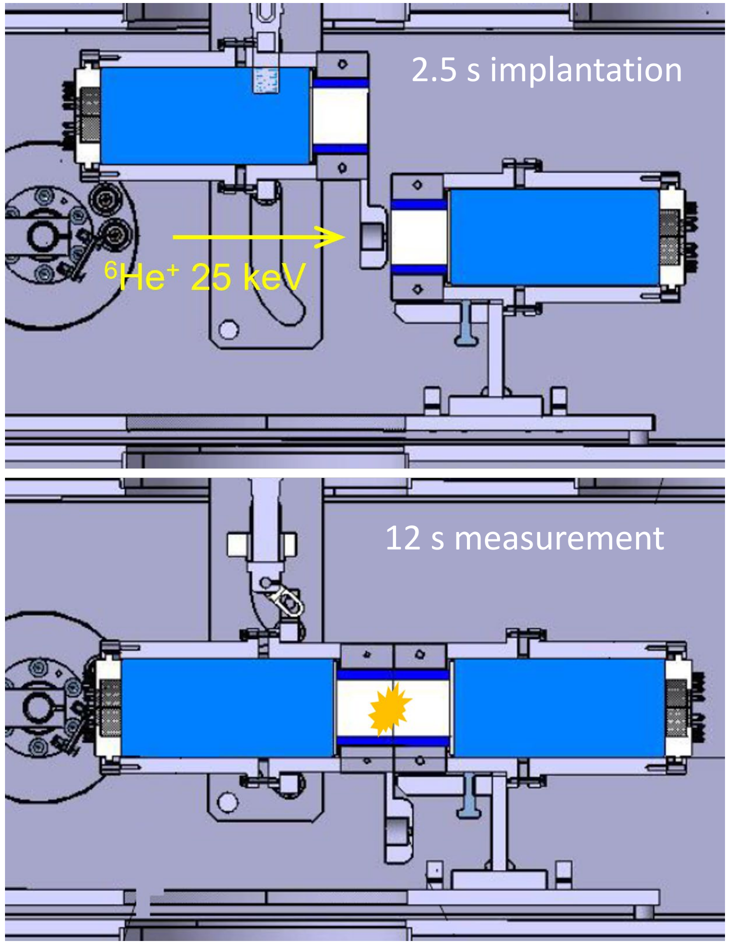


- 72 independent spectra
- 8×10^6 effective statistics

Uncertainties

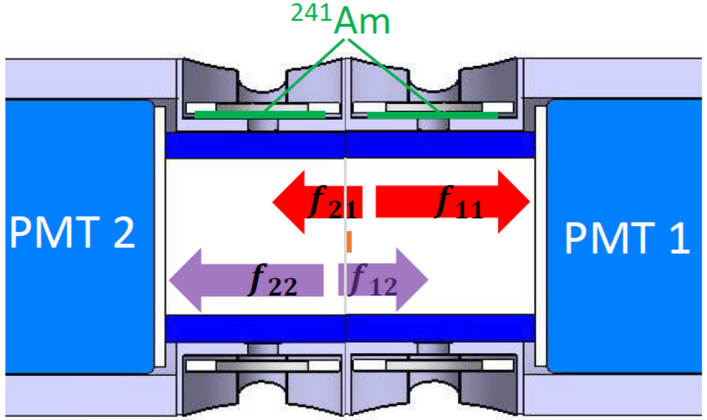
- Statistical, $\Delta b_{stat} \sim 5.5\times10^{-3}$
- Theoretical, $\Delta b_{theo} \sim 3.2\times10^{-3}$
- Instrumental, $\Delta b_{sys} > 5.0\times10^{-3}$

Calorimetry with 25 keV ^{6}He beam

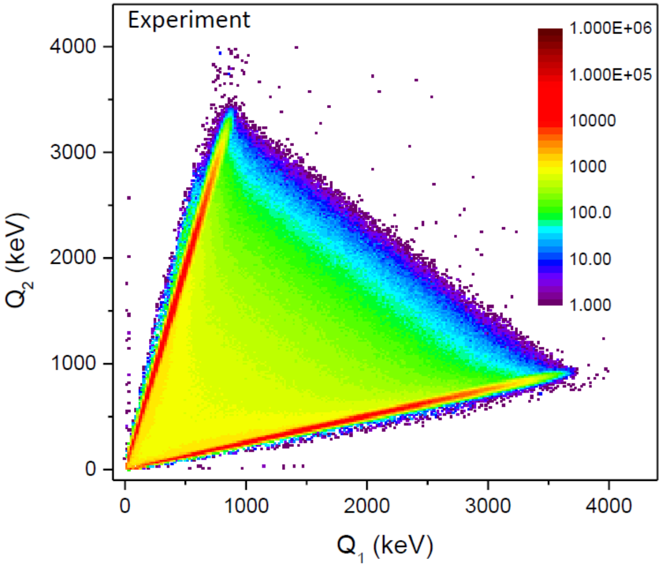


X. Fléchard talk
Fri. May 30 @ 9:25
Room 5 – 1F#102

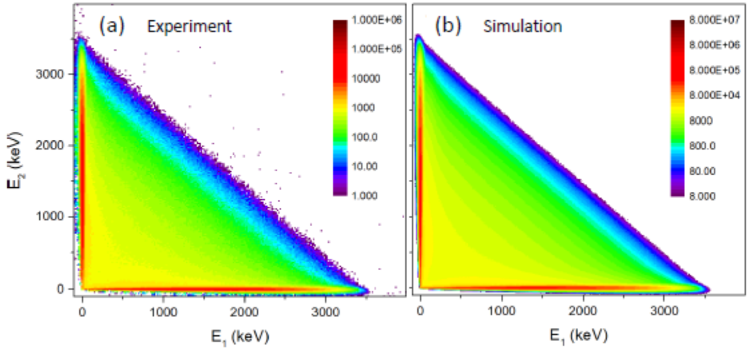
- YAP:Ce scintillators surrounded by PVT



