Center for Experimental Nuclear Physics and Astrophysics (CENPA)
University of Washington

Cyclotron radiation spectroscopy to search for tensor currents

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U.S. DEPARTMENT OF ENERGY | Office of Science

Nuclear beta decay: beyond *V-A*?

Standard Model

Right-handed

$$H_{V,A} = \sum_{i=V,A} \bar{\Psi}_f\, O_i^{\mu} \Psi_0 \left[(C_i + C_i{}') \,\bar{e}^L\, O_{i,\mu} \nu_e{}^L + (C_i - C_i{}')\, \bar{e}^R O_{i,\mu} \nu_e{}^R \right]$$

$$O_i^{\mu} = \begin{cases} \gamma^{\mu} & i = V \\ \gamma^{\mu}\gamma_5 & i = A \end{cases}$$

chirality flipping

$$H_{S,T} = \sum_{i=S,T} \bar{\Psi}_f\, O_i \;\; \Psi_0 [(C_i + C_i{}') \,\bar{e}^R\, O_i \nu_e{}^L + (C_i - C_i{}')\, \bar{e}^L O_i \nu_e{}^R]$$

$$O_i = \begin{cases} 1 & i = S \\ \sigma^{\mu\nu} & i = T \end{cases}$$

Nuclear beta decay: beyond *V-A*?

- Will not address right-handed currents.
- Existing good limits on scalar currents.
- Will concentrate on tensor.

Standard Model

$$H_A = \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_0 \left[(2C_A)\, \bar{e}^L \gamma_\mu \gamma_5\, \nu_e{}^L \right] +$$

chirality flipping

$$\bar{\Psi}_f\, \sigma^{\mu\nu}\, \Psi_0 \left[(C_T + C_T{}')\, \bar{e}^R \sigma_{\mu\nu} \nu_e{}^L + (C_T - C_T{}')\, \bar{e}^L \sigma_{\mu\nu} \nu_e{}^R \right]$$

Decay rate:

$$dw = dw_0 \left[1 + a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

$$a \approx -\frac{1}{3}\left(1 - \frac{C_T^2 + C'^2_T}{2\, C_A^2} \right)$$

β-ν correlation

$$b \approx \pm (C_T + C_T{}')/C_A$$

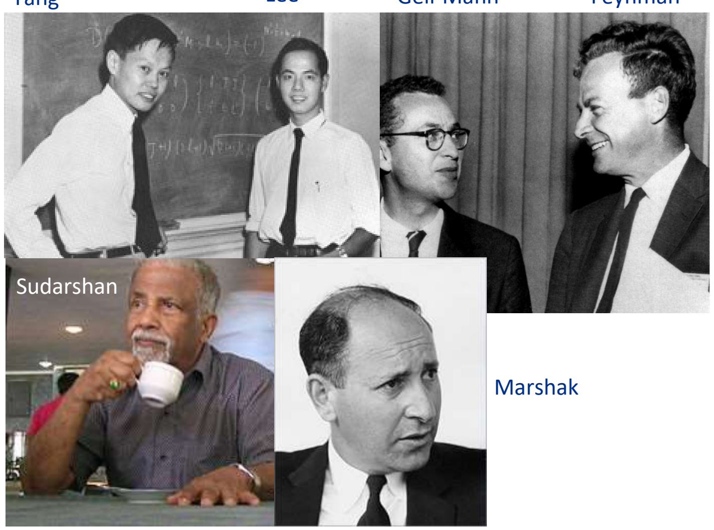
Fierz interference

Charged weak current in SM only sensitive to *L*:

$$\bar{\psi}_e O^\mu \psi_\nu = \bar{\psi}_e^L \gamma^\mu \psi_\nu^L$$

Sorting this out took much experimental effort and ingenuity to come out of confusing times

Yang Lee Gell-Mann Feynman



Marshak

From “The 7% solution” article in *Surely you are joking, Mr. Feynman!*

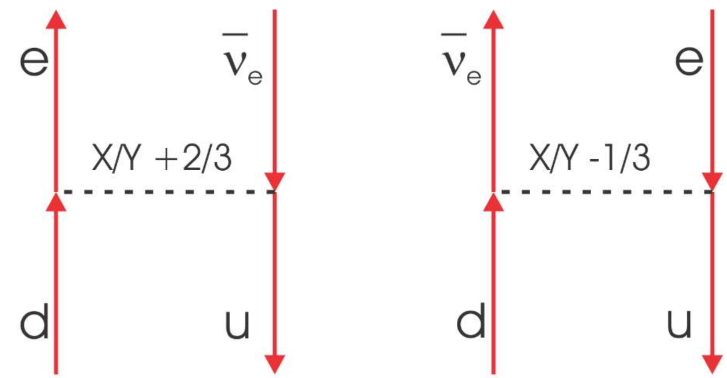
When I came back to the United States, I wanted to know what the situation was with beta decay. I went to Professor Wu's laboratory at Columbia, and she wasn't there, spinning to the left in the beta decay, came out on the right in some cases. Nothing fit anything. When I got back to Caltech, I asked some of the experimenters what the situation was with beta decay. I remember three guys, Hans Jensen, Aaldert Wapstra, and Felix Boehm, sitting me down on a little stool, and starting to tell me all these facts: experimental results from other parts of the country, and their own experimental results. Since I knew those guys, and how careful they were, I paid more attention to their results than to the others. Their results, alone, were not so inconsistent; it was all the others plus theirs.

Finally they get all this stuff into me, and they say, "The situation is so mixed up that even some of the things they've established for years are being questioned - such as the beta decay of the neutron is S and T. It's so messed up. Murray says it might even be V and A."

I jump up from the stool and say, "Then I understand EVVVVVERYTHING!"

Chirality-flipping as means of detection of new physics.

Small contribution that could be detected with precision experiments

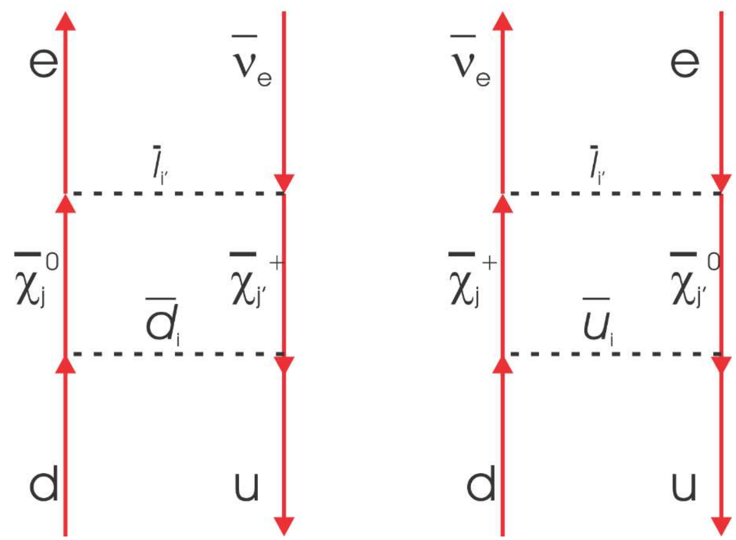


Leptoquarks:
X: scalar; Y: Vector
Predicted by
Grand Unified Theories

Profumo, Ramsey-Musolf, Tulin
Phys. Rev. D **75**, 075017 (2007)

Vos, Wilschut, Timmermans,
Rev. Mod. Phys. **87**, 1483 (2015)

Bhattacharya et al.
Phys. Rev. D **94**, 054508 (2016)



Predicted by
Supersymmetric
Theories

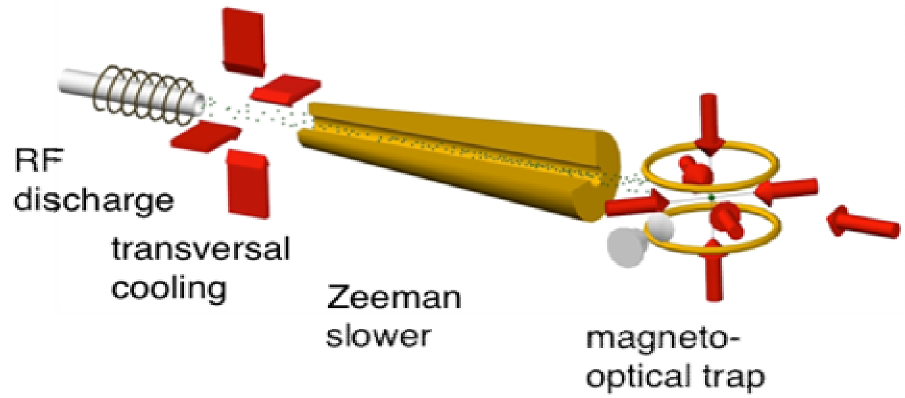
Or maybe something not considered so far…

^{6}He β-ν angular correlation at CENPA

Y. Bagdasarova[1], K. Bailey[2], X. Fléchard[3], A. Garcia[1,*], R. Hong[1], A. Knecht[4], A. Leredde[2], E. Liennard[3], P. Mueller[2,*], O. Naviliat-Cuncic[5], T. O'Connor[2], M. Sternberg[1], H.E. Swanson[1], F. Wauters[1]

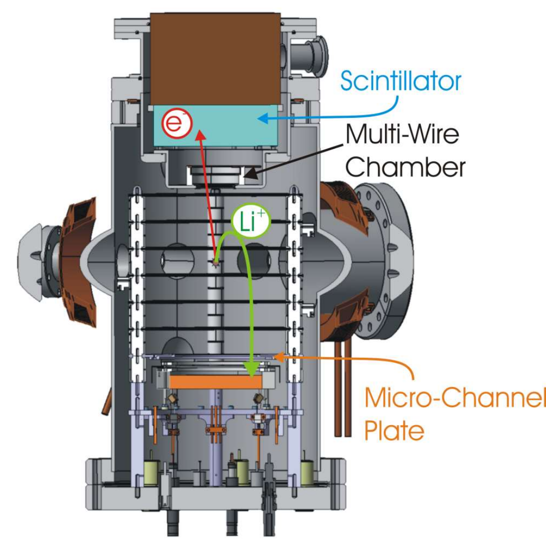
[1]*UW,* [2]*ANL,* [3]*LPC-CAEN(France),* [4]*PSI,* [5]*NSCL*

[*]Spokepersons



- Goal: measure "little *a*" to 0.1% in ^{6}He
  - pure Gamow-Teller decay
  - sensitive to tensor couplings
  - simple nuclear and atomic structure
- Laser cooling and trapping to prepare ^{6}He source
- Detect electron and ^{6}Li in coincidence
- ΔE-E scintillator system for electron detection (energy, start of time-of-flight)
- Micro-channel plate detector for ^{6}Li detection (position, time-of-flight)

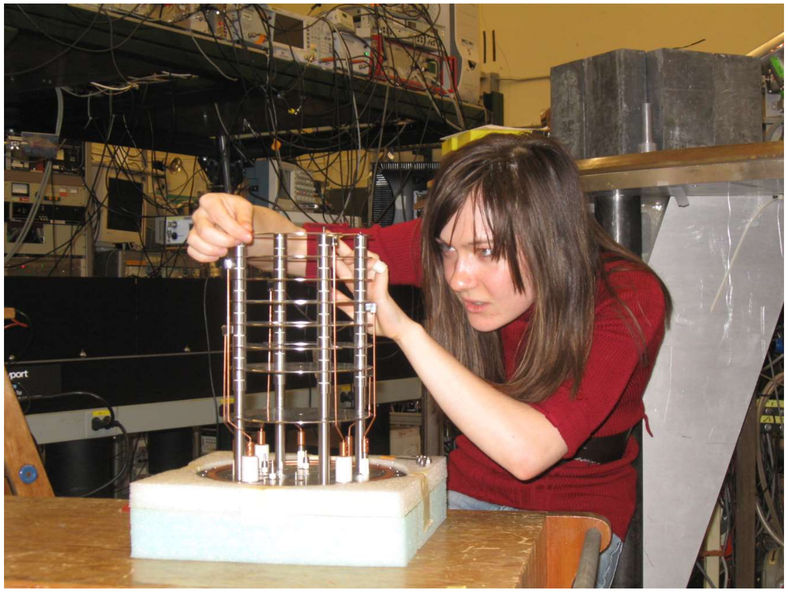
^{6}He Trap/Detector Chamber



^{6}He β-ν angular correlation at CENPA

^{6}He Source: Reliable source of ~10^{10} ^{6}He's/s in low-background
A. Knecht et al. NIM A. **660**, 43 (2011)

Laser trapping and detection systems:
All systems working after much development



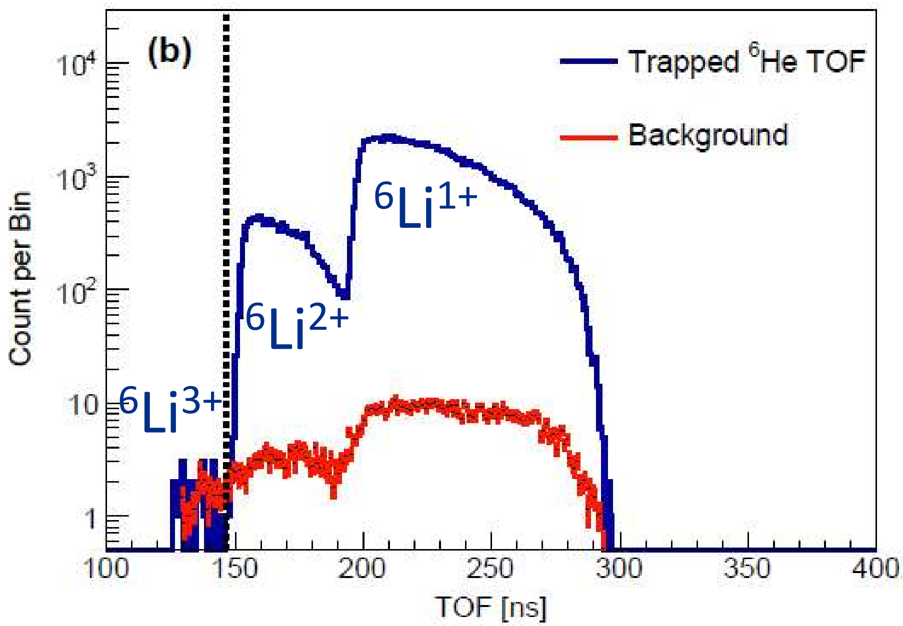
Status:

- Now efficiencies good for little-a statistics at the 1% level in 3 days.
- Aiming for $\Delta a/a$ <1% in near future.
- Presently working on systematic uncertainties.

