Overview of Nuclear Beta Decay Tests of Fundamental Symmetries

CIPANP—2018

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A more appropriate title:

Chirality properties as a tool to search for New Physics in nuclear beta decay

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 effort and ingenuity to come out of confusing times

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

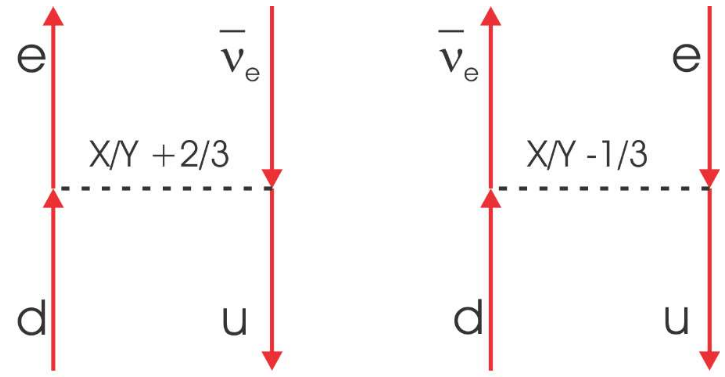
When I came back to the United States, I wanted to know what the situation was with beta decay. I went to Professor Wu's laboratory at Columbia, and she wasn't there, spinning to the left in the beta decay, came out on the right in some cases. Nothing fit anything. When I got back to Caltech, I asked 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!"

Modern context: Chirality-flipping as means of detection of new physics.

Small contribution that could be detected with precision experiments

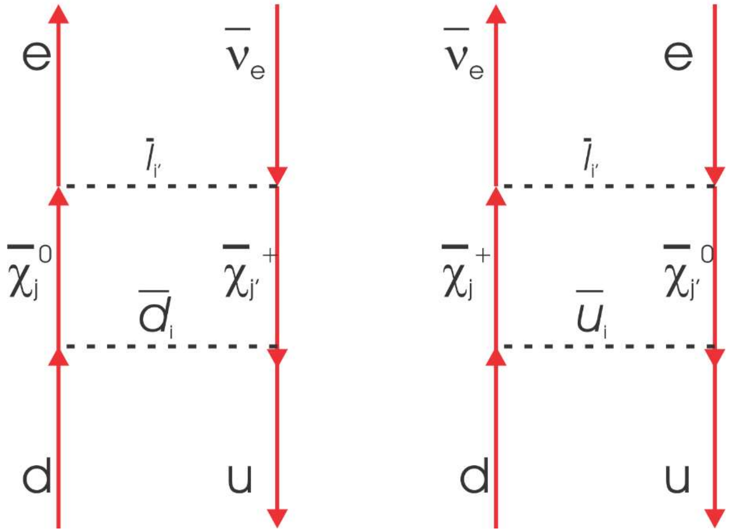


Leptoquarks:
X: scalar; Y: Vector
Predicted by
Grand Unified Theories

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…

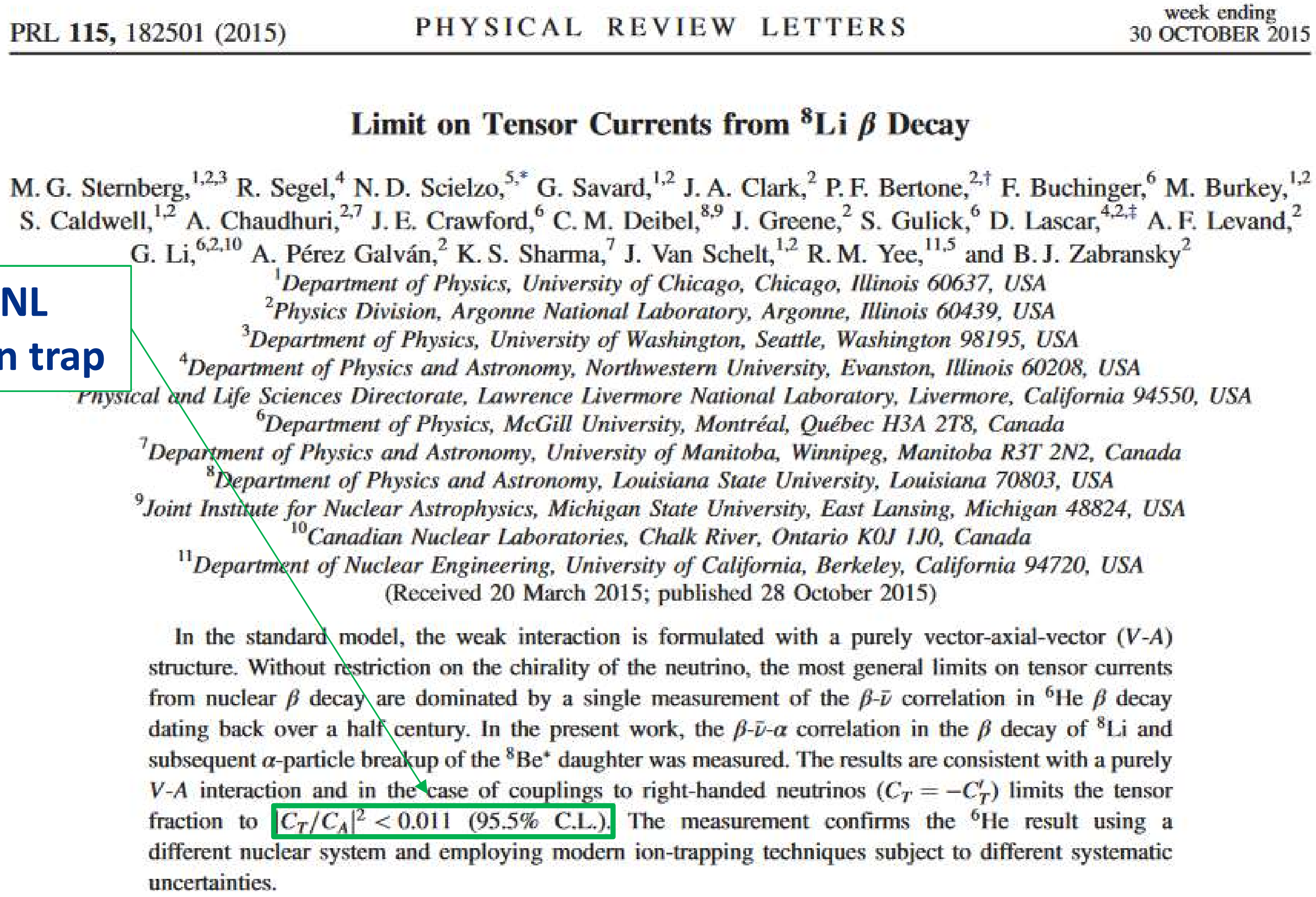
Type of experiments that determined *V-A* structure have been recently improved using ion and atom traps.

$\beta - \nu$ correlation from ^{8}Li

(Sternberg et al., Phys. Rev. Lett. **115**, 182502 (2015))

β asymmetry from polarized ^{37}K

(Fenker et al., Phys. Rev. Lett. **120**, 062502 (2018))



PRL 115, 182501 (2015) PHYSICAL REVIEW LETTERS week ending 30 OCTOBER 2015

Limit on Tensor Currents from ^{8}Li β Decay

M. G. Sternberg,[1,2,3] R. Segel,[4] N. D. Scielzo,[5,*] G. Savard,[1,2] J. A. Clark,[2] P. F. Bertone,[2,†] F. Buchinger,[6] M. Burkey,[1,2]
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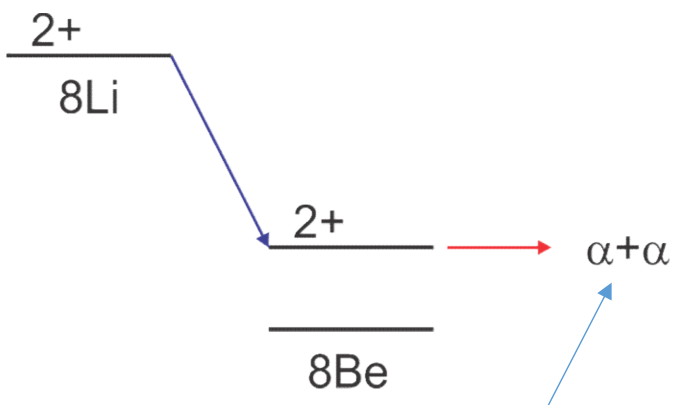
(Received 20 March 2015; published 28 October 2015)

In the standard model, the weak interaction is formulated with a purely vector-axial-vector (V-A) structure. Without restriction on the chirality of the neutrino, the most general limits on tensor currents from nuclear β decay are dominated by a single measurement of the β-$\bar{\nu}$ correlation in ^{6}He β decay dating back over a half century. In the present work, the β-$\bar{\nu}$-α correlation in the β decay of ^{8}Li and subsequent α-particle breakup of the ^{8}Be* daughter was measured. The results are consistent with a purely V-A interaction and in the case of couplings to right-handed neutrinos ($C_T = -C'_T$) limits the tensor fraction to $\boxed{|C_T/C_A|^2 < 0.011 \quad (95.5\% \text{ C.L.})}$. The measurement confirms the ^{6}He result using a different nuclear system and employing modern ion-trapping techniques subject to different systematic uncertainties.