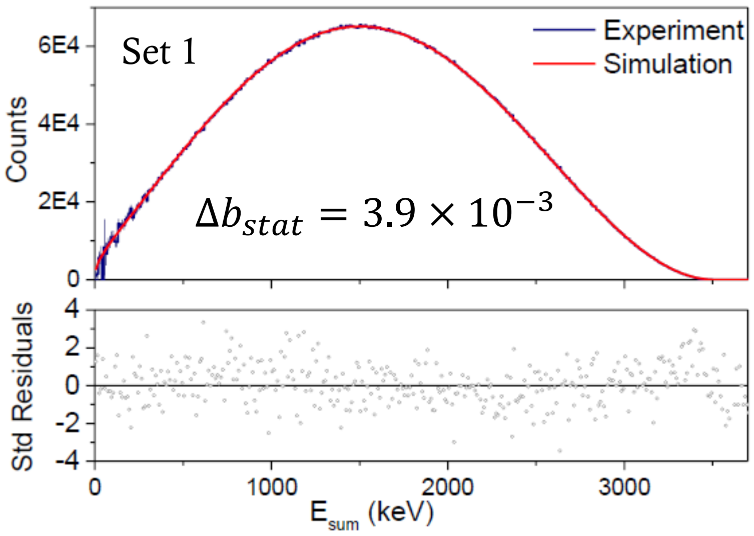
- Detectors are optically coupled



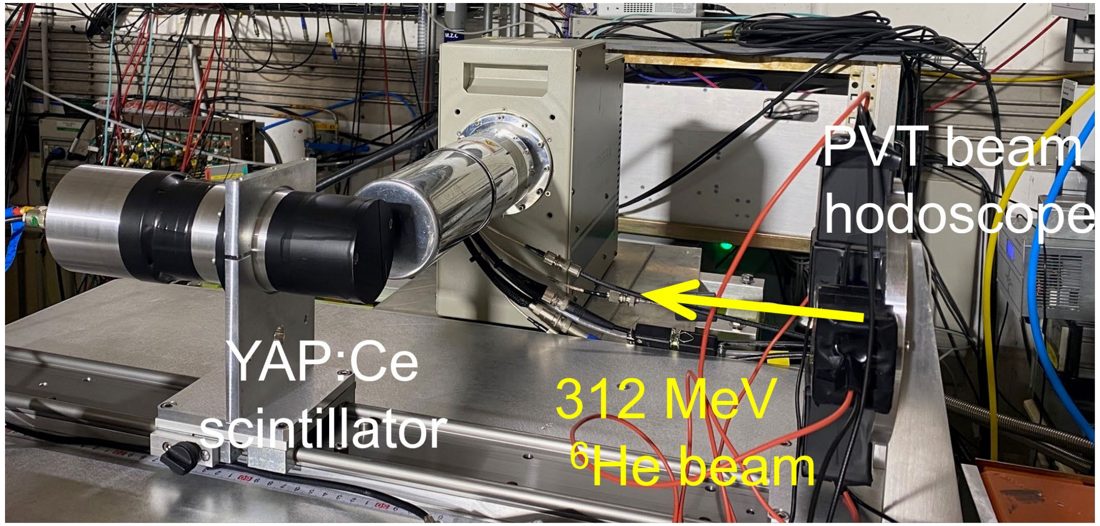
- Simultaneous calibration and optical cross talk correction