Charge distribution of ^{6}Li ions in ^{6}He decay: a simple problem?

Phys. Rev. A **96**, 053411 (2017)

Helium electronic structure + sudden approximation. Very simple, but…



TOF between fast beta and ^{6}Li ions

Calculated vs Measured ^{6}Li ion charge fractions in % for ^{6}He decays

Ion	Theory[a] [16]	This work
Li^+	88.63(2)	90.5(1)
Li^{2+}	9.5(1)	9.5(1)
Li^{3+}	1.9(1)	≤ 0.01

19σ discrepancy with theory!

Recent calculations: PRA **92**, 050701(R) (2015)

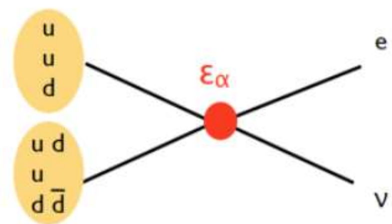
Connection to LHC data via EFT calculations

Cirigliano et al.
PPNP **71**, 93 (2013)

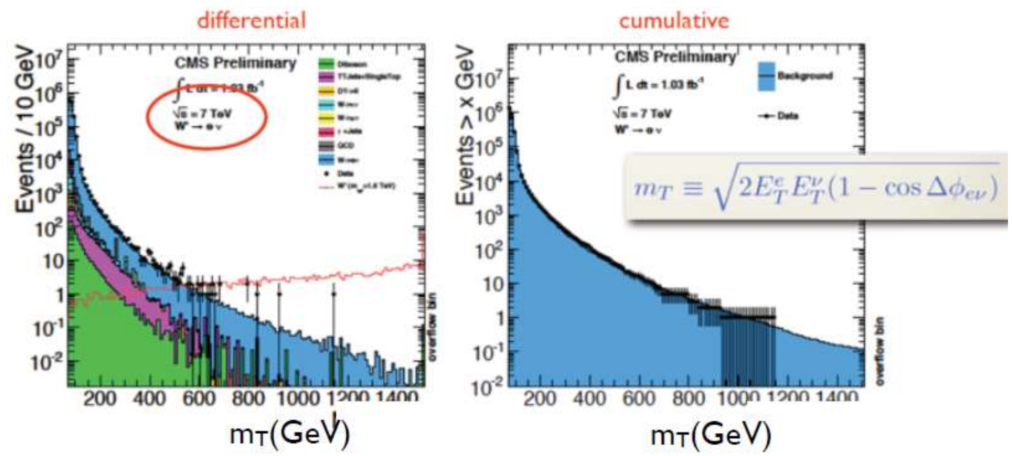
LHC (I): contact interactions

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

- The effective couplings ε_α contribute to the process p p → e ν + X



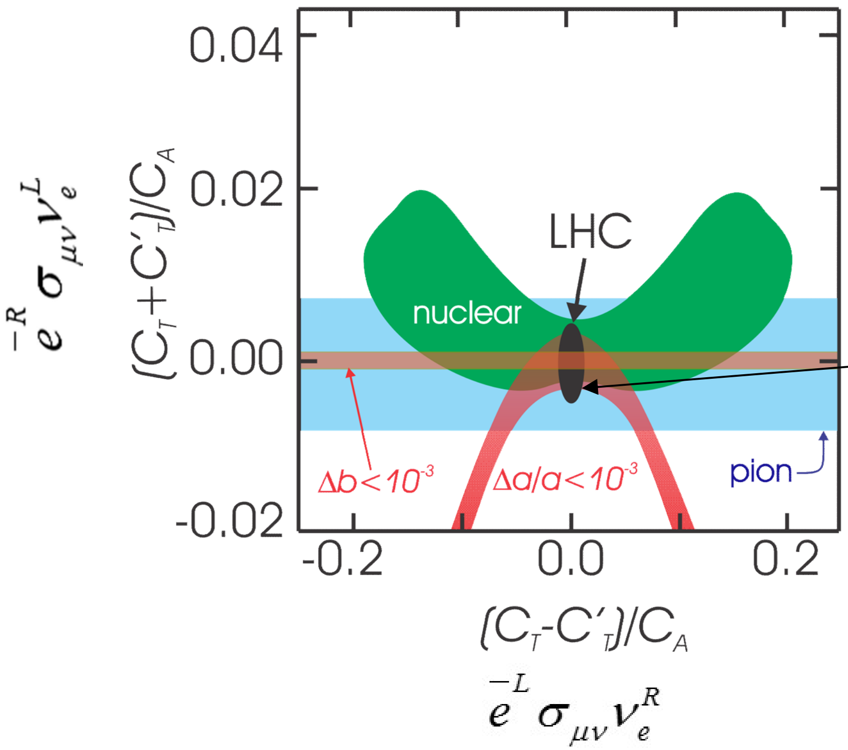
- No excess events in transverse mass distribution: bounds on ε_α



Precision beta decay versus others:

Can "precision" compete with "energy"?

Bhattachary a et al.
Phys. Rev. D **94**, 054508 (2016)

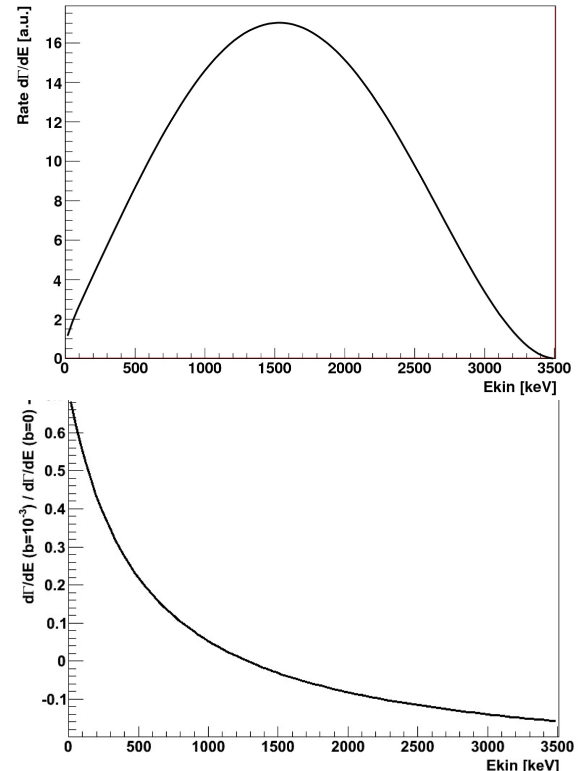


F. Wauters et al.
PRC **89**, 025501
(2014)

Best limits now from LHC
PRD **94**, 054508 (2016)

IS THIS THE END OF SEARCHING FOR THIS PROBE OF FUNDAMENTAL PHYSICS?

Reach sensitivities beyond the LHC?
Most sensitive probe is Fierz interference



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Fierz interference

Detect little *b*

Is it possible to reach into $b < 10^{-3}$?

Ongoing efforts in neutron beta decay:

- Nab aiming at $b \approx 3 \times 10^{-3}$.
- PERC, $b \approx 1 \times 10^{-3}$.

Nab:
Si detector to measure b

NIM A **611**, 211 (2009)

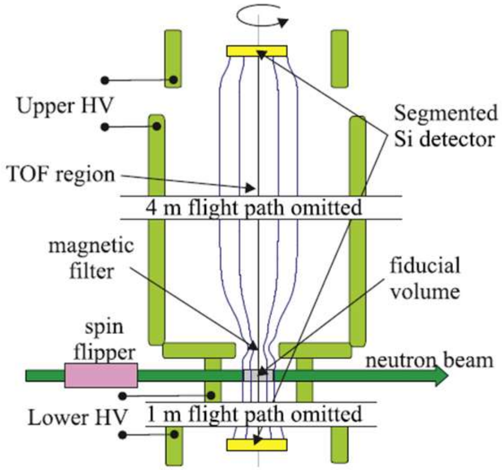

Figure 9. Principle of the Nab spectrometer in the vertical orientation. Magnetic field lines (shown in blue) electrodes (light green boxes), and coils (not shown) possess cylindrical symmetry around the vertical axis. The neutron beam is unpolarized for Nab, but can be polarized for later experiments.

PERC/Vienna:
RxB spectrometer to measure b

NIM A **701**, 254 (2013)

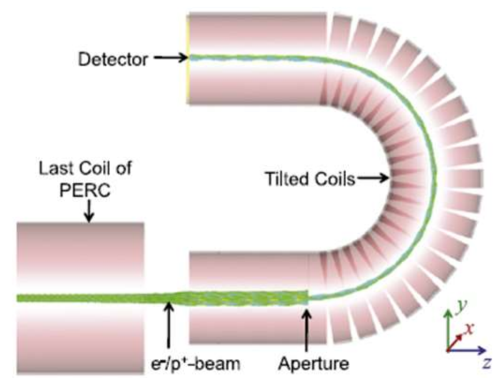

Fig. 5. The design of the $\mathbf{R} \times \mathbf{B}$ drift spectrometer at the end of PERC, and the simulated trajectories of e^-/p^+.

Detect little *b*

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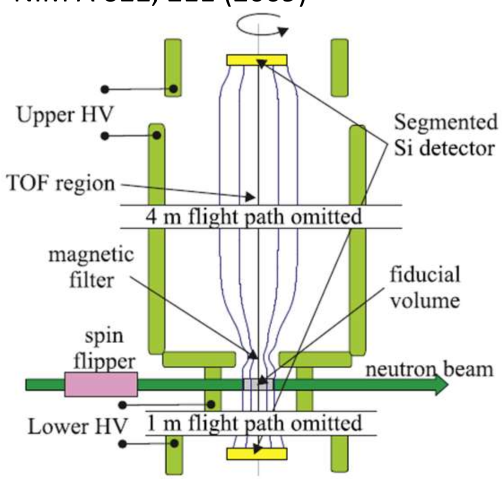
An experiment using ^{6}He could confirm a signal and potentially move beyond

Nab:
Si detector to measure b

NIM A **611**, 211 (2009)



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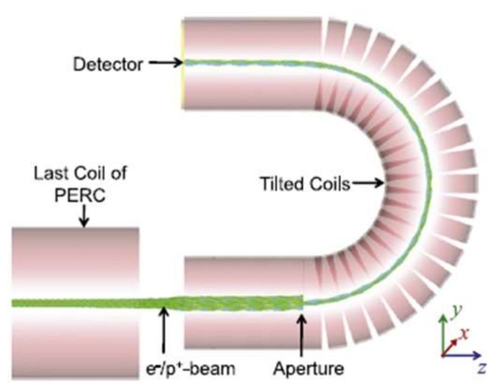
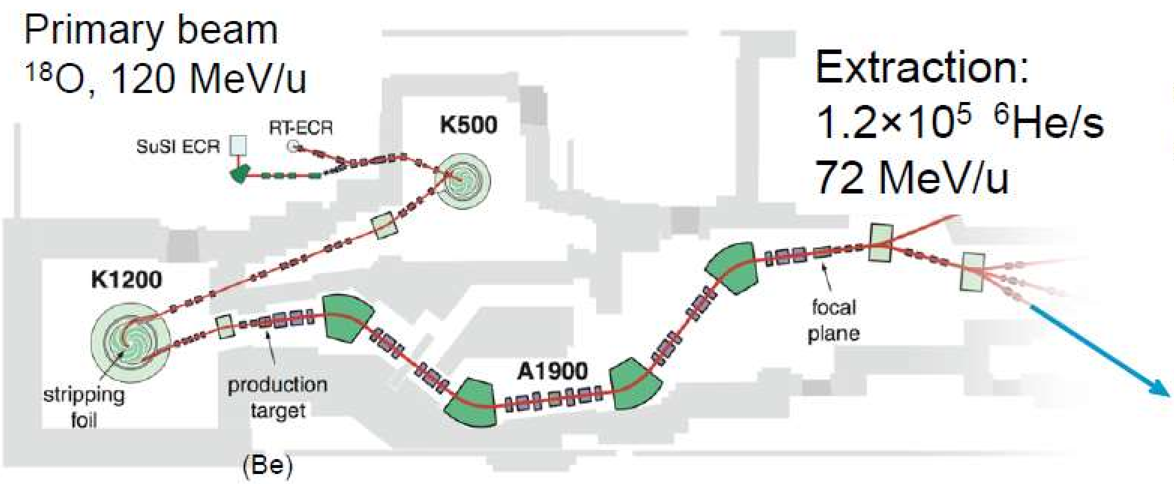
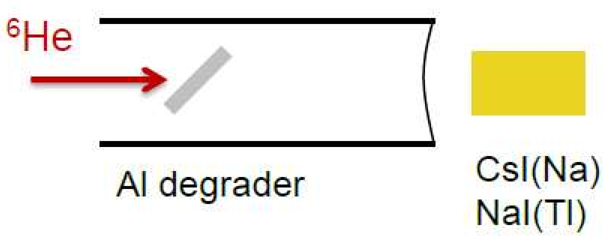


Fig. 5. The design of the R × B drift spectrometer at the end of PERC, and the simulated trajectories of e^-/p^+.