From ANL with ion trap

$\beta-\nu$ correlation from for A=8



The $\beta-\nu$ correlation is deduced from the difference between the α’s kinetic energies

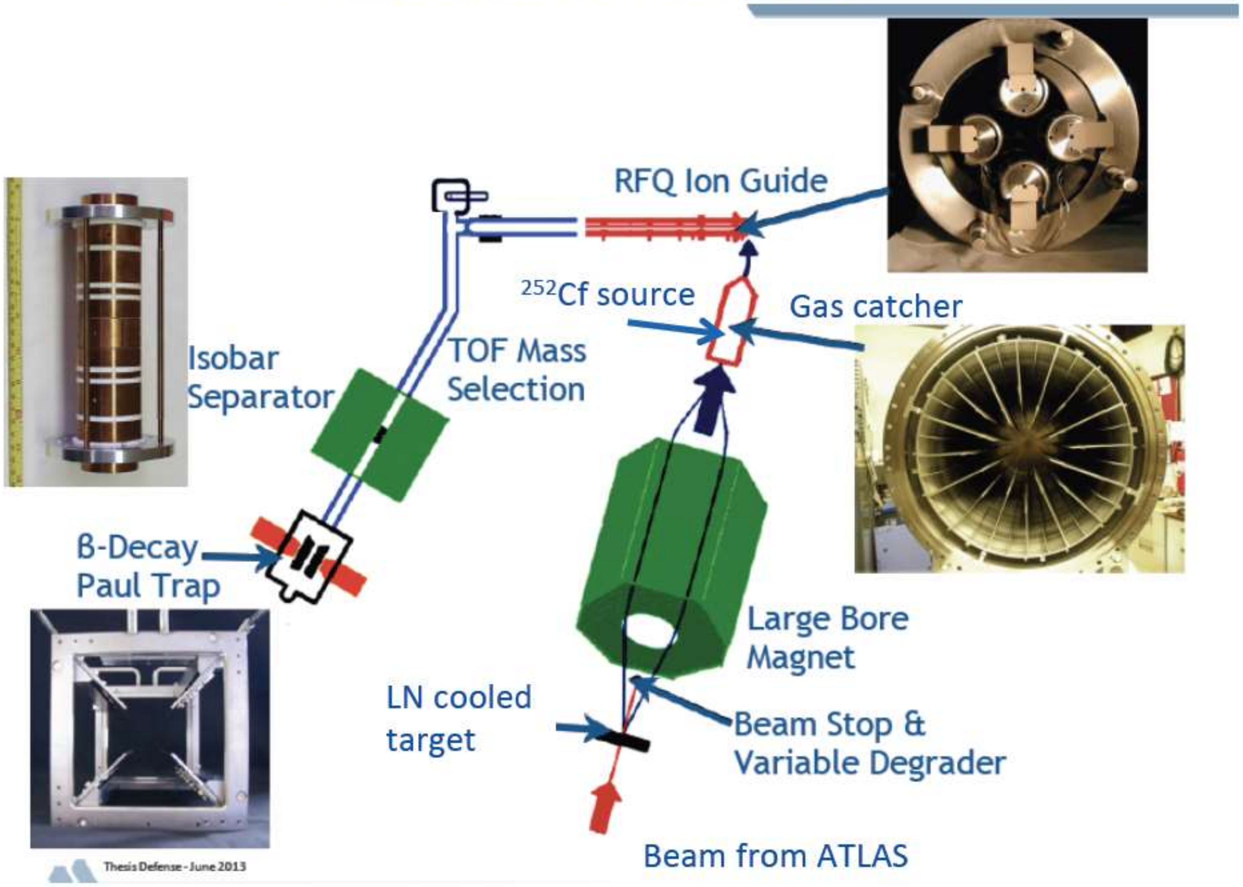
The α’s can’t carry ang. momentum along their path, so only Mf=0:

Mi	Mf	SM Correlation	Clebsch
+2	+2		
	+1		
+1	+2		
	+1		
	0	$1-\cos\theta$	1/2
0	+1		
	0	$1+\cos\theta$	0
	-1		
-1	0	$1-\cos\theta$	1/2
	-1		
	-2		
-2	-1		
	-2		

The non-flip transition does not contribute
$<\{2,0\}\{1,0\}|\{2,0\}>=0$

The effective correlation is then
$1-\frac{p}{E}\cos\theta$ for the standard model
$1+\frac{p}{E}\cos\theta$ for purely tensor

Ongoing improvements in production and delivery of ^{8}Li/^{8}B to BPT



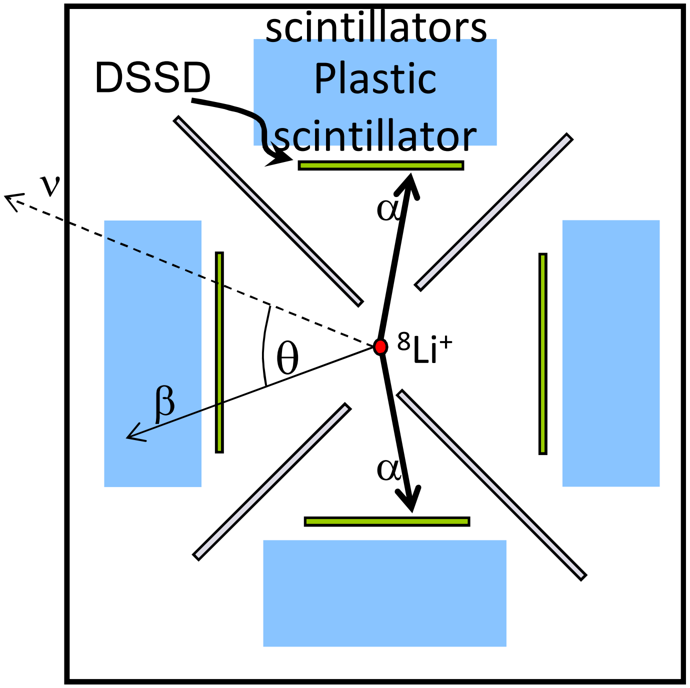
- **Gas target geometry better matched to reactions**
- **New gas catcher optimized to handle lighter masses and space-charge issues**

Upgrades resulted in 10× increase in ion delivery to BPT

→ measure ^{8}B to study decay correlations + recoil-order terms

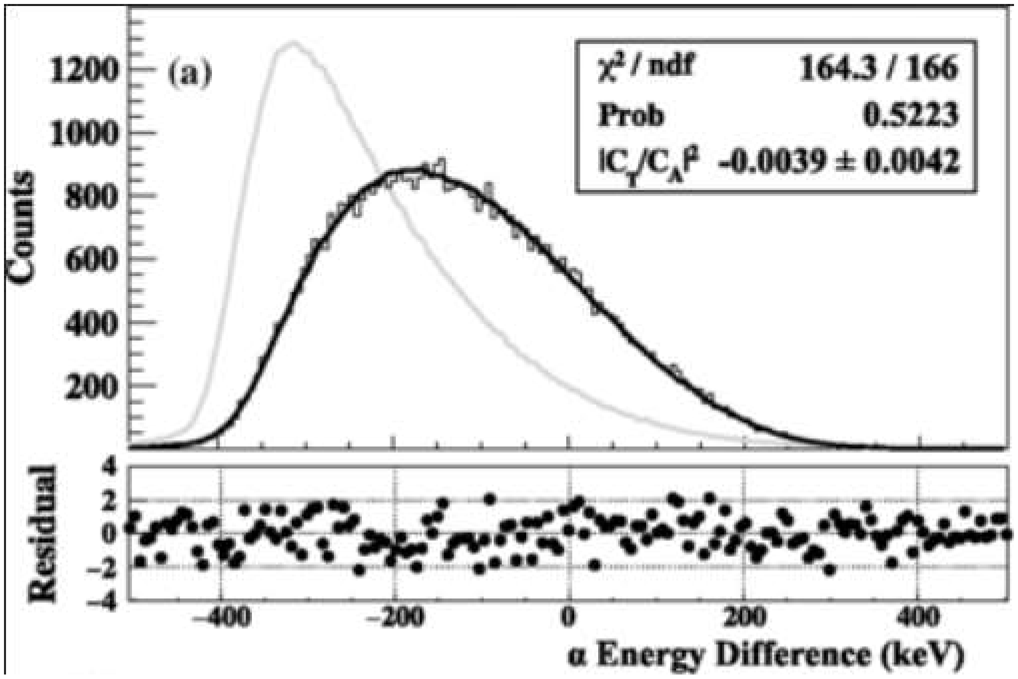
→ revisit ^{8}Li with 10× higher statistics

trapped ions surrounded by DSSDs and plastic scintillators



Ion trap used to hold *A=8* nuclei.
α's and β's measured with streep Si detectors.
Hit locations allow tracking back to the emission point.