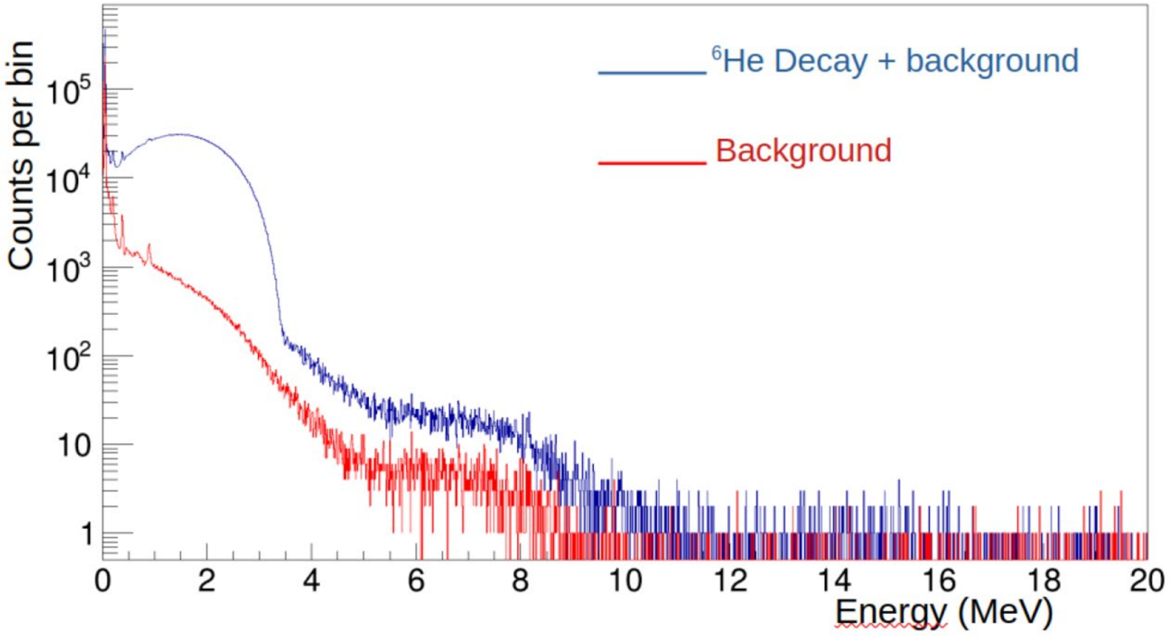
- Reconstruction of total energy



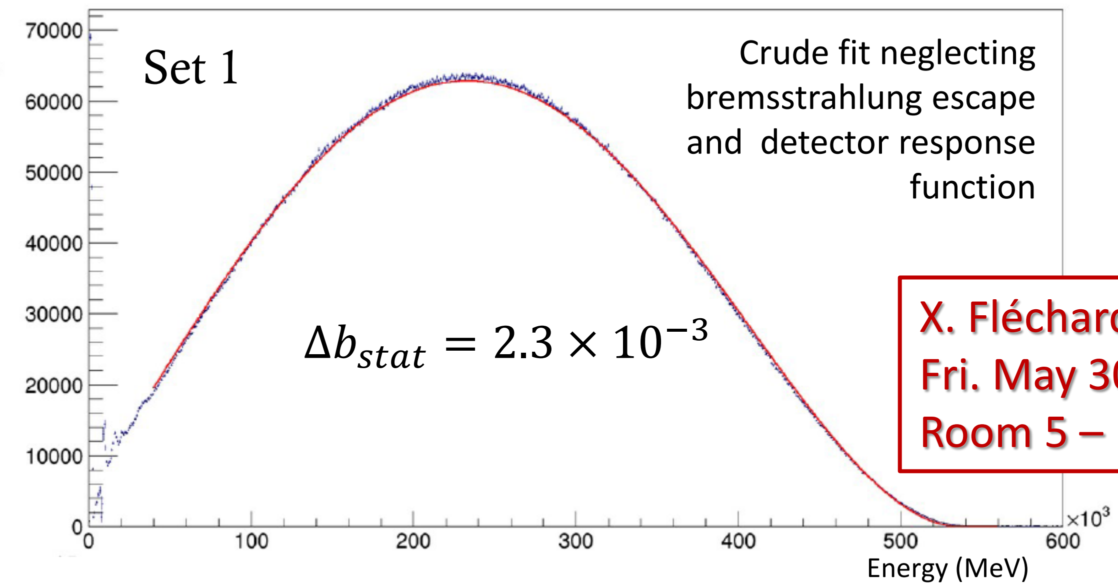
Calorimetry with 312 MeV ^{6}He beam



- 52 MeV/nucleon ^{6}He beam implanted at 9.5 mm into a YAP(Ce) scintillator
- Background analysis: traces of ^{8}Li, ^{16}C, ^{16}N and ^{89m}Y
- Impact on extraction of Fierz term is $\Delta b_{sys} < 1 \times 10^{-3}$
- Total statistical uncertainty $\Delta b_{stat} < 1.5 \times 10^{-3}$



Ambient background subtracted spectrum



X. Fléchard talk
Fri. May 30 @ 9:25
Room 5 – 1F#102

Si detector:
Nab collaboration

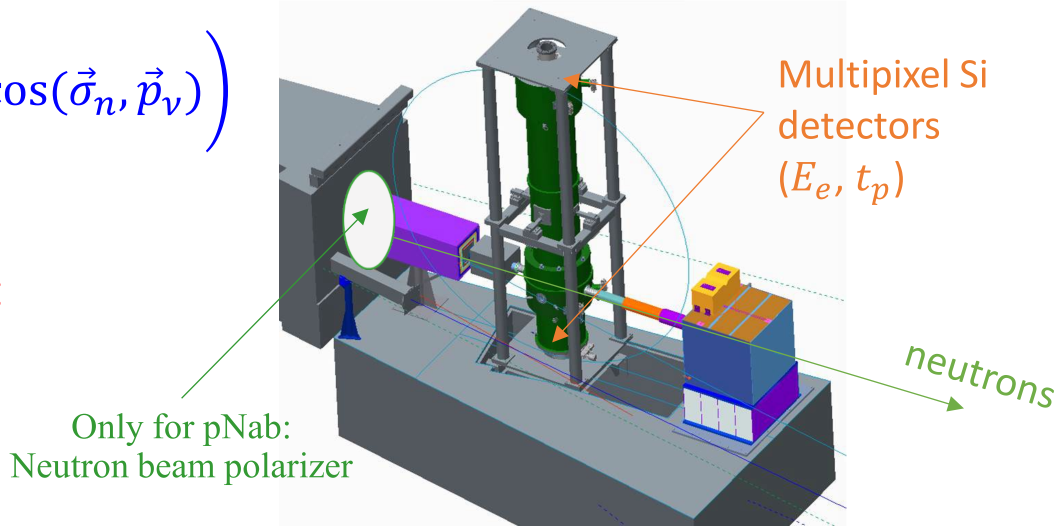
Nab and pNab experiments

Neutron decay probability:

$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos(\vec{p}_\nu,\vec{p}_e) + b\frac{m_e}{E_e} + A\frac{p_e}{E_e}\cos(\vec{\sigma}_n,\vec{p}_e) + B\cos(\vec{\sigma}_n,\vec{p}_\nu)\right)$$

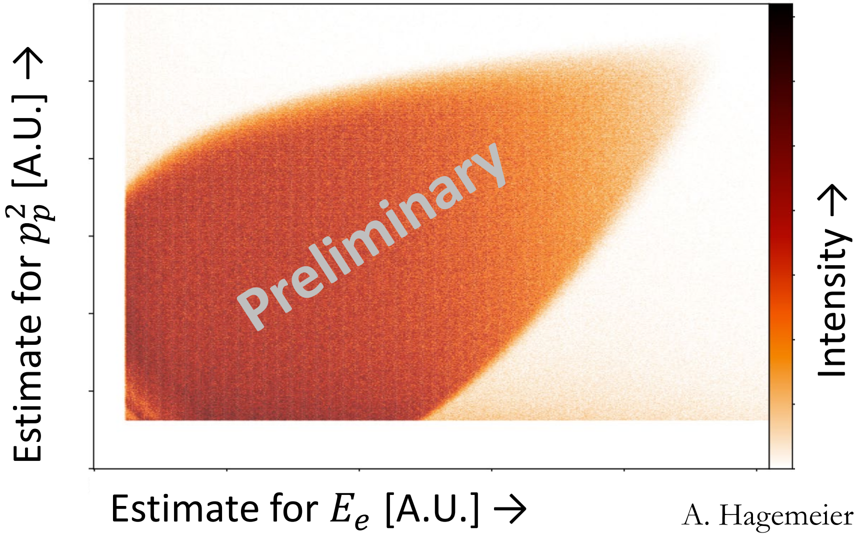
Nab measures electron-neutrino asymmetry a and Fierz term b with unpolarized neutrons.:

- $a = a(\lambda)$ from (E_e, p_p^2)-spectrum, goal $\Delta a/a \sim 10^{-3}$, for test of CKM unitarity
- b from E_e spectrum, goal $\Delta b \sim 3 \cdot 10^{-3}$, for S,T interactions
- E_e from backscatter-suppressed Si detectors
- p_p inferred from proton TOF t_p



Summer 2023: Commissioning: Experiment working, but major challenges with detector system

October 2024: Major challenges resolved, data taking started



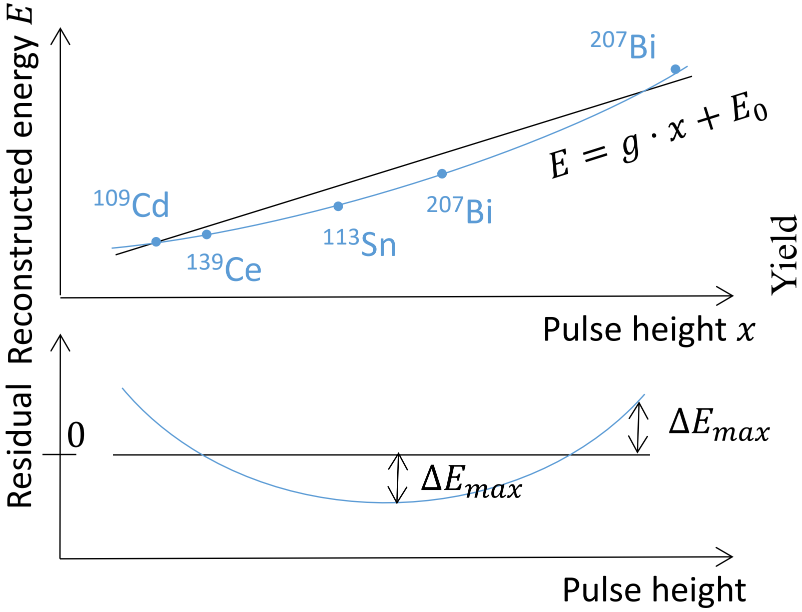
A. Hagemeier (UVA)

pNab measures beta asymmetry A and neutrino asymmetry B:

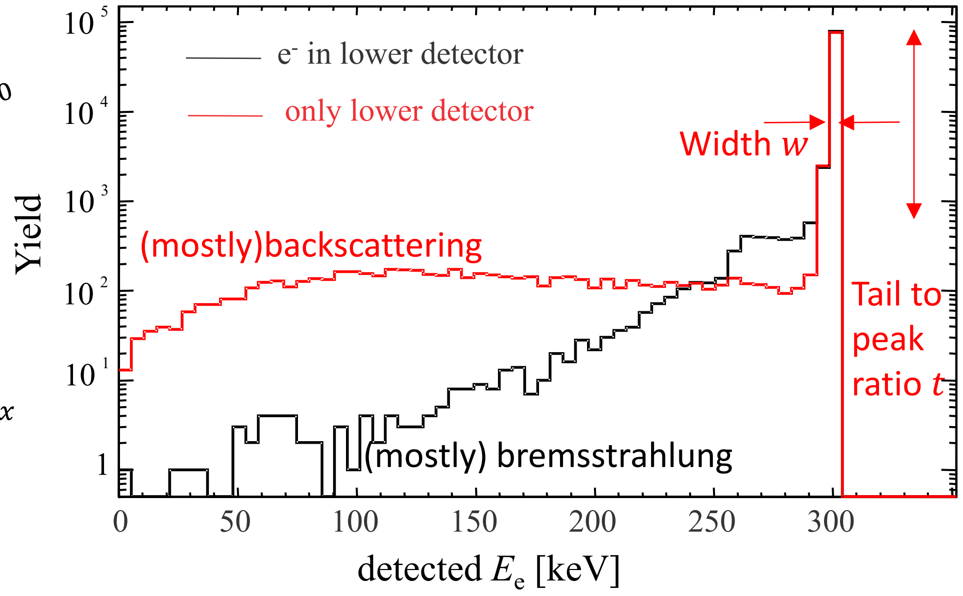
- $A = A(\lambda)$ from beta asymmetry with respect to spin, goal $\Delta A/A < 10^{-3}$, for CKM unitarity
- $B = B_0(\lambda) + b_\nu m_e/E_e$ from E_e spectrum, goal $\Delta B < 10^{-3}$
- Neutron Beam Polarization is major uncertainty, plan on using novel Solid State Polarizer or Helium-3 polarizing station.

Major challenge for both Nab and pNab: Electron energy calibration

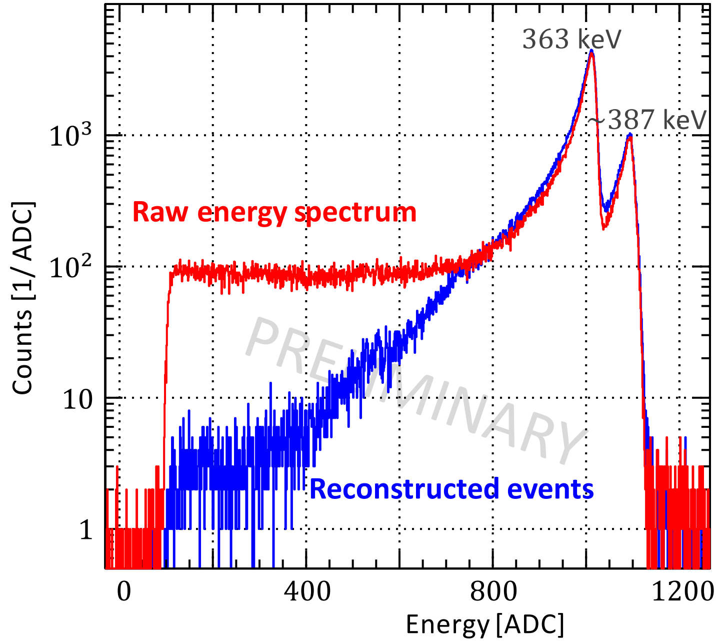
Electron energy calibration:



Simulated detector response in Si detector for incoming E_e = 300 keV, (Maximum impact angle of electrons is 12°, due to filter)



Recent data from Sn-113 source



J. Choi, NCSJ

Specification for	$\Delta a = 3 \cdot 10^{-5}$ in Nab	$\Delta b = 5 \cdot 10^{-4}$ in Nab	$\Delta A = 3 \cdot 10^{-5}$ in pNAB
gain factor ($\Delta g/g$)	fit parameter	fit parameter	**0.18% ✓**
Offset E_0 (ΔE_0)	**0.3 keV**	0.04 keV	0.2 keV
nonlinearity (ΔE_{max})	**1.5 keV ✓**	0.04 keV	0.3 keV
peak width (Δw)	**1 keV ✓**	**negligble**	**10 keV ✓**
tail amplitude (Δt of peak)	10^{-4}	10^{-3}	0.024

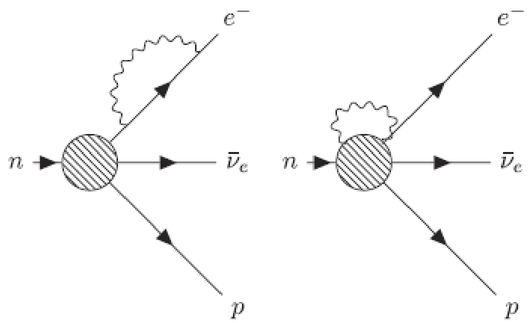
More information: Leah Broussard's talk on Nab, Ricardo Alarcon's talk on pNab

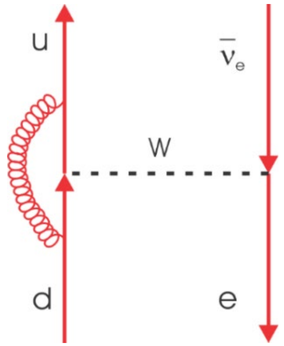
Detector calibration is work in progress, green specs have been fulfilled

Specs: H. Li, Ph.D. thesis (2021)

Theory Needs

Dominant uncertainties on SM spectra are radiative and recoil-order corrections [1,2]





Help from Nature:

- Dominant part of recoil-order correction (Weak Magnetism)
  ^{19}Ne: related to well-known magnetic moments of initial/final states
  ^{14}O: no such contribution.
- For both decays a symmetry implies that pseudo-induced tensor matrix element, typical source of uncertainties, is highly suppressed.

Summary
- ^{6}He seems under control [3,4]
- For ^{14}O, ^{19}Ne, ^{20}F :
  Uncertainties in our calculations of beta spectra are at the 10^{-3} level, below present experimental sensitivity but needs improvement for reaching ultimate goals.
- For neutron: improvements needed to go beyond $\Delta\lambda \leq 10^{-3}$

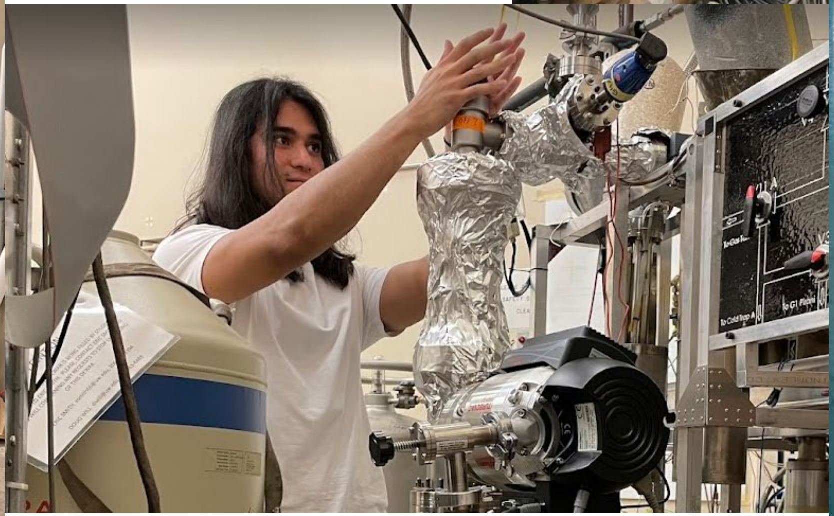
This is a call to our theory colleagues to help us in moving beyond this limiting uncertainty.

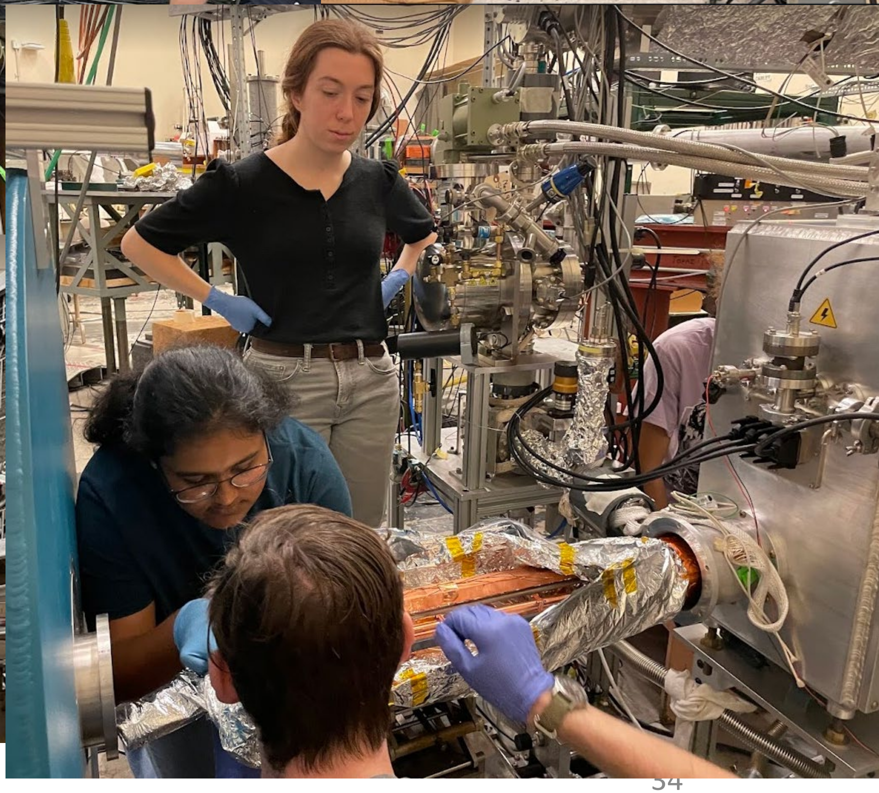
[1] Hayen et al. *Rev. Mod. Phys.* **90**, 015008 (2018)
[2] Glick-Magid et al. *J. Phys. G* **49** 105105 (2022)
[3] Glick-Magid et al. *Phys. Lett.* **B832** 137259 (2022)
[4] King et al. *Phys. Rev. C* ***107***, 015503 (2023)