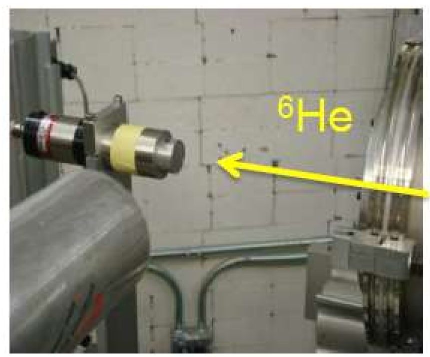
6He at NSCL: Naviliat-Cuncic et al.



- $\Delta p/p$ = 1%
- $\Delta x\times\Delta y$ = 1.5×2 mm^2



46 MeV/nucleon after degrader

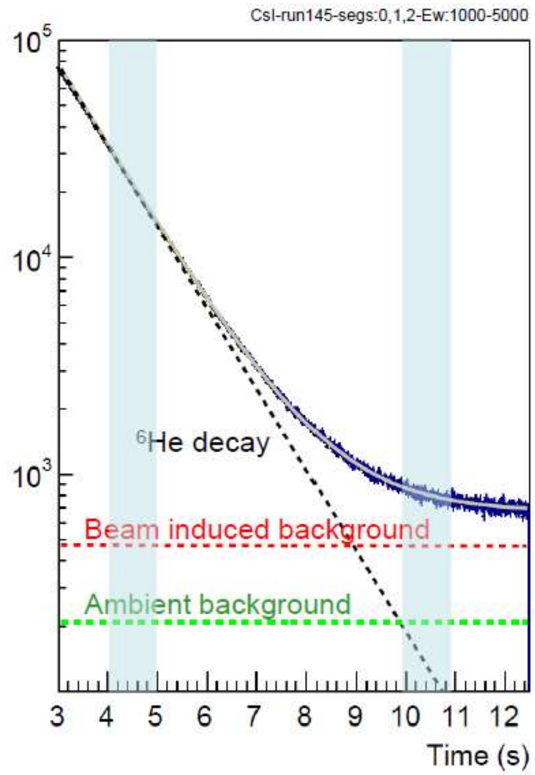


- CsI(Na) (2"×2"×5")
- NaI(Tl) (Ø3"×3")
- (Ø1"×1") CsI(Na)
- (Ø1"×1") NaI(Tl)

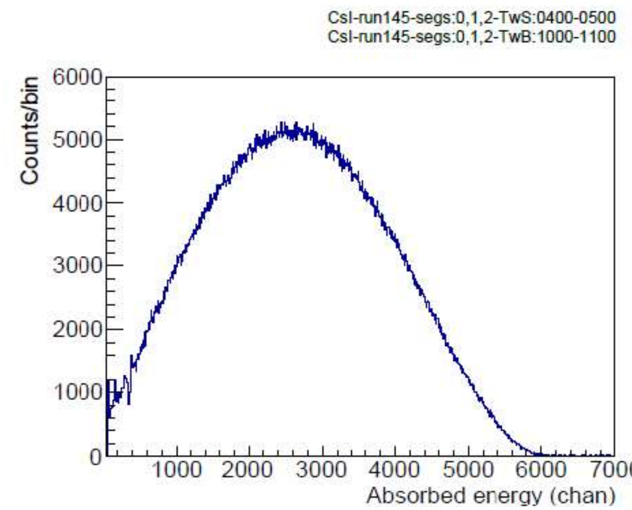
6He at NSCL: Naviliat-Cuncic et al.

Sample of experimental spectra

Beam ON/OFF sequence



No traces of "short lived" beam induced background



- We collected typically 10^7 events in 1 h run
- We define 7 slices between 3 and 5 s, with 10^6 events in each spectrum.

- ~100 spectra with CsI(Na)
- ~100 spectra with NaI(Tl)

New idea: use CRES technique

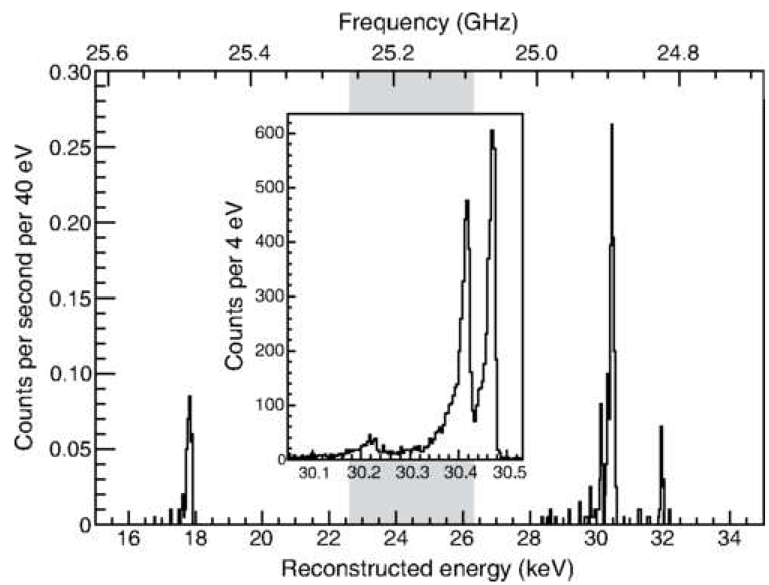
Selected for a Viewpoint in *Physics*
PRL **114**, 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

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)

Project 8 collaboration gets FWHM/E $\approx 10^{-3}$ resolution for conversion electrons of 18-32 keV.



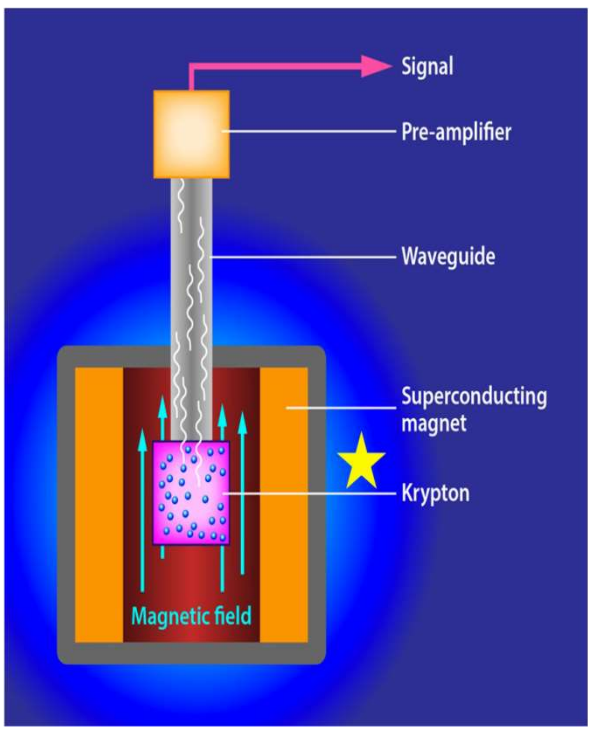
Can the technique be applied to a beta continuum with $E_\beta = 0 - 4$ MeV ?

New idea: use CRES technique

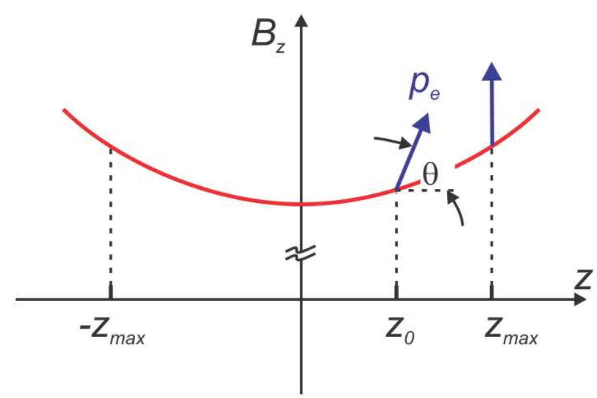
Project 8 in a nutshell

Looking at Tritium decay to get ν mass. Electrons emitted in an RF guide within an axial *B* field. Antenna at end detects cyclotron radiation.

$$\omega = \frac{qB}{E}$$



Electrons of ~ 30 keV from a gaseous source were let to decay within a 1 tesla field with an additional pair of coils to set up a *magnetic trap*:



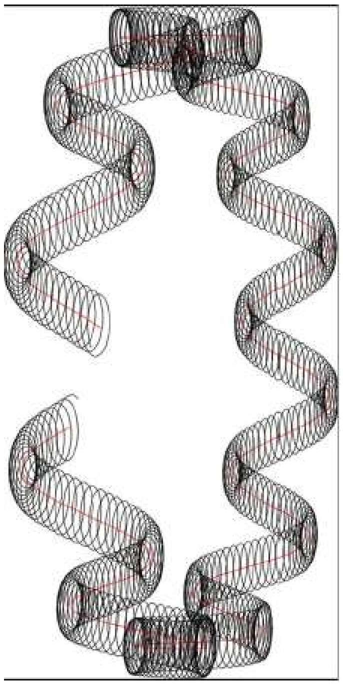
Longitudinal comp. of momentum decreases as *B* increases up to return point, z_{max}. Axial oscillations with ω_z.

New idea: use CRES technique

Some details

Motion can be thought off as cyclotron orbits, axial oscillations and magnetron motion.

$$\omega_c : \omega_z : \omega_{mag} =$$
$$\sim 1 : 4 \times 10^{-3} : 2 \times 10^{-5}$$



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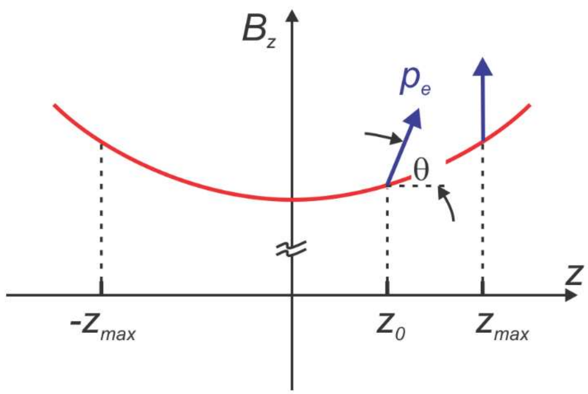

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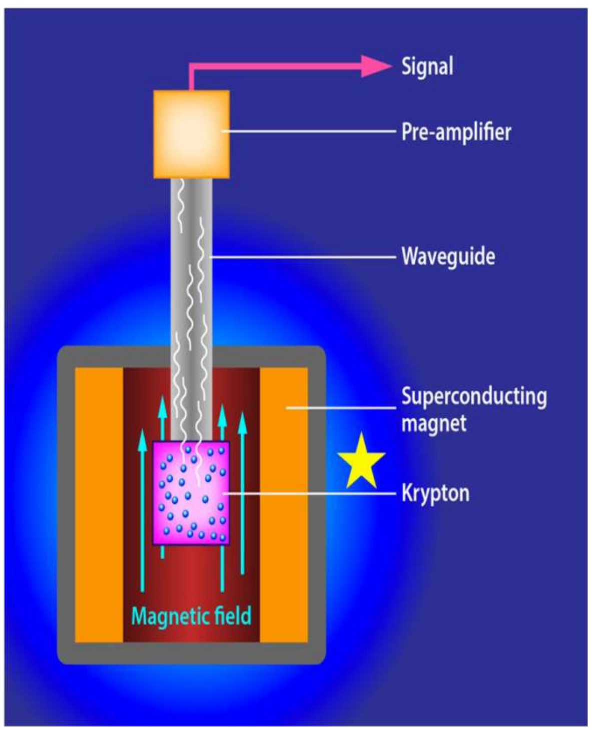
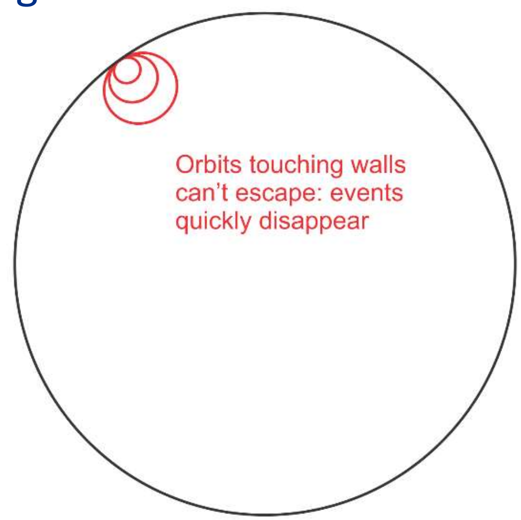