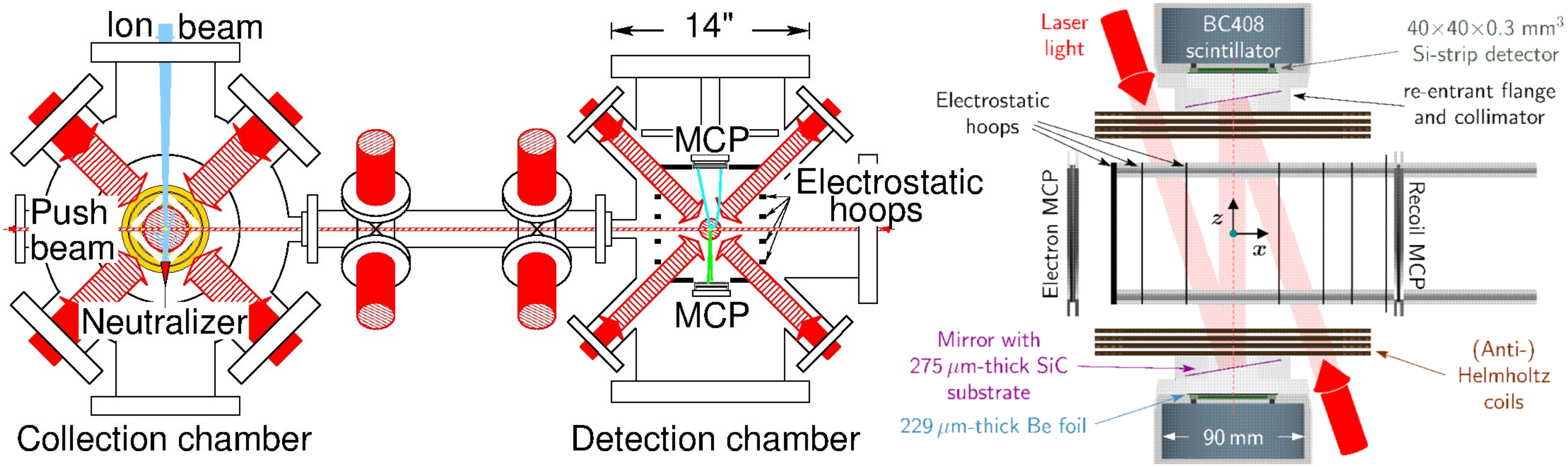
$$\boxed{|C_T/C_A|^2 < 0.011}$$



Spectrum from events with β and α particles detected on the top and bottom detector. (a) Energy difference along with the fit to the simulated spectrum and the normalized residual. The gray curve shows the expected spectra for a pure T interaction.

β-decay correlations with laser-cooled ^{37}K

- Measuring angular correlation parameters to $< 0.1\%$ are, obviously, very challenging
- The TRIUMF Neutral Atom Trap (TRINAT) collaboration has pioneered the use of MOTs with optical pumping to provide a source of short-lived ^{37}K which is very cold, localized, *and* highly polarized

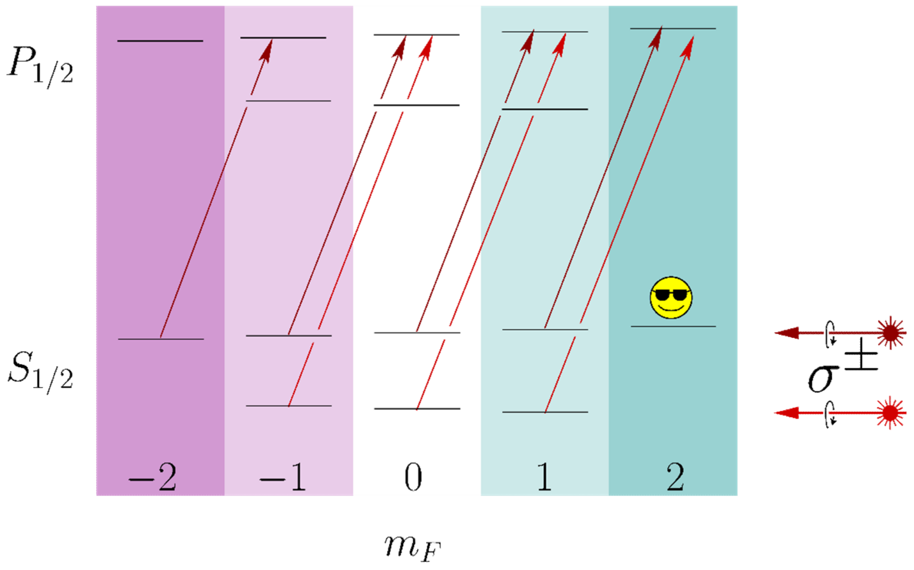


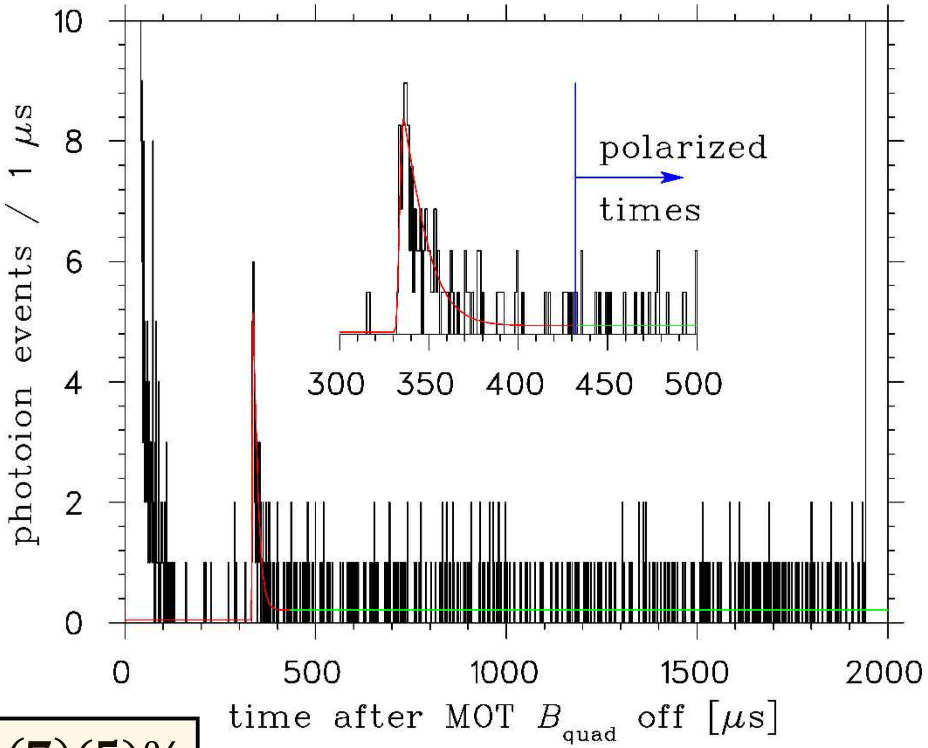
From D. Melconian, J. Behr.

Polarization via optical pumping

Fenker, New J. Phys. **18**, 073028 (2016)