Summary

Good prospects for searches for chirality flip at $\varepsilon_T, \varepsilon_S \sim 10^{-4}$

Si detector (Nab)
Calorimetry (ongoing at LPC (CAEN) and MSU)
CRES technique looks promising
Theory needs to improve for ultimate sensitivity



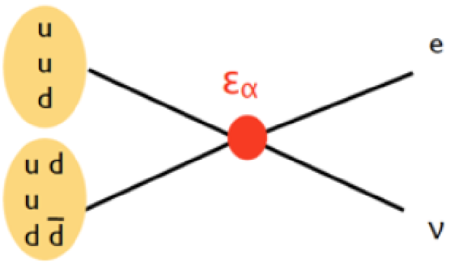



Additional slides

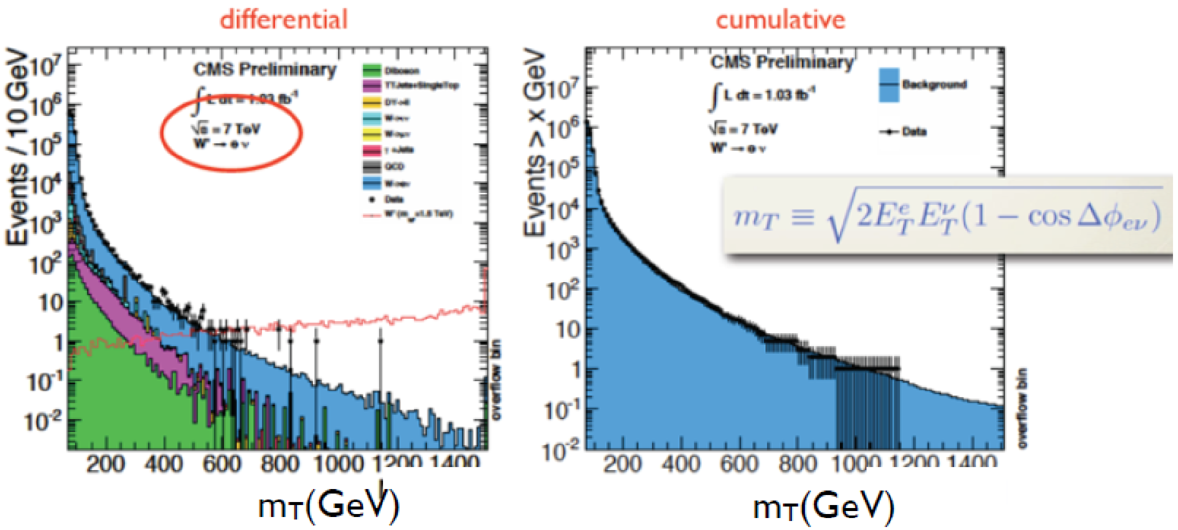
LHC (I): contact interactions

- If the new physics originates at scales $\Lambda >$ TeV, then can use EFT framework at LHC energies

- The effective couplings ε_α contribute to the process $p\,p \to e\,\nu + X$



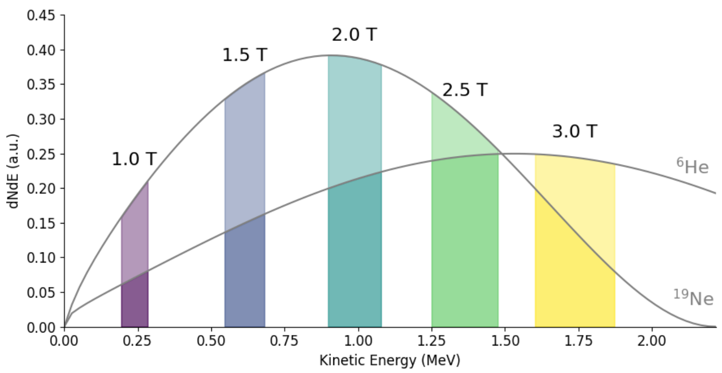
- No excess events in transverse mass distribution: bounds on ε_α

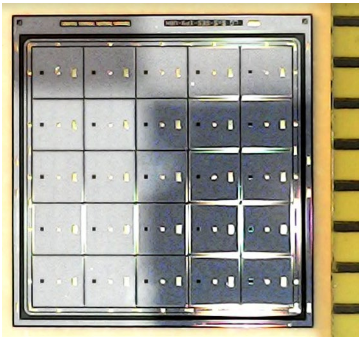


Cirigliano et al.
Prog. Part. Nucl. Phys. **71**, 93 (2013)

He6-CRES – Next

LGADs as He-6 monitor





Requirements

- 10^{-3} stability with verification
- coincidence to suppress gamma bkgd

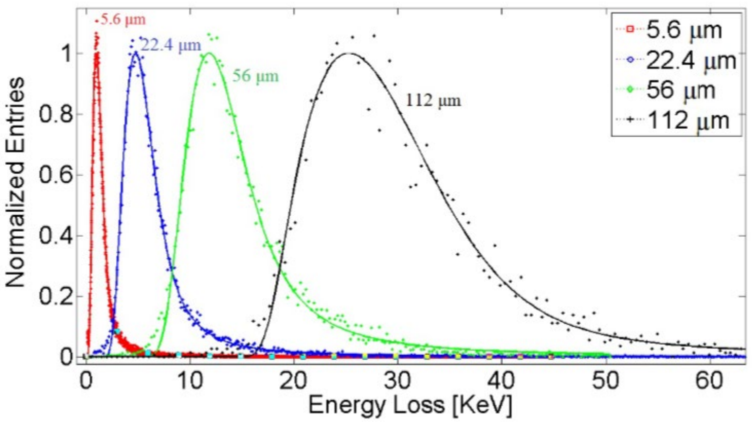
LGAD

- 4 separate channels for redundancy
- excellent S/N
- <1% instability monitored by Landau
- dead-time free
- infrastructure development PIONEER
- cost 10-20k??