Advantage

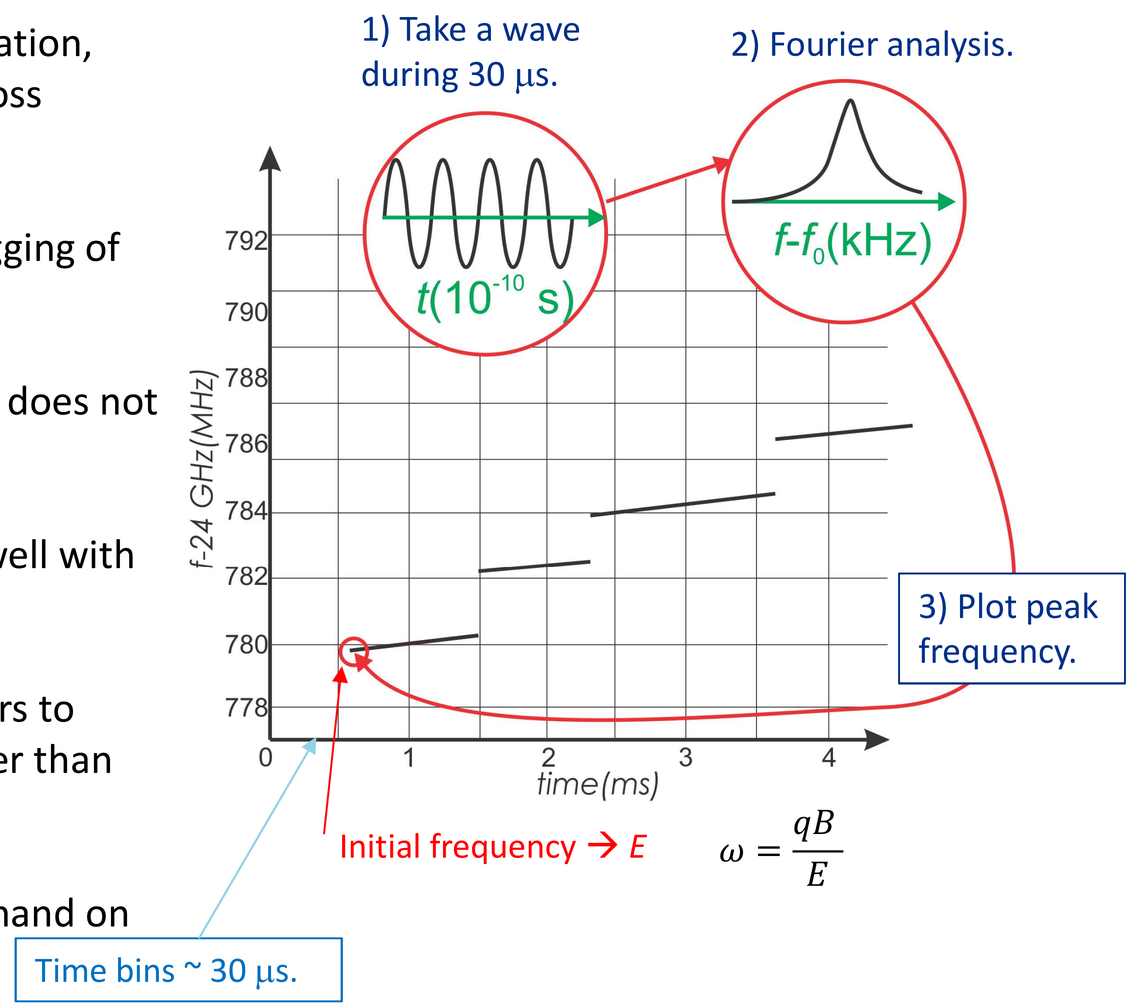
Electrons hitting walls quickly (<1 ns) loose energy and disappear.
No signal from these



For the same reason: background radiation hitting walls does not generate signals.

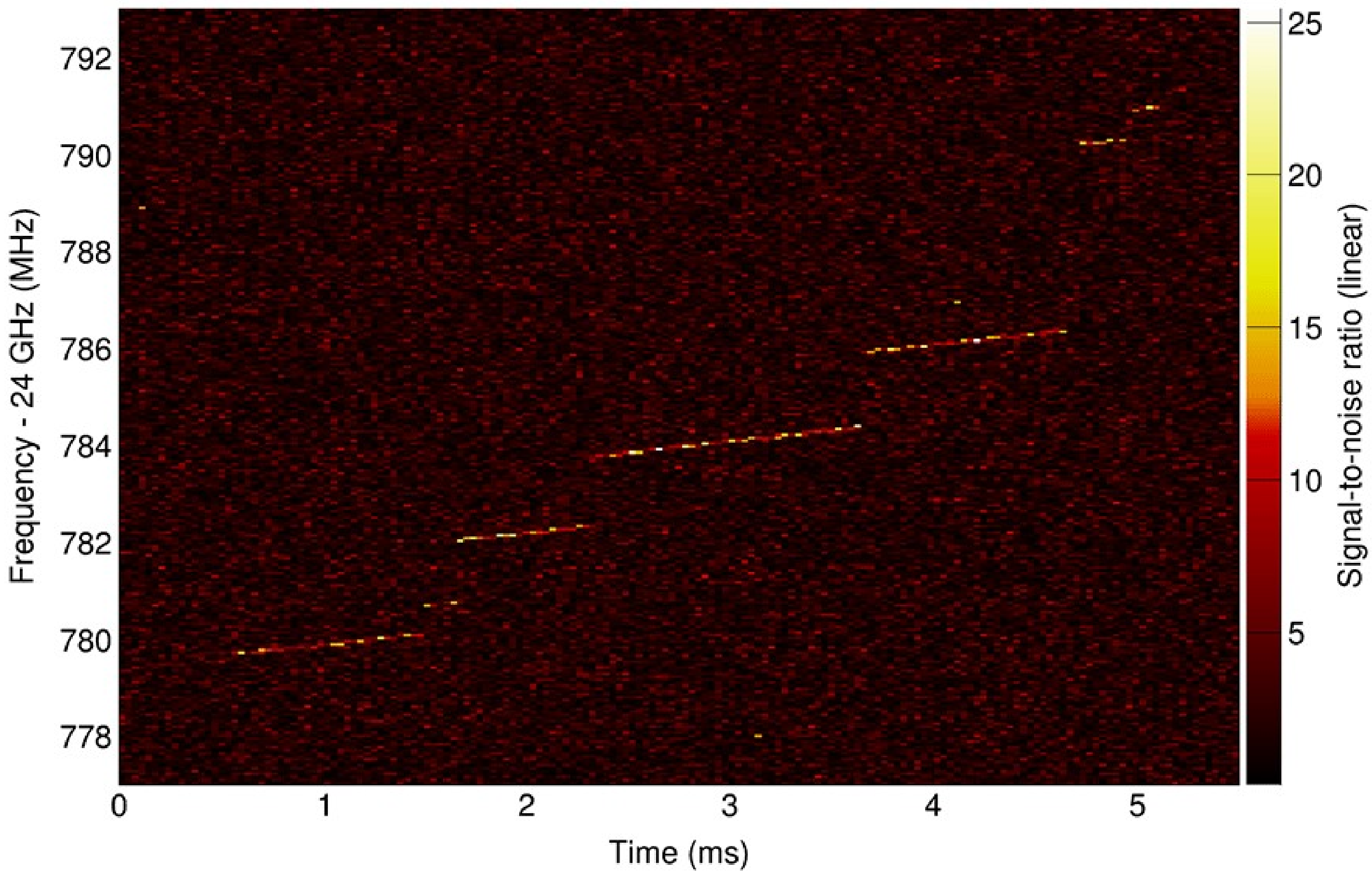
Why do we like the Project-8 technique for ^{6}He?

- Measures beta energy at creation, before complicated energy-loss mechanisms.
- High resolution allows debugging of systematic uncertainties.
- Room photon or e scattering does not yield background.
- 6He in gaseous form works well with the technique.
- 6He ion-trap (shown by others to work) allows sensitivity higher than any other proposed.
- Counts needed not a big demand on running time.



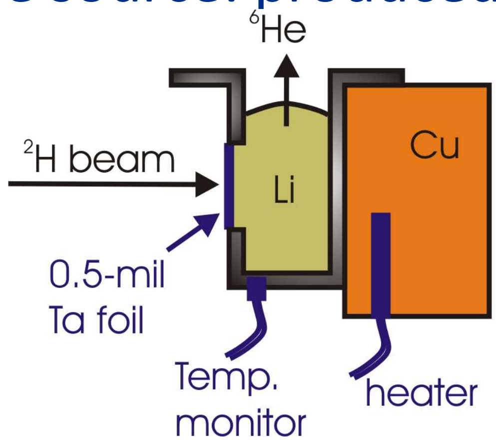
$$\omega = \frac{qB}{E}$$

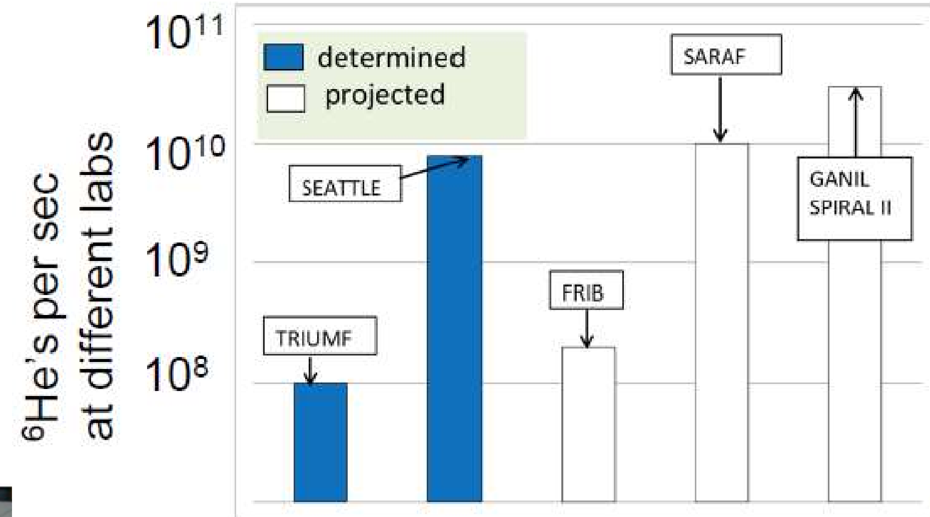
Project-8 technique



Power from a single electron orbiting in a magnetic field versus time and the frequency of the electron's orbit. The straight streaks correspond to the electron losing energy (and orbiting faster) as it radiates. The jumps correspond to the loss of energy when the electron collides with an atom or molecule.
[Asner et al. [PRL **114,** 162501]

^{6}He source: produced via ^{7}Li(d,^{3}He)^{6}He

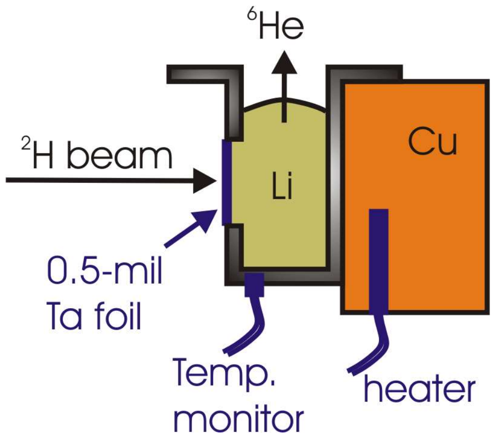




^{6}He production:
10^{10} ^{6}He/s delivered to clean lab in a stable fashion.

Knecht et al.
NIM A 660, 43 (2011)

Research with the accelerator: ^{6}He source



10^{10} ^{6}He/s in clean lab in a stable fashion.

“Statistics for searching for new physics”, compare decay densities to neutron sources:

UCN: 10^3 UCN/cc → ≈ 1 (decay/s)/cc

CN: 10^{10} CN/s cm2 → 2×10^5 CN/cc $\approx$200 (decay/s)/cc

^{6}He: $\approx 2 \times 10^6$ (decay/s)/cc

Important for using CRES technique in an RF guide.

Emerging ^{6}He little-*b* collaboration

W. Byron[1], M. Fertl[1], A. Garcia[1], G. Garvey[1], M. Guigue[4], D. Hertzog[1], K.S. Khaw[1], P. Kammel[1], A. Leredde[2], P. Mueller[2], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[3], H.E. Swanson[1], B.A. Vandeevender[4], F. Wietfeldt[5], A. Young[3]

[1]*University of Washington,*
[2]*Argonne National Lab,*
[3]*North Carolina State University,*
[4]*Pacific Northwest National Laboratory*
[5]Tulane University

- **Goals:**
  - measure "little *b*" to better than 10^{-3} in ^{6}He.
  - Highest sensitivity to tensor couplings

- **Technique**
  - Use Cyclotron Emission Spectroscopy. Similar to Project 8 setup for tritium decay
  - Need to extend the technique to higher energy betas and to a precision determination of a continuum spectrum.

We have put together a collaboration, written and submitted a proposal. Now kick-started by DOE and UW funds.

Detection of cyclotron radiation to search for chirality-flipping interactions and other applications

M. Fertl,[1] A. García,[1] M. Guigue,[2] D. Hertzog,[1] A. Hime,[2] P. Kammel,[1] A. Leredde,[3] P. Müller,[3] N.S. Oblath,[2] R.G.H. Robertson,[1] G. Rybka,[1] G. Savard,[3] D. Stancil,[4] H.E. Swanson,[1] B.A. VanDevender,[2] and A.R. Young[5]

[1]*Physics Department and CENPA, University of Washington, Seattle, WA 98195*
[2]*Pacific Northwest National Laboratory, Richland, WA 99352*
[3]*Physics Division, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439*
[4]*Electrical Engineering Department, North Carolina State University, Raleigh, NC 27695*
[5]*Physics Department, North Carolina State University, Raleigh, NC 27695*

(Dated: September 27, 2016)

We propose a sensitive search for non-Standard-Model chirality-flipping interactions by measuring the shape of the beta spectrum of ^{6}He. We will apply the technique of cyclotron radiation emission spectroscopy (CRES) recently demonstrated by the Project 8 collaboration, extending its use to the broader range of electron energies of the ^{6}He β decay. This proposal presents a phased approach to realize the goal of measuring the b_{Fierz} parameter to a precision of better than 10^{-3}. The first phase is aimed at demonstrating the validity of the technique for electrons in the few MeV range. The proposed test of the Standard Model in Phase II will have a sensitivity to new physics in a regime which exceeds the capabilities of the LHC both now and after the luminosity upgrade. Phase III is the most ambitious experiment proposed to date to detect chirality-flipping interactions.