- Fast, efficient, easy to reverse spin
- Photoions ⇒ clean fluorescence spectrum to monitor the polarization non-destructively





$$\Rightarrow \boxed{\langle P_{\mathbf{nucl}}\rangle = \mathbf{99.13(7)(5)\%}}$$

stat syst

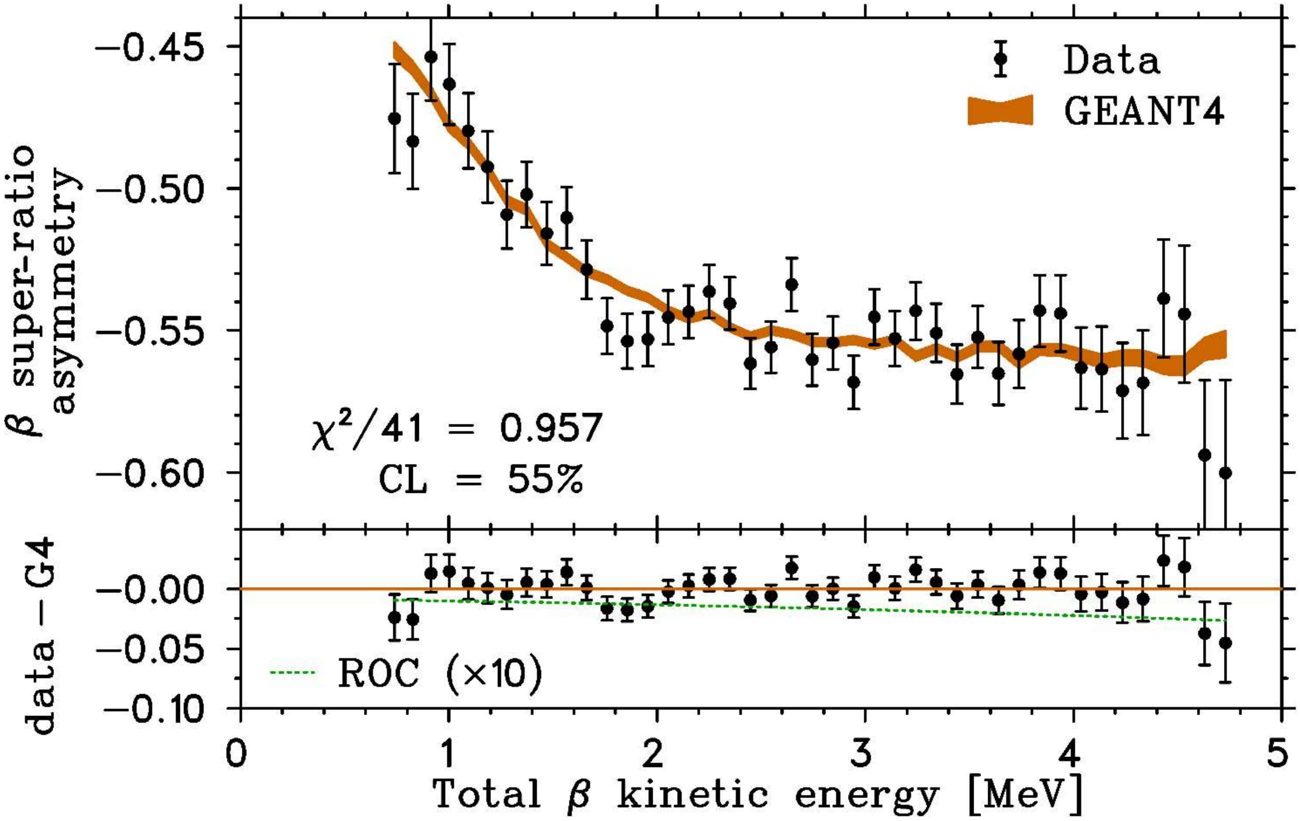
- 0.1% precision better than needed for A_β measurement

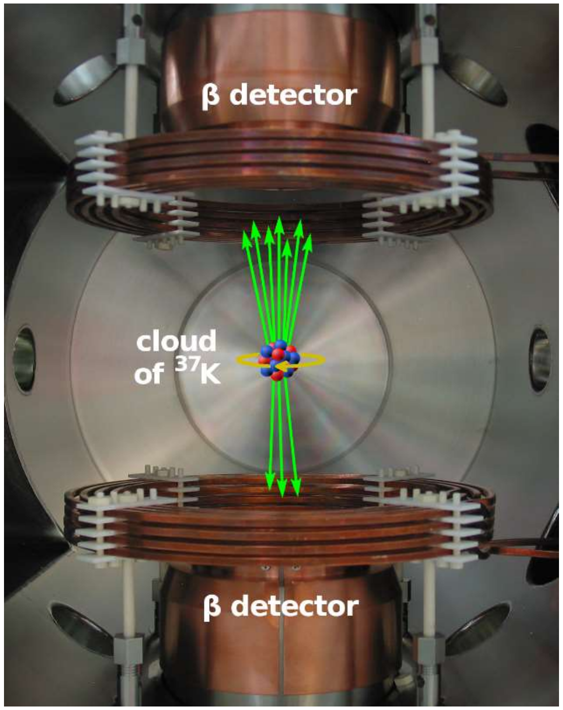
From D. Melconian, J. Behr.

The β asymmetry

- Use the super-ratio technique to minimize systematics:

$$A_{\text{obs}}(E_e) = \frac{1-S(E_e)}{1+S(E_e)}, \text{ where } S(E_e) \equiv \sqrt{\frac{r_1^-(E_e)r_2^+(E_e)}{r_1^+(E_e)r_2^-(E_e)}}$$





From D. Melconian, J. Behr.

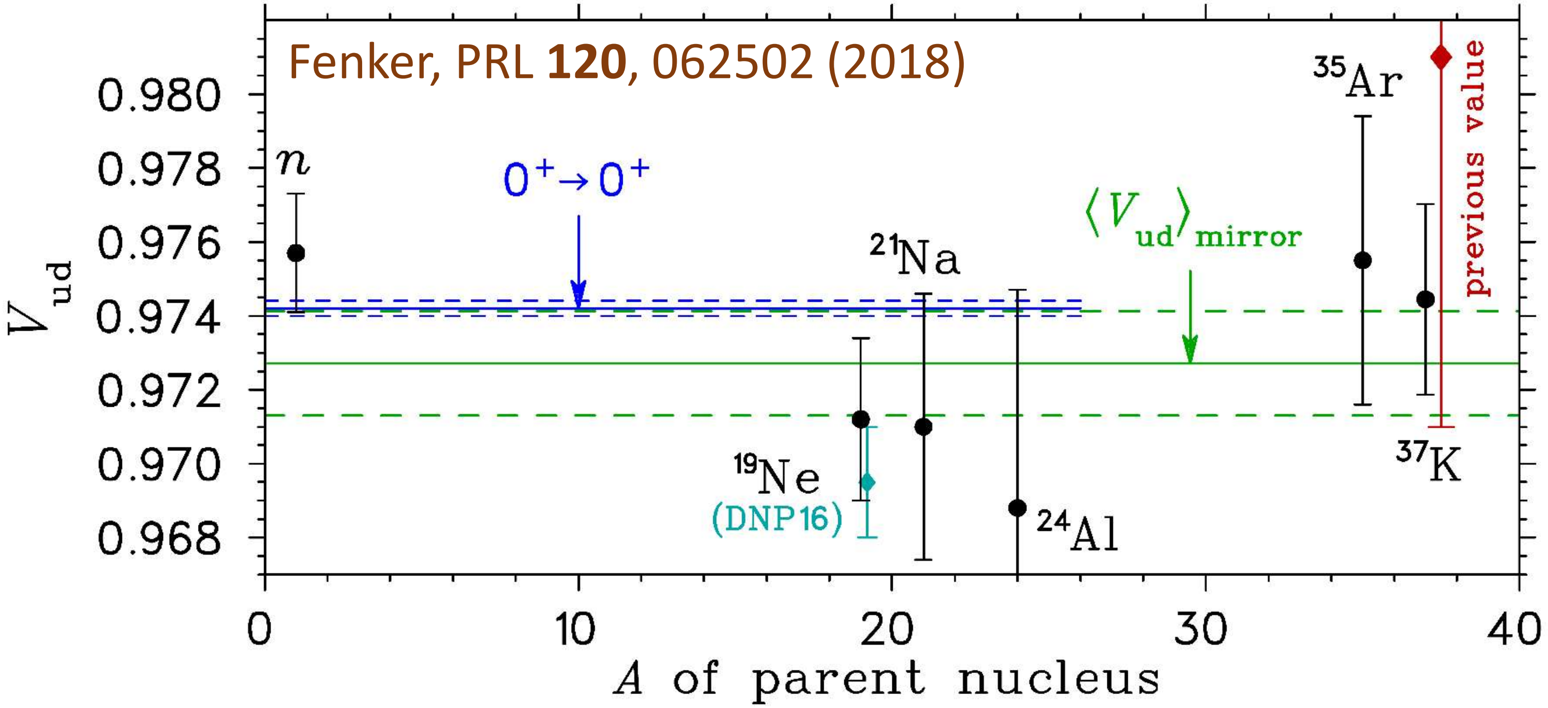
Result of the asymmetry measurement

$$A_\beta^{\text{obs}} = -0.5707(13)_{\text{syst}}(13)_{\text{stat}}(5)_{\text{pol}}$$

versus

$$A_\beta^{\text{SM}} = -0.5706(7)$$

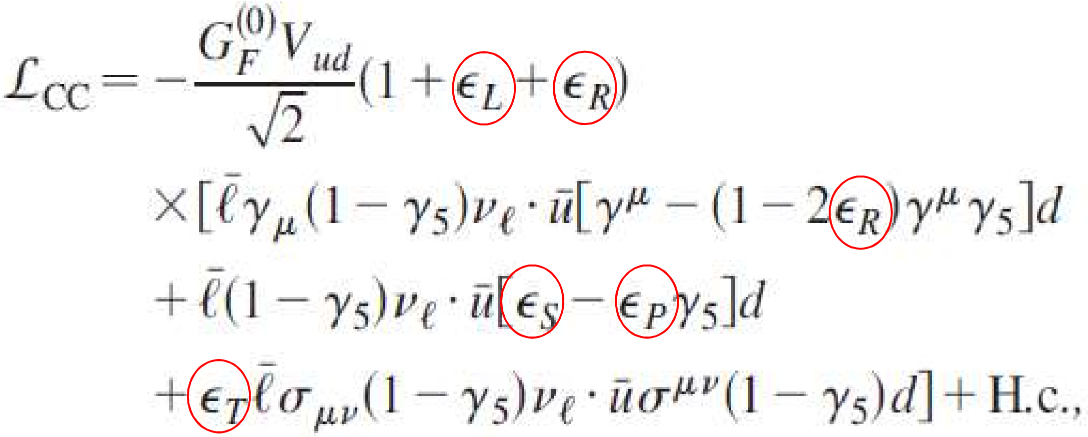
- 0.3% measurement in terms of, e.g., V_{ud}:



- Next: analyze energy-dependence (Fierz, 2nd class), then improve precision (stats; bkgd, scattering) to reach 0.1%

V. Cirigliano et al. have established a connection between hep and beta-decay observables via EFT.

Assuming only left-handed ν's:

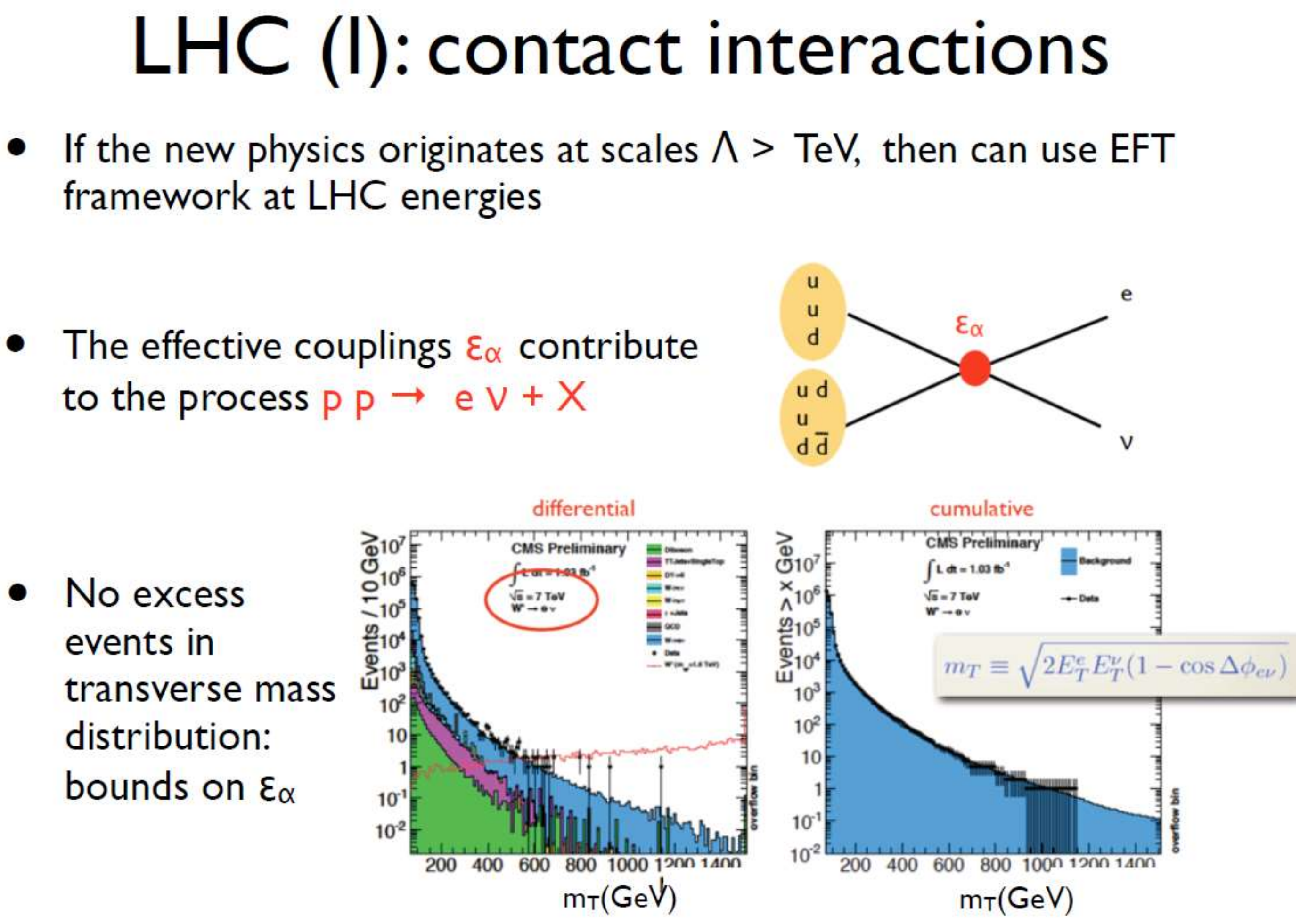


$$
\begin{aligned}
\mathcal{L}_{\mathrm{CC}} = & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}}(1+\boxed{\epsilon_L}+\boxed{\epsilon_R}) \\
& \times[\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}[\gamma^\mu-(1-2\boxed{\epsilon_R})\gamma^\mu\gamma_5]d \\
& +\bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}[\boxed{\epsilon_S}-\boxed{\epsilon_P}\gamma_5]d \\
& +\boxed{\epsilon_T}\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d]+\mathrm{H.c.},
\end{aligned}
$$

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

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 $\Lambda >$ 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

$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1 - \cos\Delta\phi_{e\nu})}$$

Nuclear beta decay: beyond *V-A*?

We still like the parametrization of Lee and Yang.

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

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

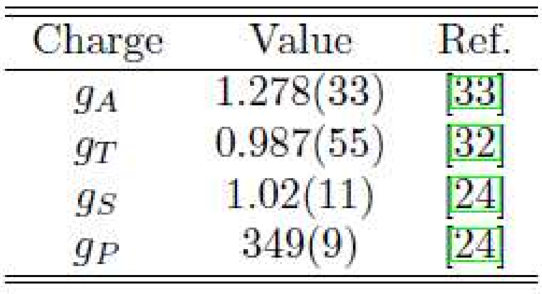
$$O_i = \begin{cases} 1 & i = S \\ \sigma^{\mu\nu} & i = T \end{cases}$$

Nuclear beta decay: beyond *V-A*?

We still like the parametrization of Lee and Yang.

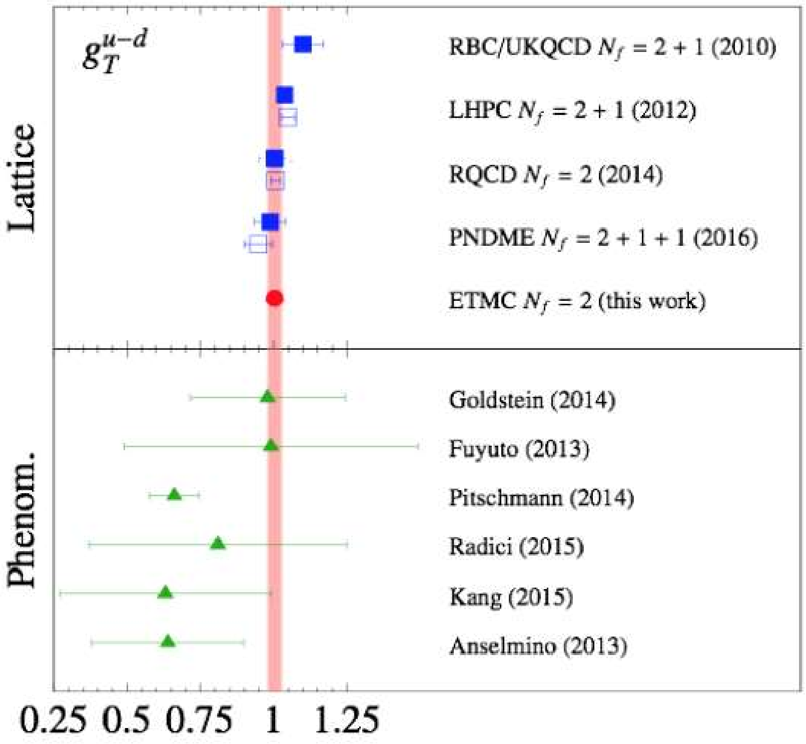
But much progress in lattice evaluation of the nucleon form factors, so we can translate from one to the other:

$$
\begin{aligned}
C_i &= \frac{G_F}{\sqrt{2}} V_{ud} \bar{C}_i \\
\bar{C}_V &= g_V(1 + \epsilon_L + \epsilon_R) \\
\bar{C}_A &= -g_A(1 + \epsilon_L - \epsilon_R) \\
\bar{C}_S &= g_S \epsilon_S \\
\bar{C}_T &= 4 g_T \epsilon_T,
\end{aligned}
$$