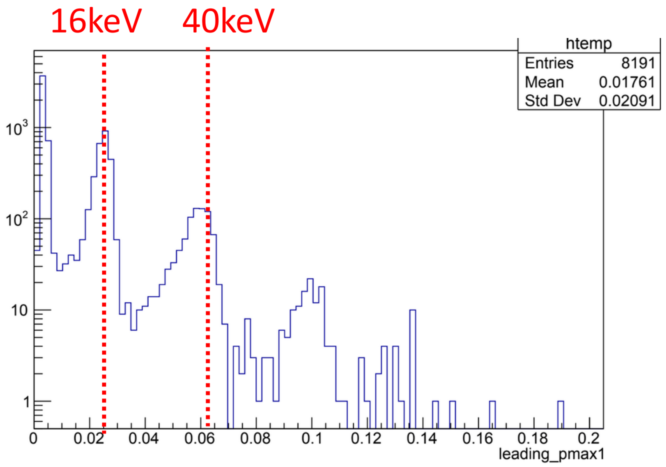
Advantage

- trigger low with good S/N, small energy loss ΔE, less sensitive to gain drifts

dE/dx Si



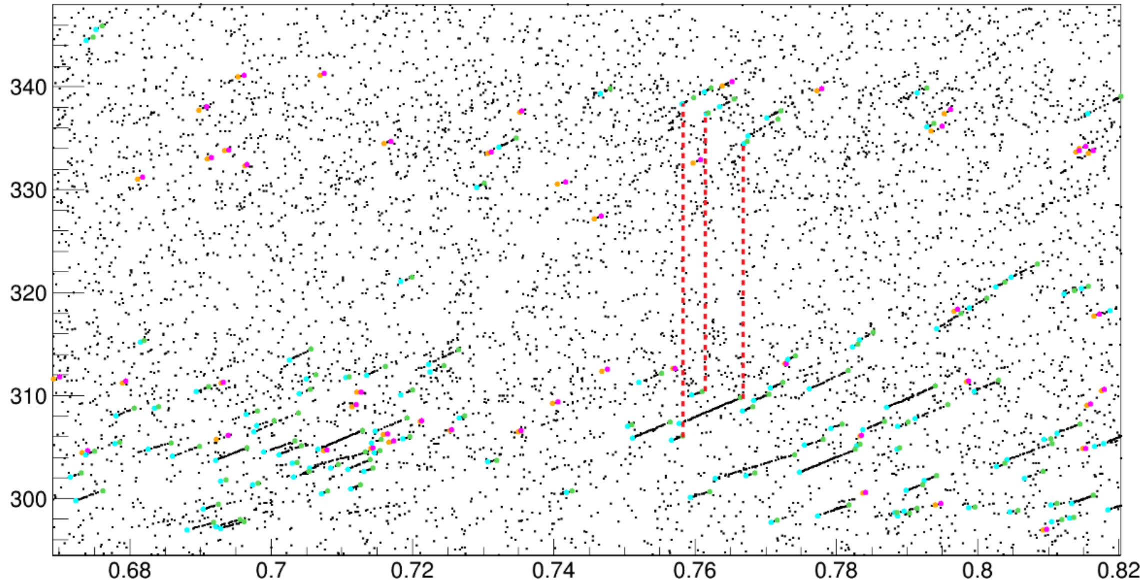
LGAD resolution at light source, S. Mazza