We also intend to develop collaborations with groups that have traditionally used radioactive ion traps and could apply the technique for nuclear-structure related spectroscopy. In particular, the measurement of small Electron Capture branches from radioactive nuclei to set benchmarks for theoretical calculations of double-beta decay matrix elements.

An existing magnet will be re-purposed for the measurement. We ask for funds for RF electronics and data acquisition and for some vacuum equipment.

We have put together a collaboration, written and submitted a proposal. Now kick-started by DOE and UW funds.

Phase I: proof of principle
- 2 GHz bandwidth.
- Show detection of cycl. radiation from 6He.
- Study power distribution.

} Mission for next three years

Phase II: first measurement ($b < 10^{-3}$)
- 6 GHz bandwidth.
- 6He and 19Ne measurements.

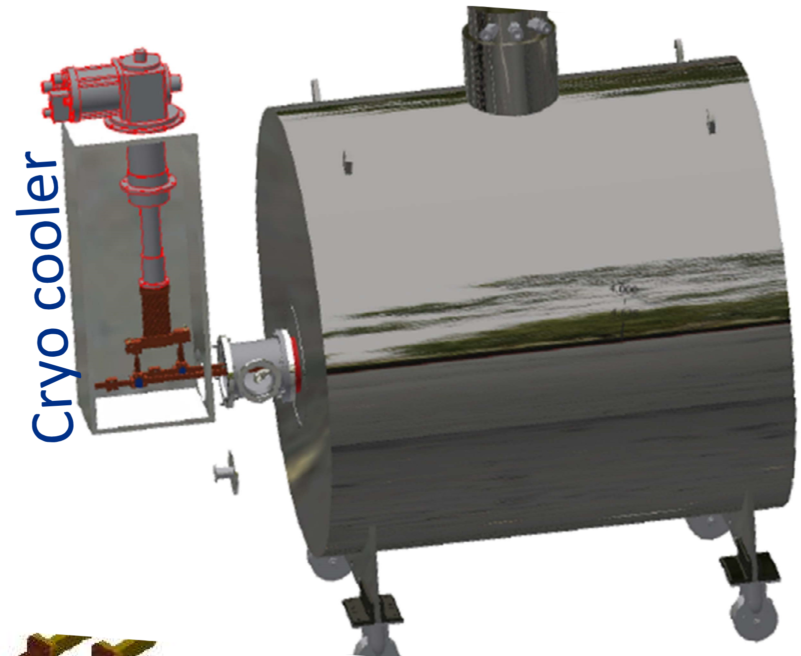
Phase III: ultimate measurement ($b < 10^{-4}$)
- ion-trap for no limitation from geometric effect.

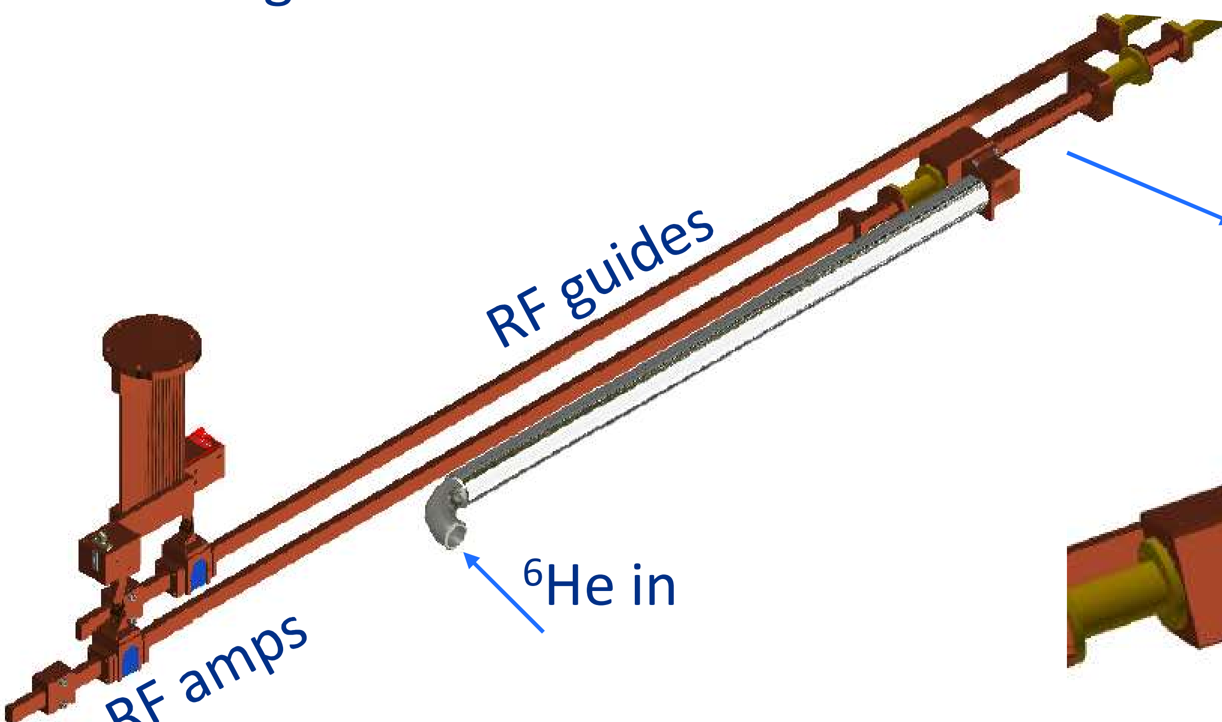
^{6}He little-*b* measurement at Seattle

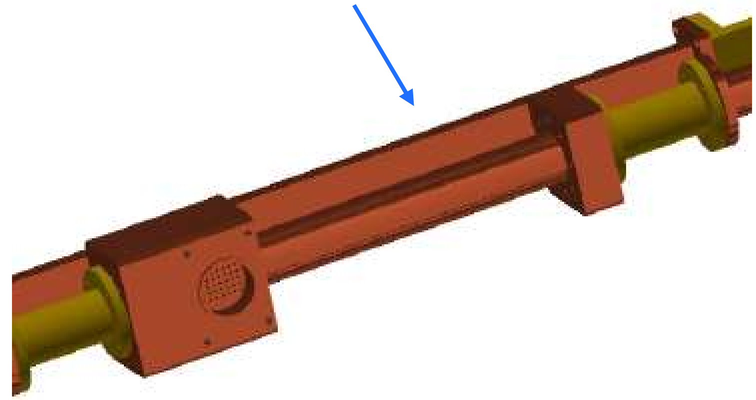
Goal: measure "little *b*" to 10^{-3} or better in ^{6}He

Stats not a problem.

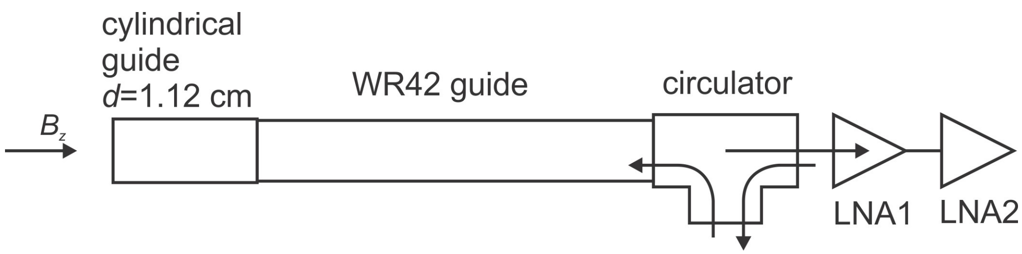
Starting construction during summer 2018.





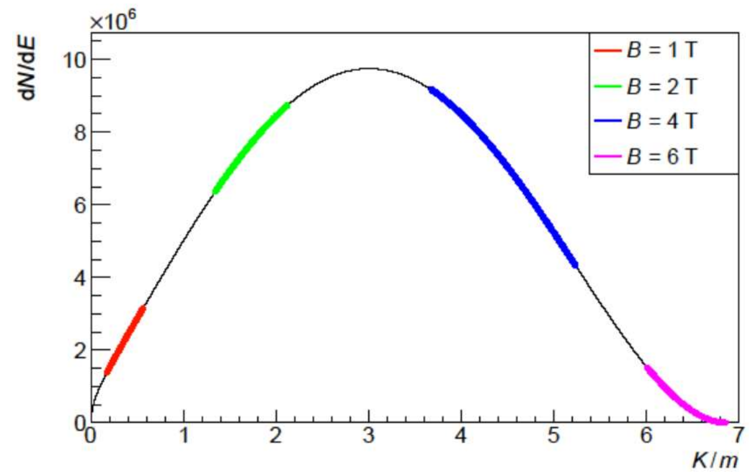


^{6}He little-b measurement at CENPA



Stage	Rate (1/s)
Incoming atoms	2×10^9
Decays within trap	1×10^6
Trapped betas	3×10^4
Trapped betas (not hitting walls)	1×10^4
Events observed within frequency window	1×10^3

Frequency band: *f*=18-24 GHz.
Monte Carlo simulation of observation in
Few days of running



^{6}He little-b measurement at CENPA

Monte Carlo simulation of observation in
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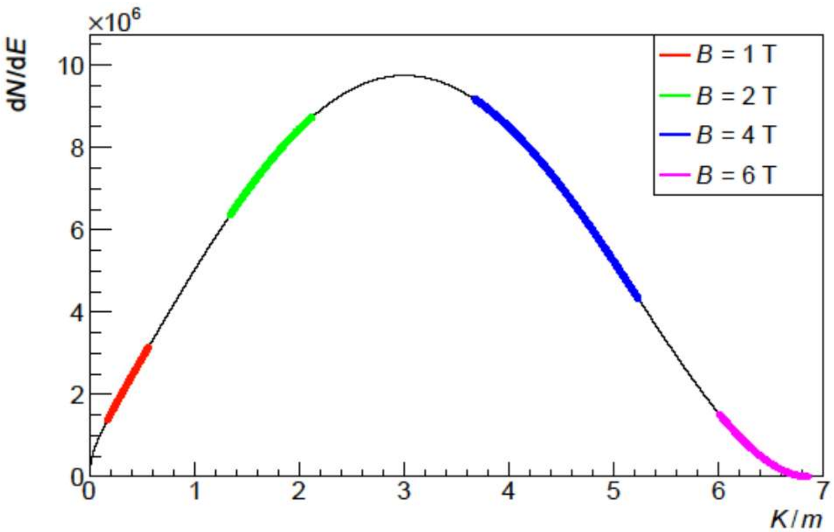
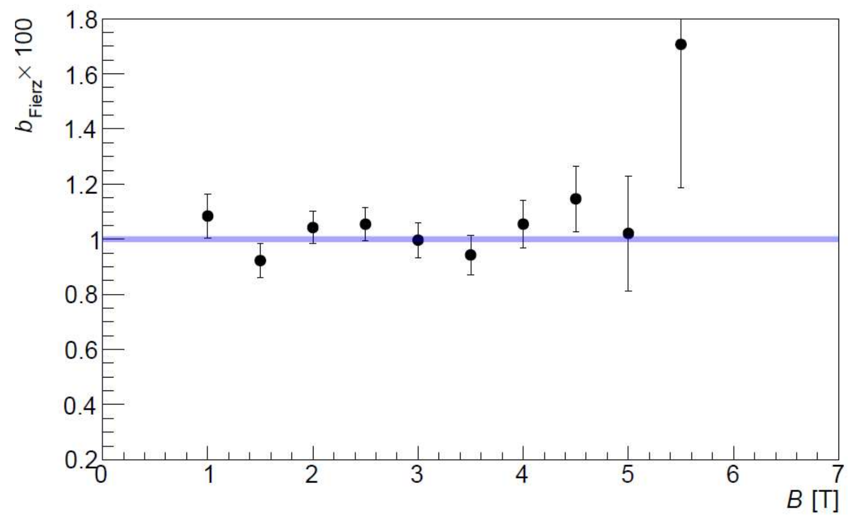
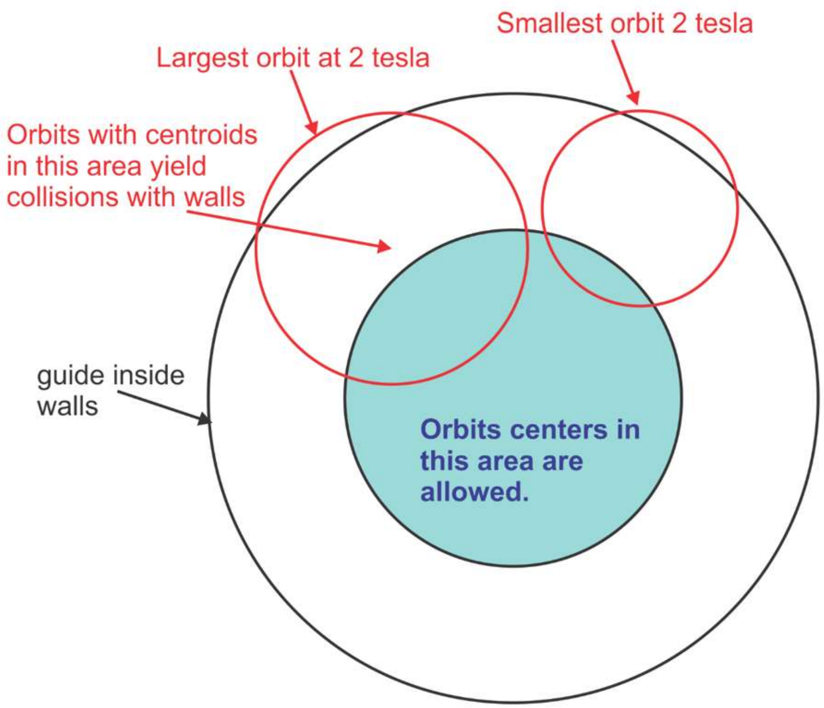


Extracting little b vs. B field
Few days of running each point
(assumed b_{MC} = 0.01)



Obvious worry: efficiency depends on energy.