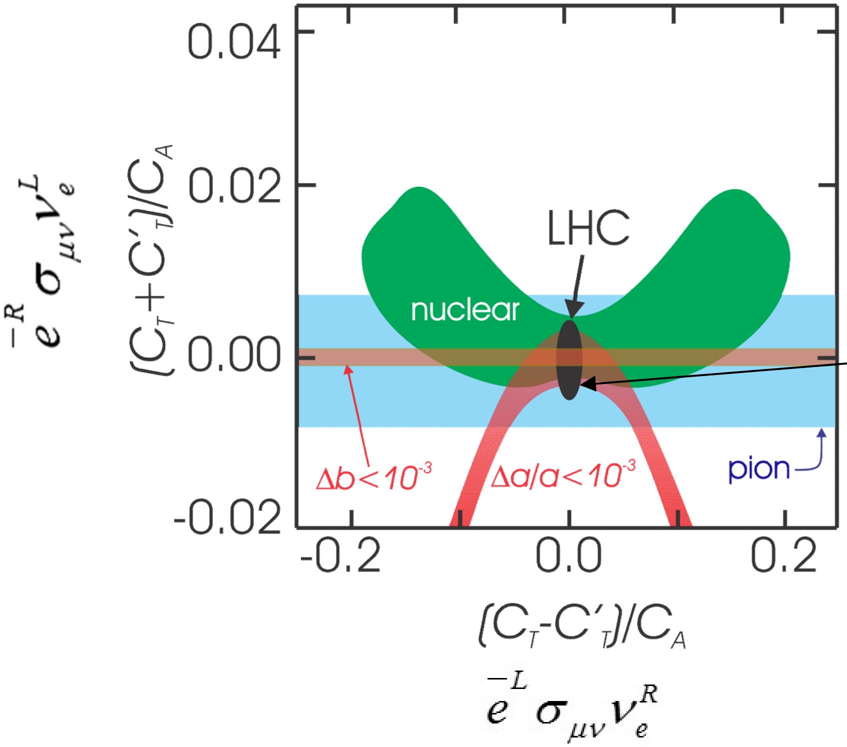
Charge	Value	Ref.
g_A	1.278(33)	[33]
g_T	0.987(55)	[32]
g_S	1.02(11)	[24]
g_P	349(9)	[24]

From Gonzalez-Alonso et al. arXiv:1803.08732v1



Precision beta decay versus others:
Can “precision” compete with “energy”?

Bhattacharya 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?

Nuclear beta decay: Fierz interference and other correlations

Example for axial decay of unpolarized parent

Standard Model

chirality flipping

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

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

Decay rate:

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

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

β-ν correlation

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

Fierz interference

Recommendation from Vincenzo Cirigliano et al.

Do searches for Fierz interference with high sensitivity:

$$b < 10^{-3}$$

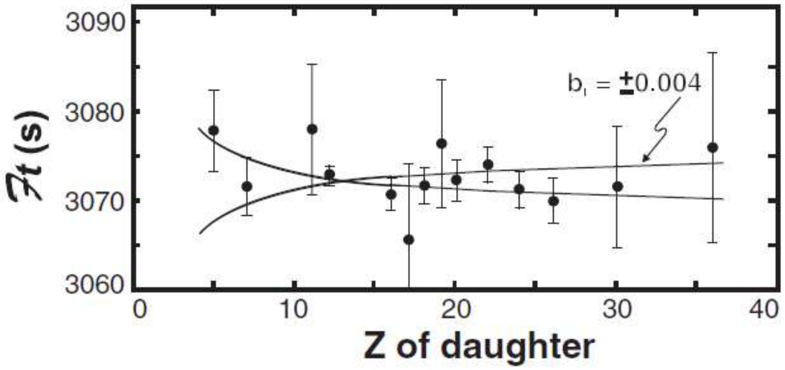
$$b_F \approx \pm\frac{(C_S + C_S')}{C_V}$$

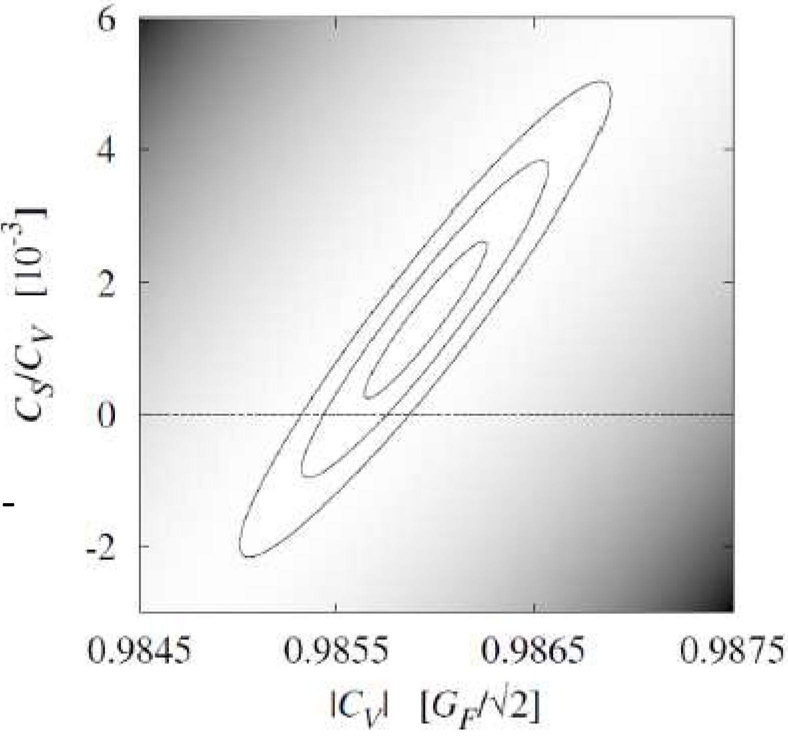
$$b_{GT} \approx \pm(C_T + C_T')/C_A$$

Best limits on scalar currents from $0^+ \rightarrow 0^+$ ft values

Hardy and Towner
PHYSICAL REVIEW C **91**, 025501 (2015)

$$dw = dw_0 \left[1 + a \frac{\overrightarrow{p_e}}{E_e} \cdot \frac{\overrightarrow{p_\nu}}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$





Gonzalez-Alonso, Naviliat-Cuncic, Severijns
hep-ph 1803.08732

Beta spectrometry to directly search for Fierz

- Scintillators
- Magnetic spectrometers
- *RxB* drift (PERC)
- Si detectors (Nab)
- Implantation into scintillators (MSU)
- Gas chamber tracking (next talk: Rozpedzik)
- Cyclotron Radiation

PHYSICAL REVIEW C **96**, 042501(R) (2017)