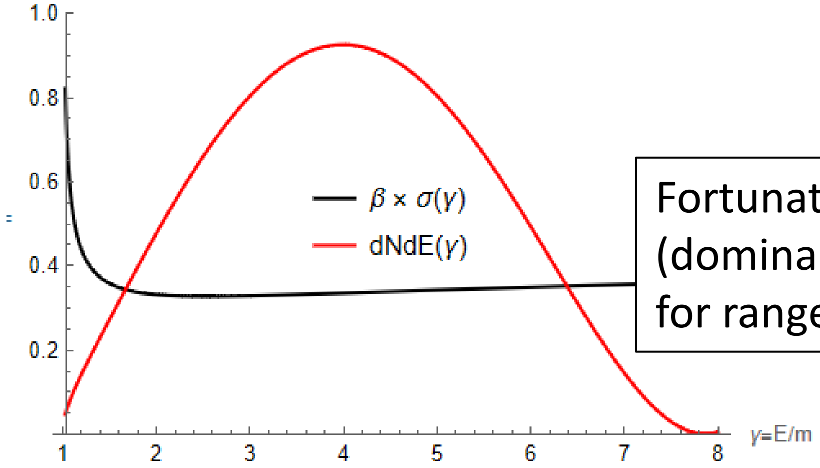


Garcia- University of Washington

He6-CRES – Scattering with residual gas

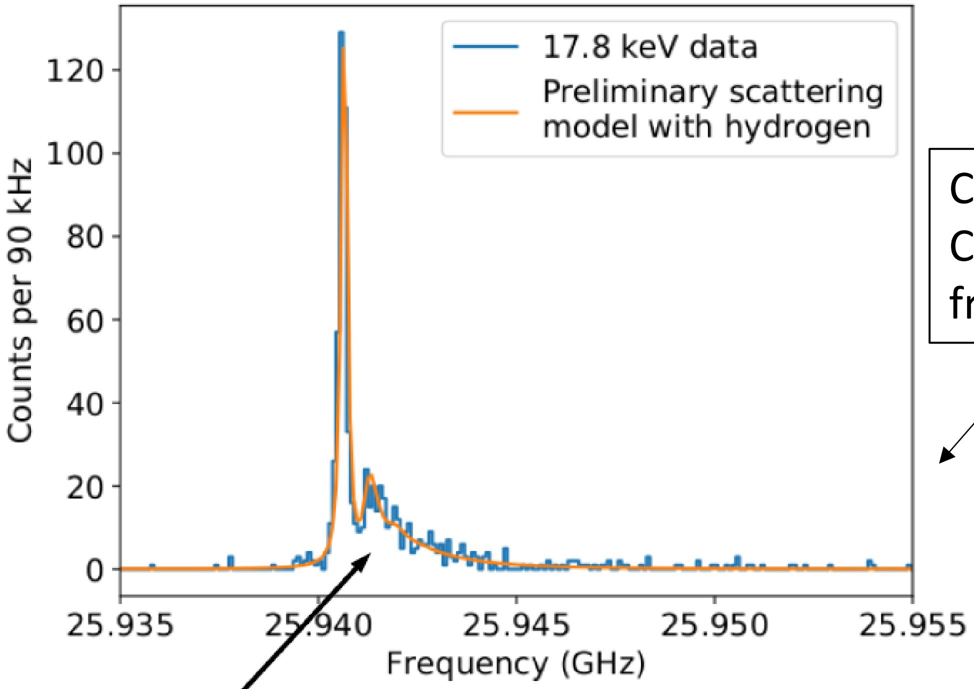
Scattering: leads to non-trivial response function





Fortunately σ on H (dominant) is rather flat for range of interest.

Miss-identification of scattering leads to asymmetrical line shapes, that could affect *b*

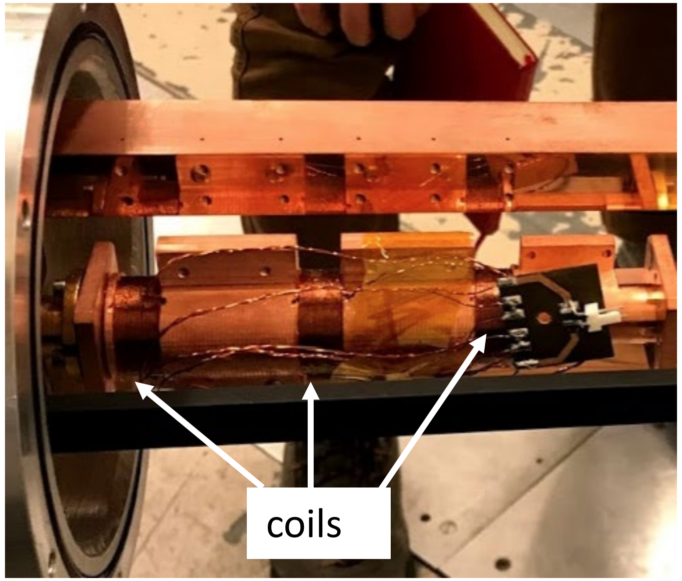


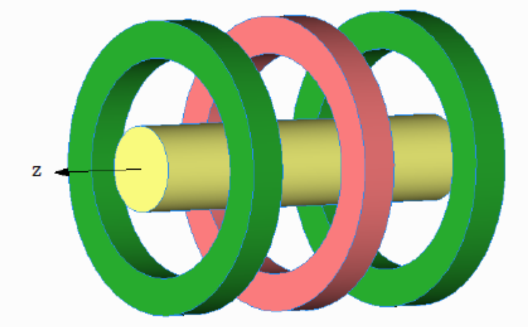
Christine Claessens from P8

Analyst: E. Machado

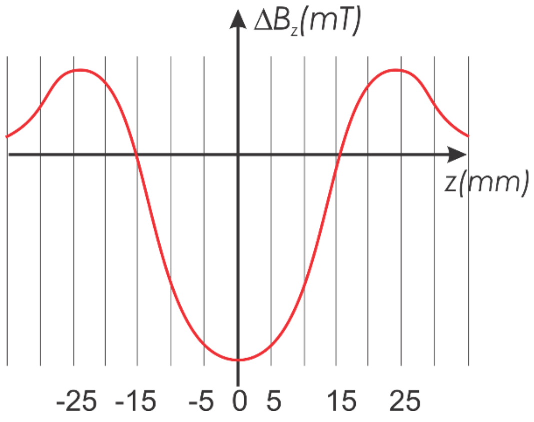
He6-CRES – magnetic trap

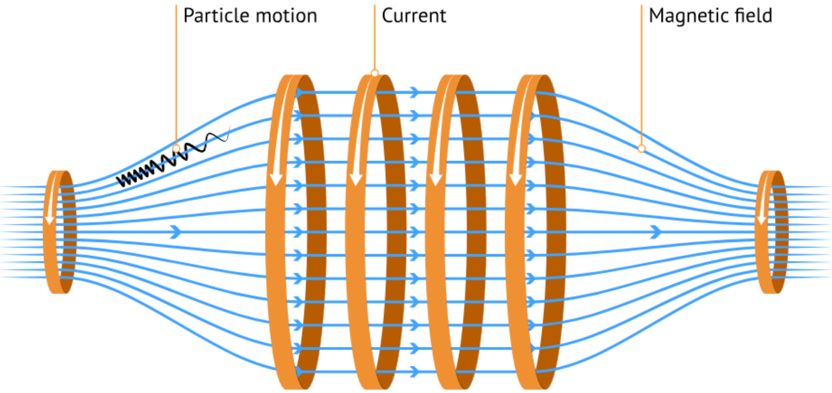
Need a magnetic trap to allow for measuring times that can extend to seconds.





$$\frac{\Delta B_z}{B_0} \sim 10^{-3}$$





https://www.energyencyclopedia.com/en/glossary/magnetic-mirror