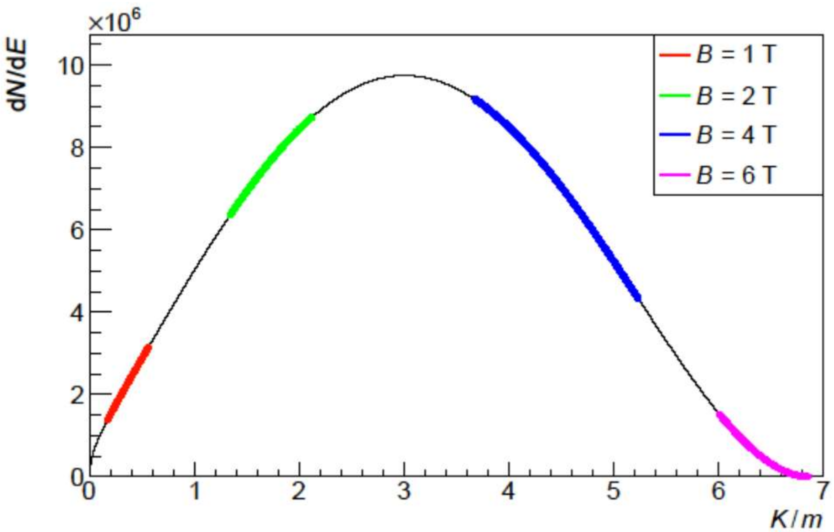
Cross sectional view of guide with electron orbit. For this radius there is a dead region shown by the white frame on the blue area.

Since blue area depends on energy there is a systematic distortion of the spectrum

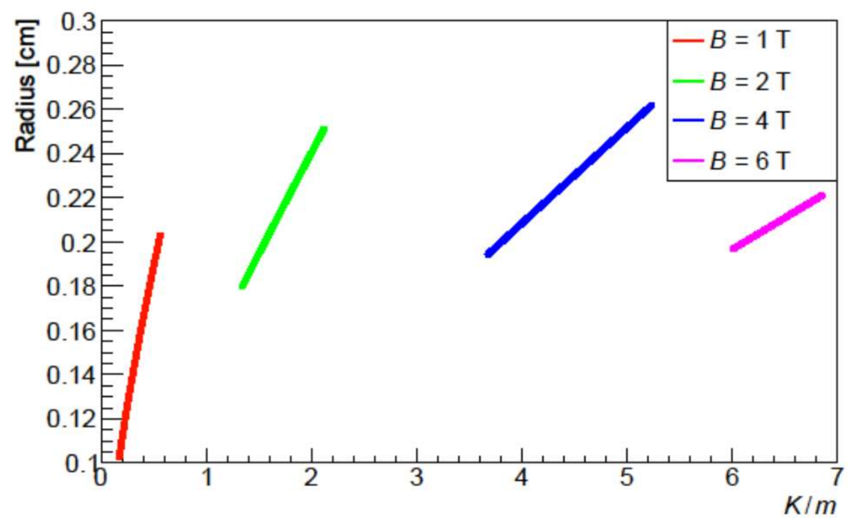
Can be studied by varying the *B* field.

Obvious worry: efficiency depends on energy.

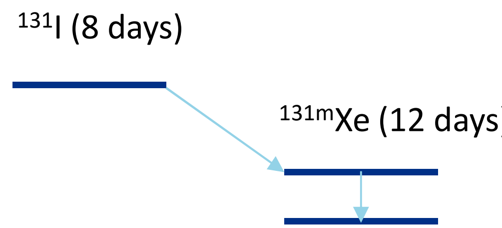
Monte Carlo simulation of observation in
Few days of running



Radii vs. *B* field
Can use this to check geometric effect

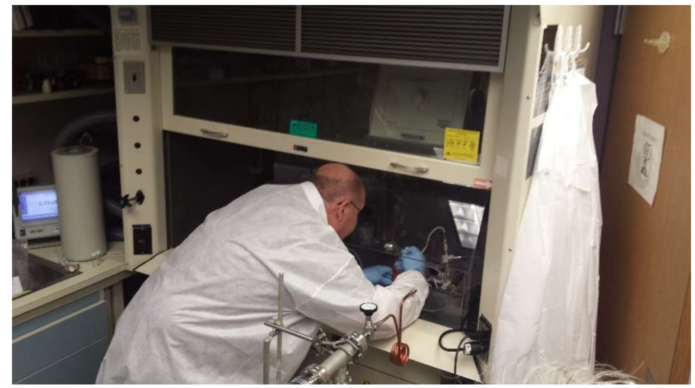


Additional tool for calibrations:
^{131m}Xe ($t_{1/2} \approx 12$ days)



Conversion electrons
E_e = 25, 129, 160 keV

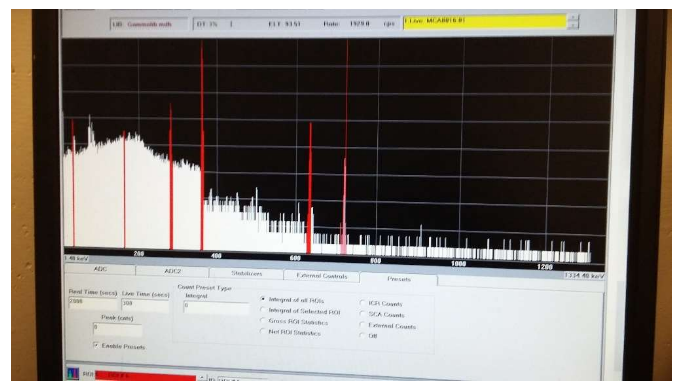
- Studying versus B field allows determining the effect.
- Showing that all is understood with higher *E* electrons is a milestone to move forward.



Need about 50 mCi of ^{131}I (→ ^{131m}Xe with $t_{1/2} \approx 8$ days)
(30 μCi of ^{131}I is a safety concern)

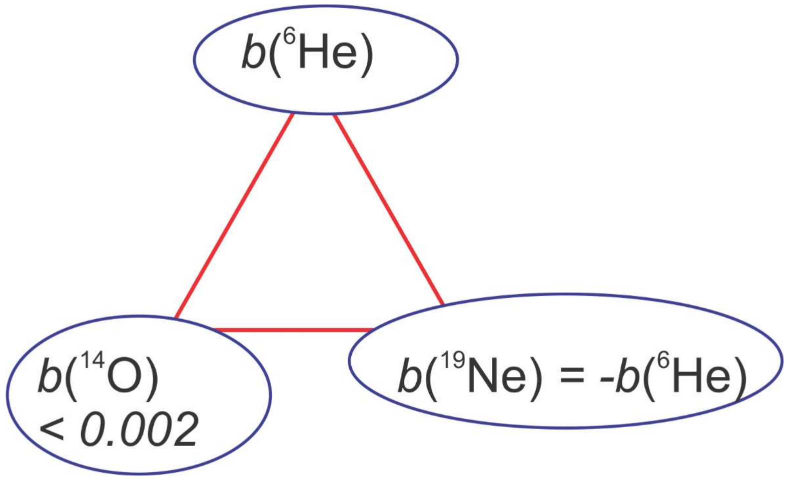
We have extracted ≈ 10^5 Becq. of ^{131m}Xe.

Ready to test as soon as we have apparatus.



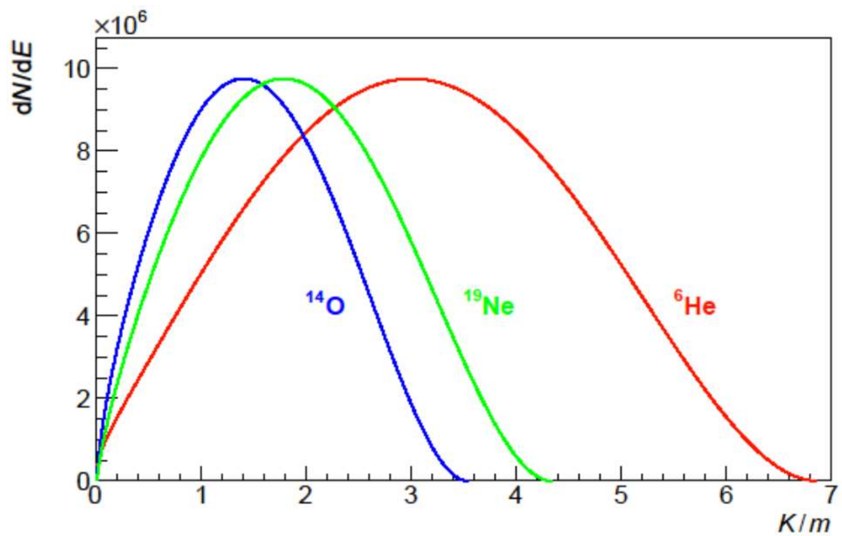
Check on signature by measuring ^{14}O and ^{19}Ne:

Both ^{14}O and ^{19}Ne can be produced in similar quantities as ^{6}He at CENPA.



^{14}O as CO (T_{freeze} = 68 K)
Previous work at Louvain and TRIUMF.

^{19}Ne source developed at Princeton appropriate.

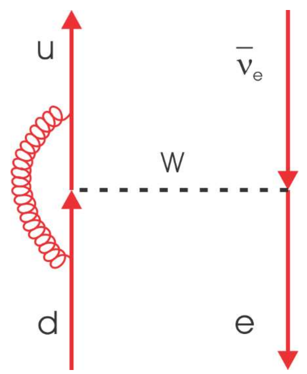


6He nuclear structure issues to reach $b < 10^{-3}$

^{19}Ne?

^{14}O?

Recoil order corrections and the SM contribution to little *b*

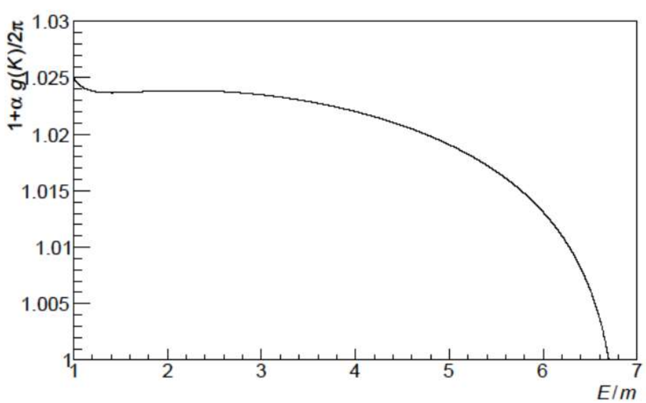


Dominant factor in recoil-order correction is interference between WM and GT:

$$R(E) \approx \underbrace{\frac{2m}{3M}\frac{\langle WM\rangle}{\langle\sigma\rangle}}_{\sim 10^{-3}}\left(2\frac{E}{m} - \frac{E_0}{m} - \frac{m}{E}\right)$$

Factor determined to $\sim$ 2% by connection to γ decay of analogue in 6Li.

Radiative corrections



Model-independent Sirlin factor.

Other nuclear-structure issues?
Need to be explored to reach beyond $b < 10^{-3}$

REVIEWS OF MODERN PHYSICS, VOLUME 90, JANUARY–MARCH 2018

High precision analytical description of the allowed β spectrum shape

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improved atomic corrections, an analytical description was presented of the allowed β spectrum shape accurate to a few parts in 10^{-4} down to 1 keV for low to medium Z nuclei, thereby extending the work by previous authors by nearly an order of magnitude.

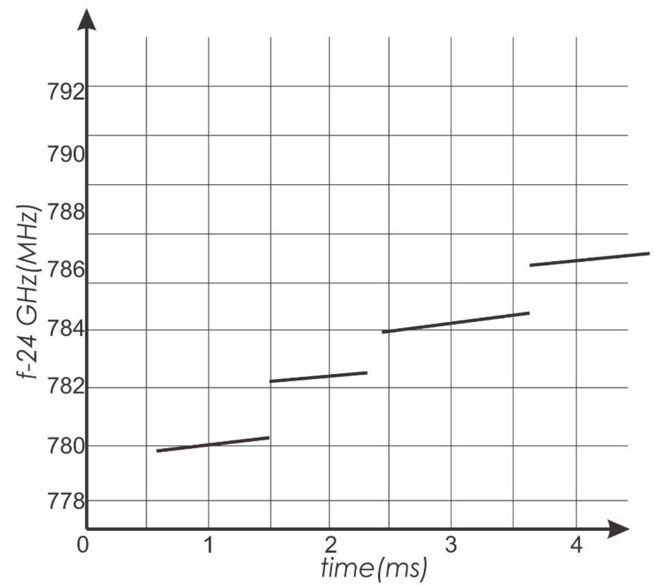
Other worries: DAQ.

To register it all, need to take about 1 byte at 5 GHz.

About 1 Peta-byte/day !!

By triggering and recording only within a Δf of interest one can decrease it to 1 Tera-byte/day.