First direct constraints on Fierz interference in free-neutron β decay

UCNA collaboration

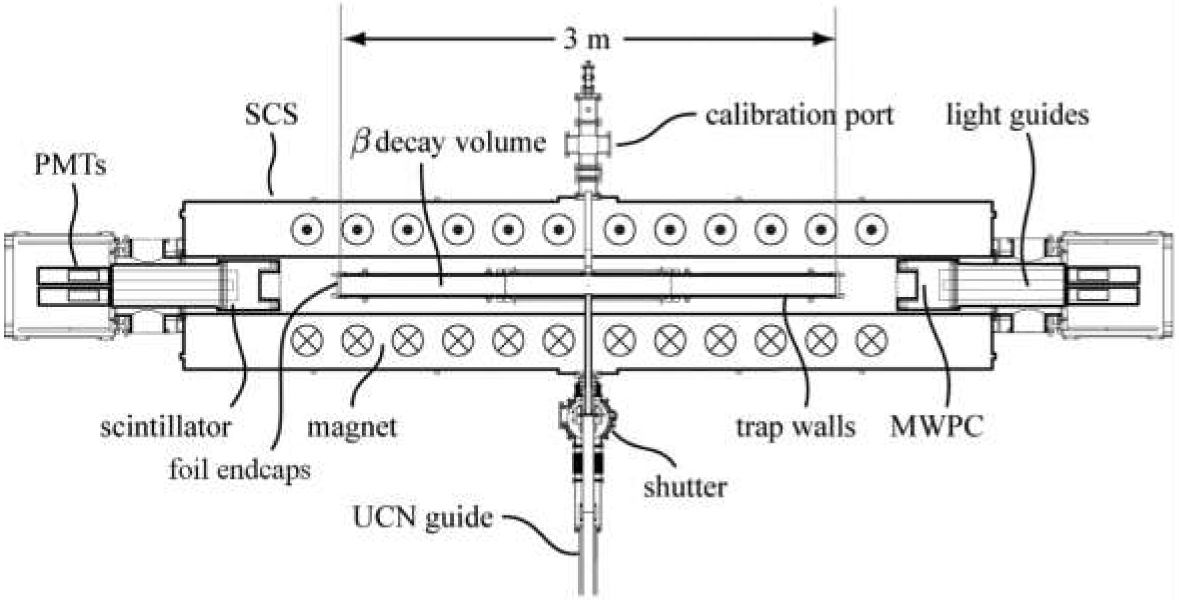
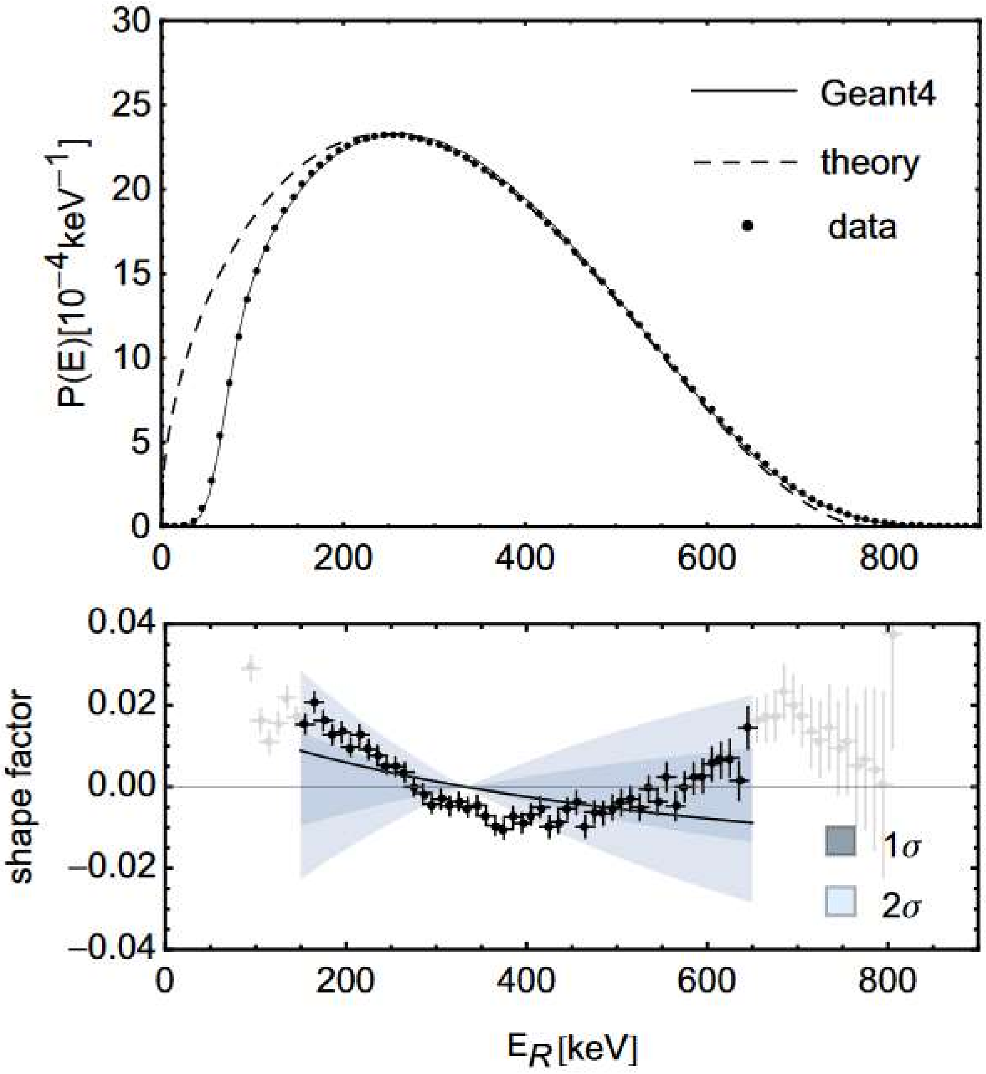


FIG. 1. Schematic diagram of the UCNA spectrometer.



UCNA collaboration

$$b_n = 0.067 \pm 0.005_{\text{stat}}{}^{+0.090}_{-0.061}{}_{\text{sys}}$$

~8 % accuracy over ~1 MeV

Magnetic spectrometer produced at Madison

L. D. Knutson et al.
Rev. Sci. Instr. **82**, 073302 (2011)

^{14}O branch
P. A. Voytas et al.
Phys. Rev. C **92**, 065502 (2015)

^{14}O spectrum
E. A. George et al.
Phys. Rev. C **90**, 065501 (2014)

^{66}Ga spectrum
G. W. Severin et al.
Phys. Rev. C **89**, 057302 (2014)

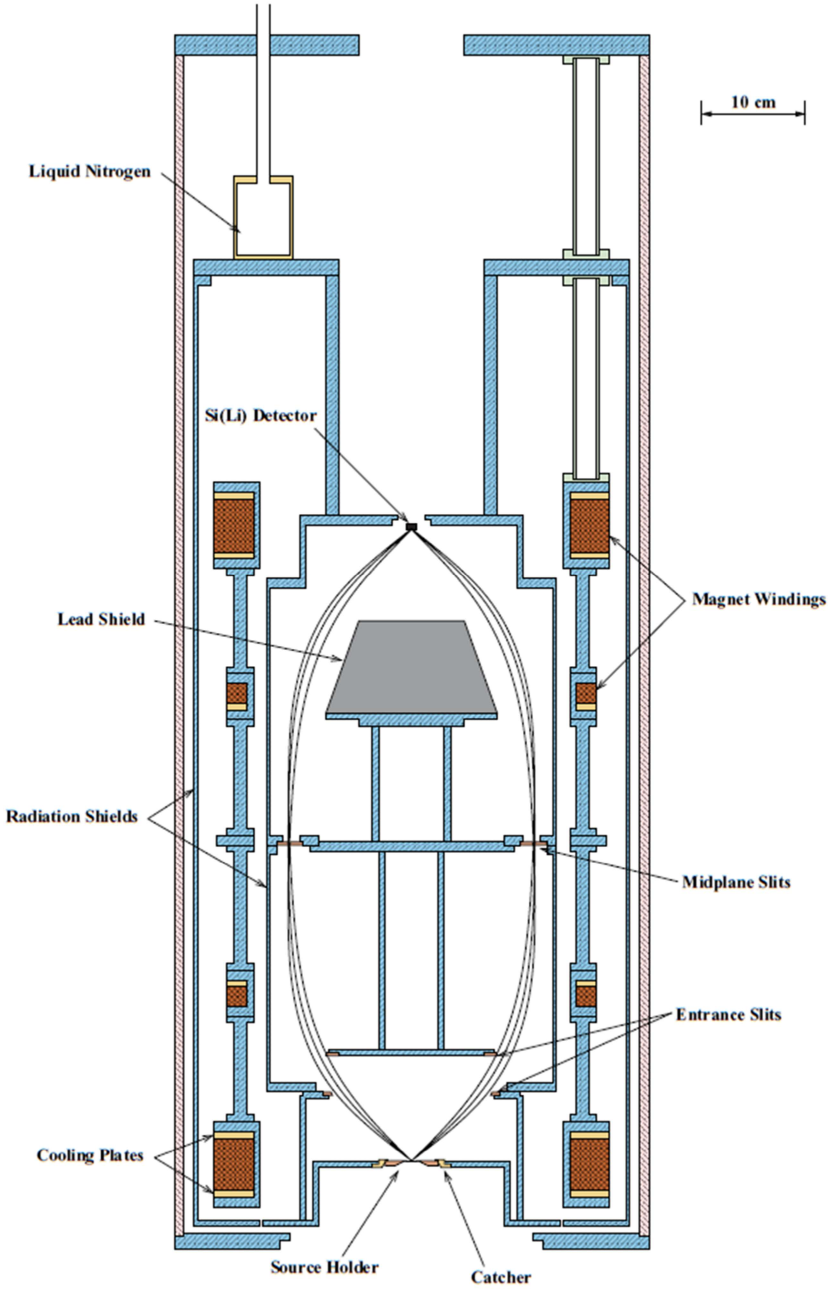


FIG. 1. (Color online) Schematic diagram of the superconducting beta spectrometer.