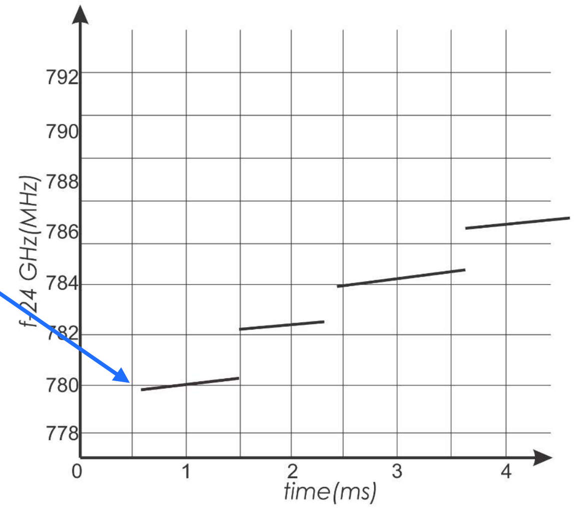
It is a concern of the Project 8 collaboration, who are working on addressing this (gpu's for FFT's, analysis with PNNL computers, etc…)



Other worries:

- Identify initial frequency?

Make sure event starts within observation window.

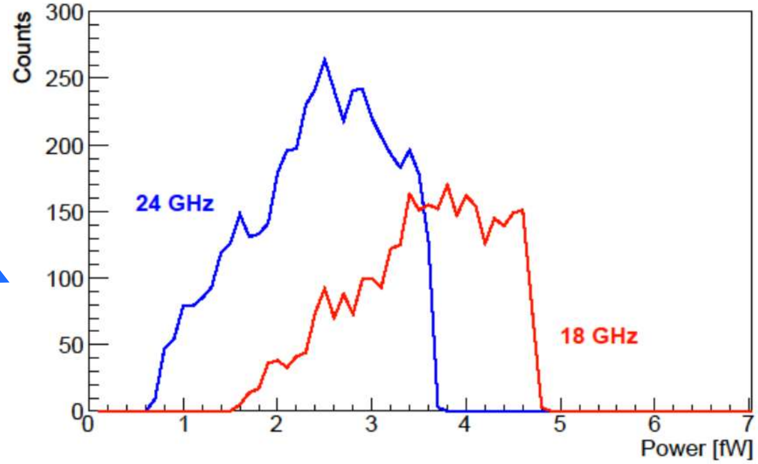


- Dependence on magnetic-field in-homogeneities?

$$\omega_c = \frac{qB}{E}$$

Good expertise in team on shimming *B* fields

- RF power variations with *E*: efficiency dependency?



Other worries: “Doppler effect” and power into sidebands.

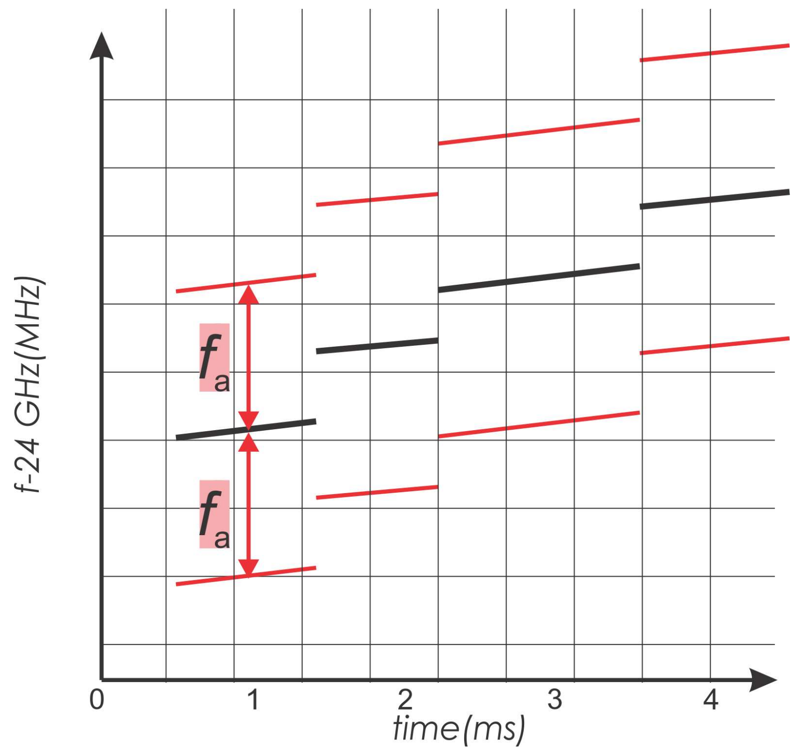
The wave generated by the electron is:

$$e^{i(\beta z- \quad)}$$

The amplifier observes a frequency:

$$\omega + \beta \, \dot{z}0/\omega$$

“Doppler effect” depends on axial speed of the electron.
Since the electron is oscillating, this leads to frequency modulation.
Part of the power goes to sidebands.

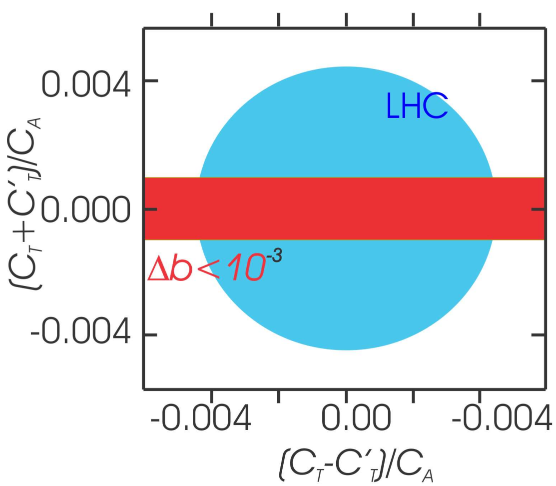


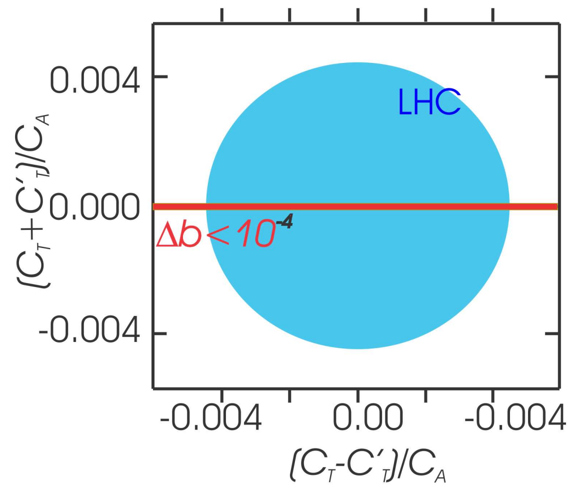
Potential reach (Monte Carlo simulations)

Phase III:
Future development,
couple to an ion trap

Effect	Δb	
	No trap	Ion trap
Magnetic field uncertainties	10^{-4}	$< 10^{-4}$
Wall effect uncertainties	10^{-3}	
RF pickup uncertainties	10^{-4}	10^{-5}
Misidentification of events	10^{-4}	5×10^{-5}

Phase II





Applications: coupling CRES with radioactive ion trap.
Benchmarks for nuclear structure and 2β decays

2β decays depend on $(g_A)^4$: can one determine g_A versus A?

Suhonen et al. suggest extracting g_A using forbidden decays (PRC **96**, 024317 (2017)).

CRES technique coupled to an ion trap with FRIB would allow for systematically measuring a broad range of spectra.

JOEL KOSTENSALO AND JOUNI SUHONEN

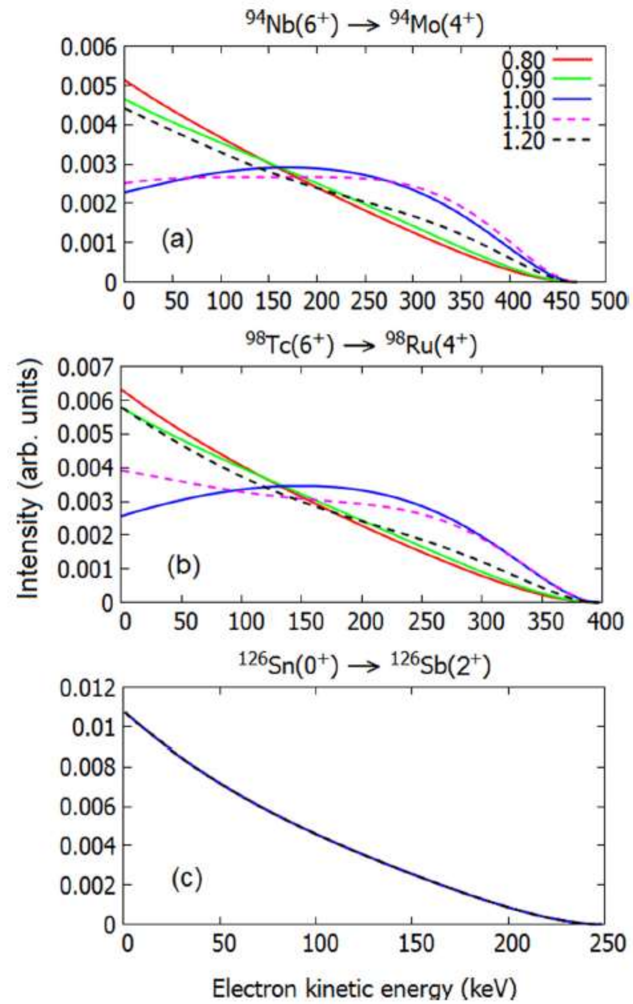


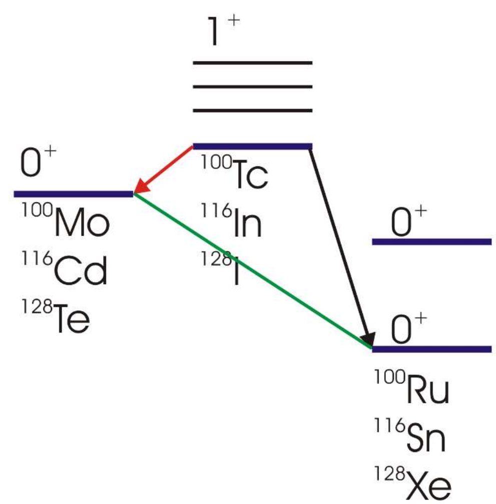
FIG. 2. Same as Fig. 1 but for the second-forbidden nonunique decays of ^{94}Nb [panel (a)], ^{98}Tc [panel (b)], and ^{126}Sn [panel (c)].

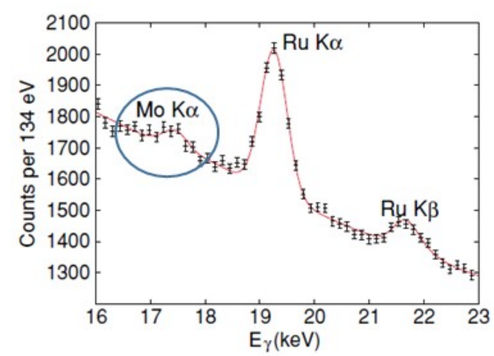
A different application: coupling CRES with radioactive ion trap. Benchmarks for nuclear structure?

- 2ν–2β decays
- single beta decays
- single electron capture decays

In 3 cases one can check all of the above for the same nucleus:
good for understanding overarching issues (role of p-p, p-h correlations, deformation, etc...)

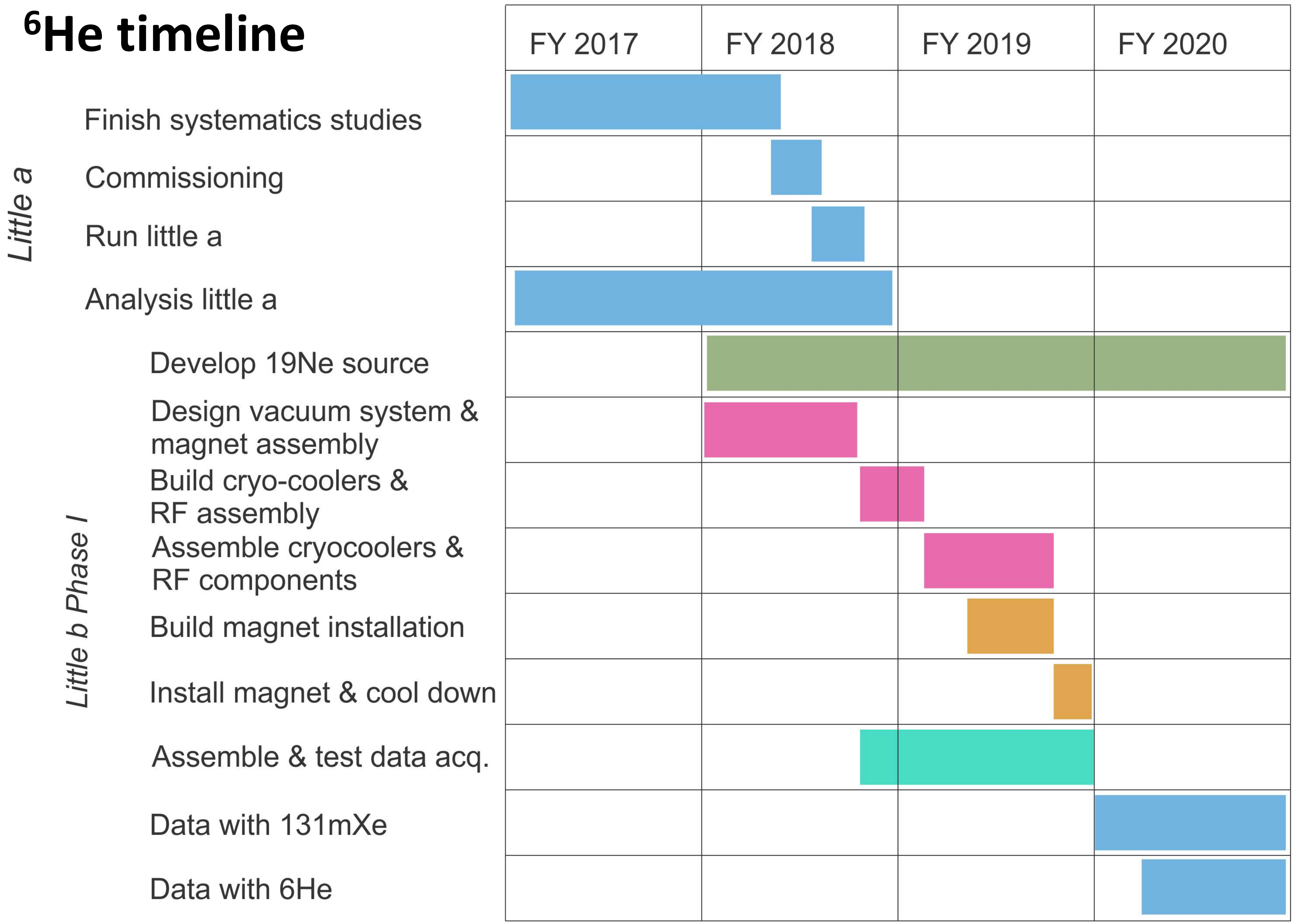
Previous experiments limited by energy resolution. CRES technique would improve it by 100.





S. Sjue, Thesis 2008;
Sjue et al.,
PRC **78,** 064317 (2008)

^{6}He timeline



Conclusion ^{6}He

- Exploring the CRES (Project 8) technique
- Presently working on design
- Start assembling during summer 2018
- Monte-Carlo calculations show technique could eventually reach $b < 10^{-4}$, surpassing any other probe.

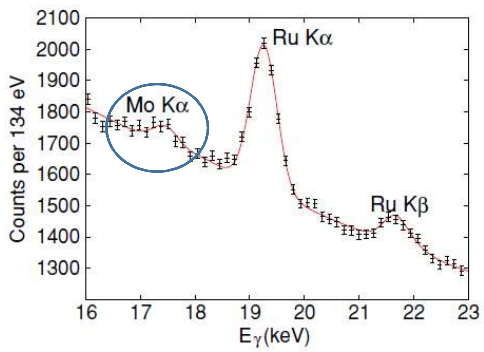
- THEORISTS: Please help! Is theory reliable to extract $b < 10^{-4}$?

- Our developments (coupling of CRES to ion traps) could lead to spectroscopy technique useful for FRIB.

Backup slides

Previous measurements limited by energy resolution:
With Project 8 technique energy resolution could improve by 100!

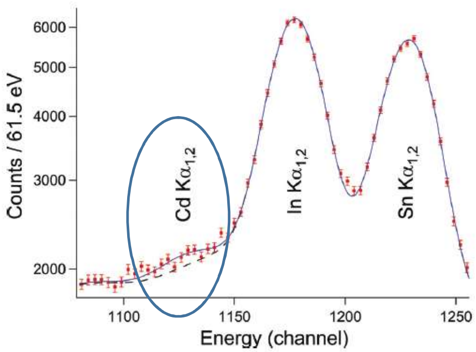
^{100}Tc EC decay:
BR(EC) = $(2.6\pm0.4)\times10^{-5}$



S. Sjue, Thesis 2008;
Sjue et al.,
PRC **78,** 064317 (2008)

^{116}In EC decay:
BR(EC) = $(2.3\pm0.6)\times10^{-4}$

PHYSICAL REVIEW C **87**, 031303(R) (2013)



Wrede et al.,
PRC **87**, 031303(R) (2013)

Both of our results are consistent with complete *ground state dominance*: just using the ground state accounts for the measured 2ν-2β decay rate.

Waveguides: each mode propagates above a certain *cut-off freq*.

$$\left(\nabla^2 + \frac{\omega^2}{c^2}\right)\begin{Bmatrix}\boldsymbol{E}\\ \boldsymbol{B}\end{Bmatrix} = 0$$

$$\left.\begin{matrix}\boldsymbol{E}\\ \boldsymbol{B}\end{matrix}\right\} = \begin{cases}\boldsymbol{E}(x,y)e^{\pm ikz - i\omega t}\\ \boldsymbol{B}(x,y)e^{\pm ikz - i\omega t}\end{cases}$$

$$\left[\nabla_t^2 + \left(\frac{\omega^2}{c^2} - k^2\right)\right]\begin{Bmatrix}\boldsymbol{E}(x,y)\\ \boldsymbol{B}(x,y)\end{Bmatrix} = 0$$

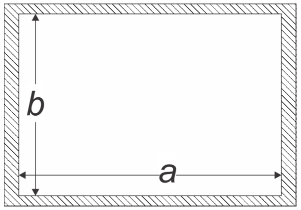
$$\frac{\omega^2}{c^2} - k^2 \equiv \gamma^2$$

$$\boldsymbol{E} = \boldsymbol{E}_z + \boldsymbol{E}_t$$

TM waves: $\boldsymbol{E}_t = \pm \frac{ik}{\gamma^2}\boldsymbol{\nabla}_t\psi$

TE waves: $\boldsymbol{H}_t = \pm \frac{ik}{\gamma^2}\boldsymbol{\nabla}_t\psi$

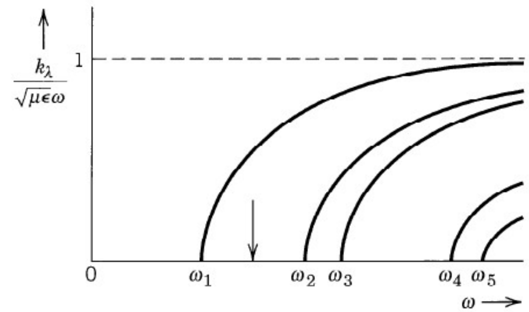
$$(\nabla_t^2 + \gamma^2)\psi = 0$$



$$\psi_{m,n}(x,y) = H_0 \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)$$

$$k = \frac{\sqrt{\omega^2 - \omega_c^2}}{c}$$

There are *cutoff frequencies* for each mode

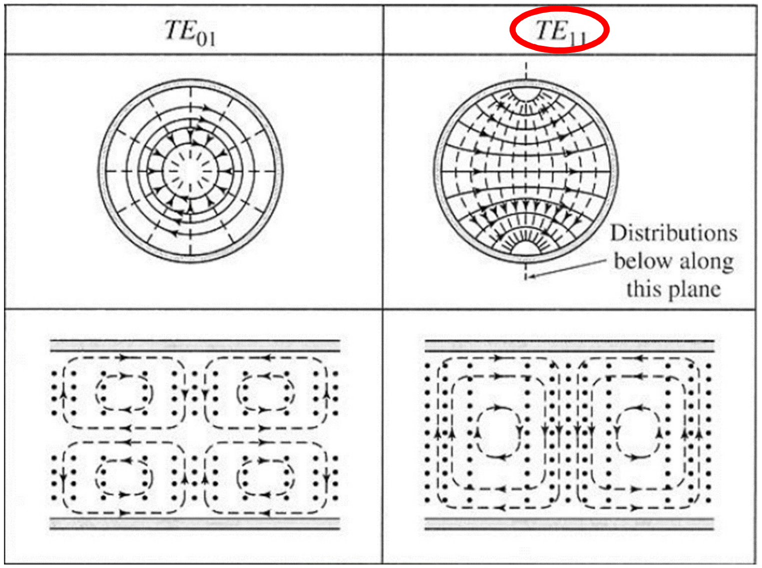


Cutoff frequencies for d=1cm guide. For 0.455" divide by 1.1557.

Active in 18-24 GHz: $TE_{1,1}$, $TM_{0,1}$ (but $TM_{0,1}$ doesn't couple to WR42)

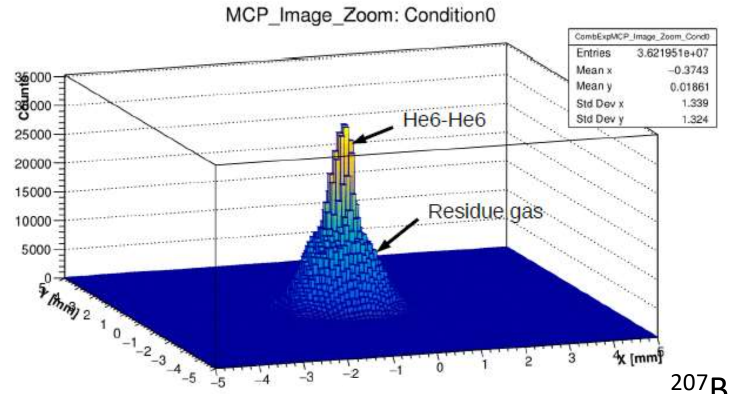
n	$f^{TE}_{n,1}$	$f^{TE}_{n,2}$	$f^{TE}_{n,3}$	$f^{TM}_{n,1}$	$f^{TM}_{n,2}$	$f^{TM}_{n,3}$
0	36.57	67.00	97.15	22.97	52.71	82.64
1	17.58	50.90	81.51	36.59	67.00	97.15
2	29.16	64.03	95.21	49.03	80.38	110.96

Only the TE11 mode transmits



Little a next:

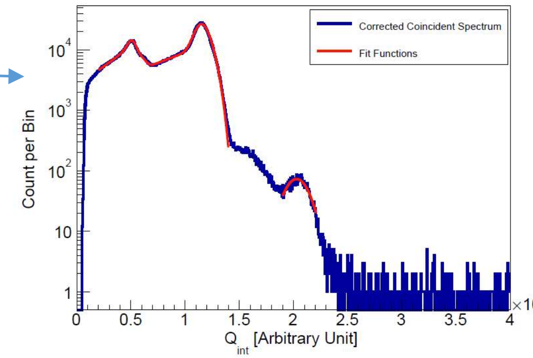
Penning Ions allow unique visualization

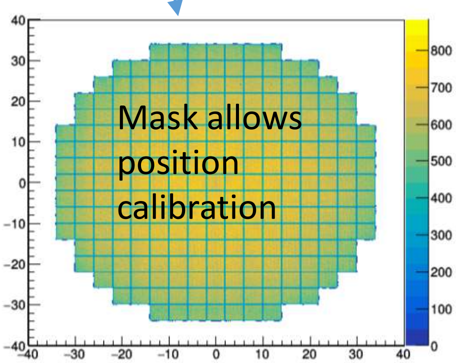


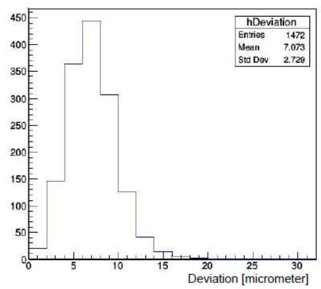
Issues under control

- Stability of MOT dimensions and position
- MCP position accuracy, MCP efficiency
- MWPC position resolution
- Scintillator response, ΔE.
- Timing resolution
- Background effects

^{207}Bi source







After calibration

Variable	$(da/dx)/a$ (Sensitivity)	dx	units	da/a (%)
MOT - MCP Distance	15.00	0.030	mm	0.45
MCP Position Calibration	-5.50	0.010	mm	0.06
MOT Radial Position	0.50	0.030	mm	0.02
MOT Width (Sigma)	-1.70	0.030	mm	0.05
Electric Field Scaling	8.00	0.010	fraction	0.08
Electrode Spacing	8.70	0.030	mm	0.26
Beta Energy Threshold	0.03	2.400	keV	0.08
Timing Resolution	-0.21	0.040	ns	0.01
Scattering*	2.30	0.100	fraction	0.23
Background**	20.00	0.003	fraction	0.06
MCP Efficiency Non-Uniformity*				0.18
Total				0.61

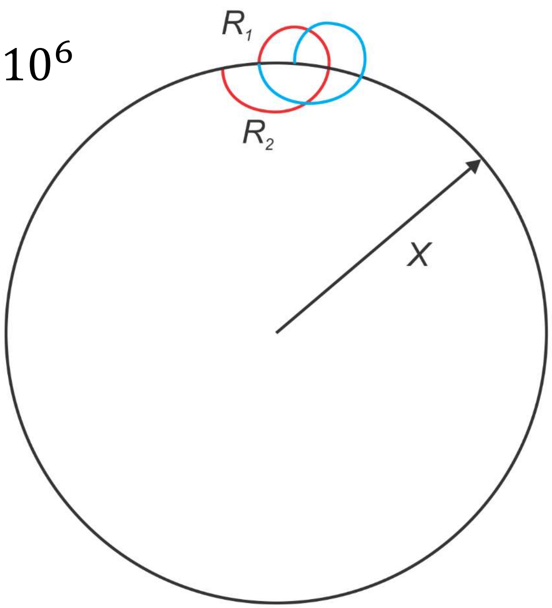
Issues to be solved

- High-voltage noise and stability
- Electric field scaling
- Photo-ion TOF data (^{3}He, ^{4}He, ^{6}He)

Magnetron motion. For harmonic traps no bias (E-dependence)

$$\omega_m = \frac{\omega_z^2}{2\omega_c}$$

$$\frac{\omega_c}{\omega_m} = N \sim 10^6$$



For each cyclotron turn the orbits displaces:

$$\Delta \approx R_1 - R_2 \approx R(1 - B_1/B_2) \approx R\left(\frac{\partial B/\partial r}{B} R\right)$$

Then the radius X of magnetron motion:

$$X \approx \frac{N\Delta}{2\pi} \approx N\frac{R^2}{2\pi}\frac{\partial B/\partial r}{B}$$

Use $\frac{\partial B/\partial r}{B} \sim r\frac{10^{-2}}{cm^2}$ Harmonic trap

$$X \approx N\frac{R^2}{2\pi} X \frac{10^{-2}}{cm^2} \rightarrow N = \frac{2\pi}{10^{-2}R^2} \approx 10^5$$

X cancels: magnetron radius independent on *R* in harmonic trap.