Magnetic spectrometer produced at Madison

^{14}O spectrum
E. A. George et al.
Phys. Rev. C **90**, 065501 (2014)

^{66}Ga spectrum
G. W. Severin et al.
Phys. Rev. C **89**, 057302 (2014)

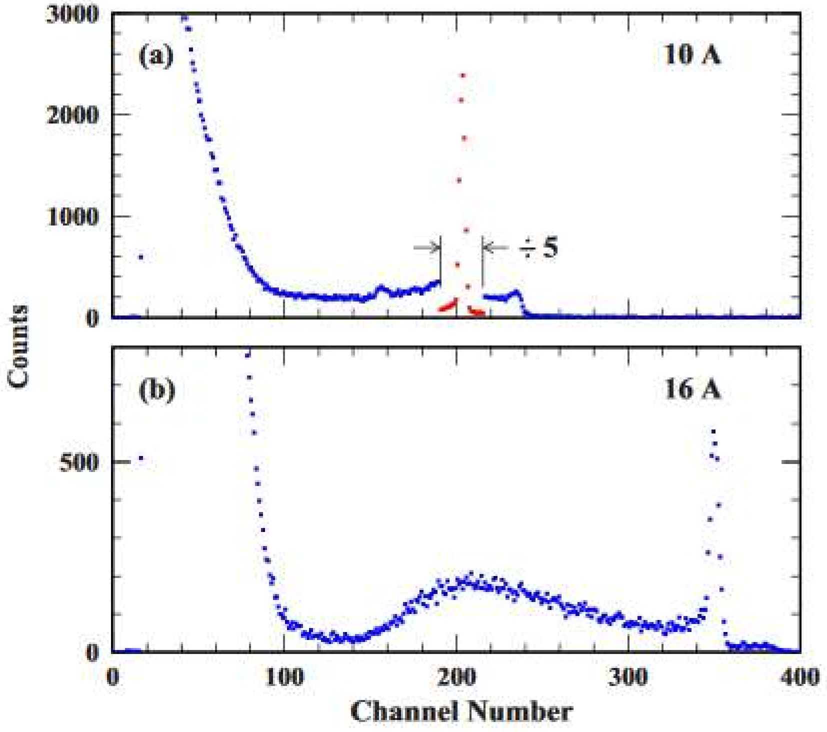


FIG. 6. (Color online) Accumulated Si(Li) spectra for all data taken at two spectrometer currents. Panel (a) shows the 10 A data which correspond to about 2.9 × 10^{10} decays, while the 16 A data in panel (b) correspond to 3.1 × 10^{10} decays.

~1% accuracy over few MeV’s

Neutron decay:

RXB spectrometer in combination with
PERC at TU Wien, Vienna

X. Wang, G.Konrad, H.Abele
NIM A **701**, 254 (2013)

PERC: *Proton and Electron Radiation Channel*
Magnetic system to transport large numbers of betas and protons from neutron beta decay for spectroscopy.

Beta drift in *y* direction \prop p_b

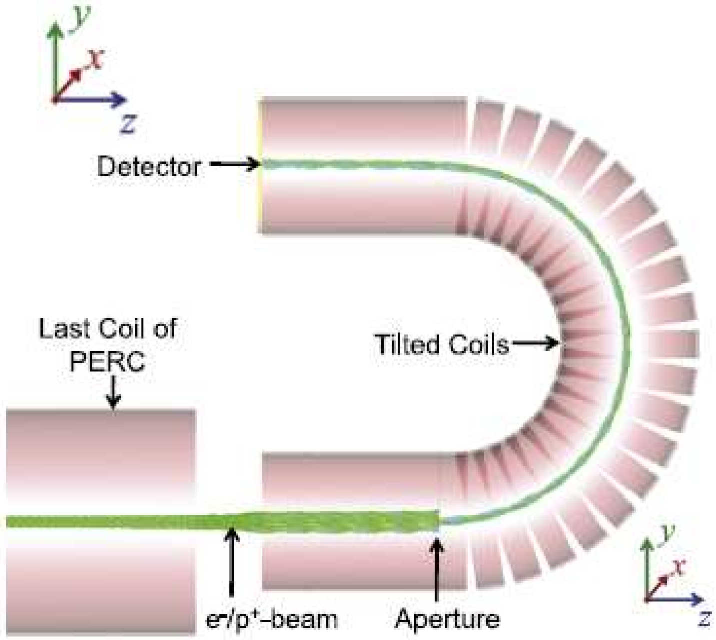
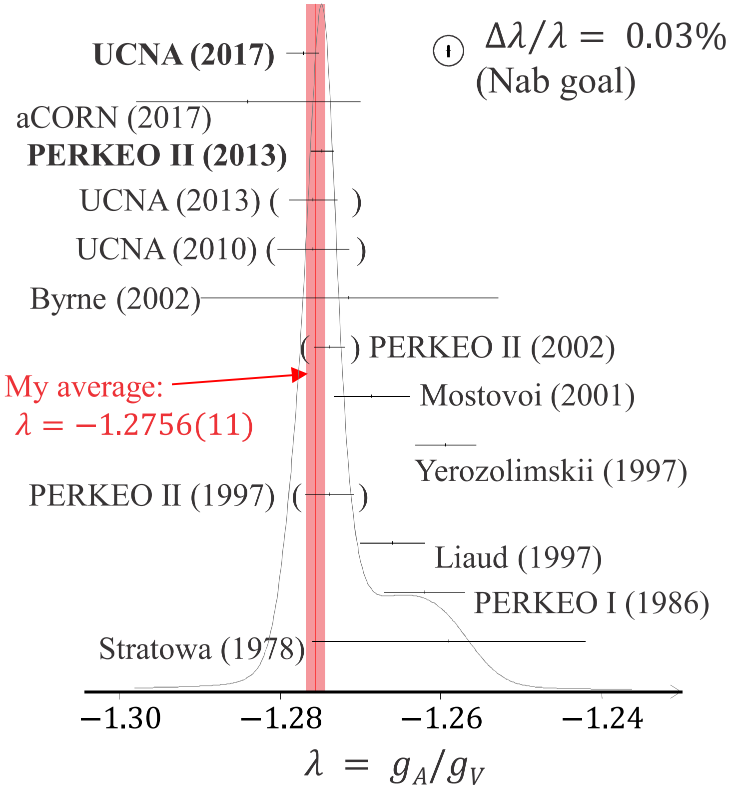


Fig. 5. The design of the $\mathbf{R} \times \mathbf{B}$ drift spectrometer at the end of PERC, and the simulated trajectories of e^-/p^+.

The measurement of neutron beta decay observables with the Nab spectrometer

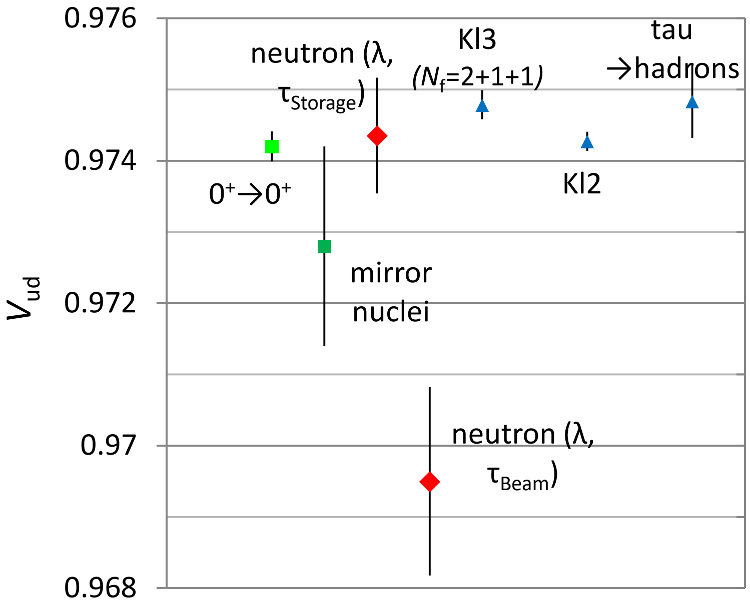
The **physics goal** of Nab is:

- Determination of $\lambda = g_A/g_V$, the ratio of the standard model coupling constants in semileptonic weak interactions
- Test of the unitarity of the Cabbibo-Kobayashi-Maskawa matrix
- Search for novel interactions that manifest themselves as scalar and tensor interactions at low energies.



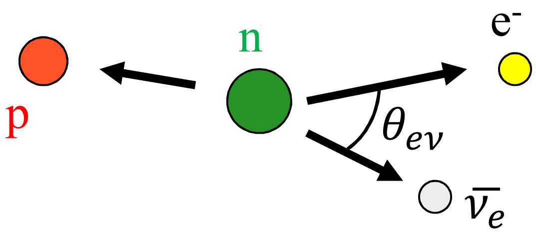
① $\Delta\lambda/\lambda = 0.03\%$ (Nab goal)

My average: $\lambda = -1.2756(11)$



For neutron data to be competitive, want:
$\Delta\tau_n/\tau_n \sim 0.3$ s (and resolve discrepancy)
$\Delta\lambda/\lambda \sim 0.03\%$

Idea of Nab @ SNS



$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$

Kinematics in Infinite Nuclear Mass Approximation:

- Energy Conservation:

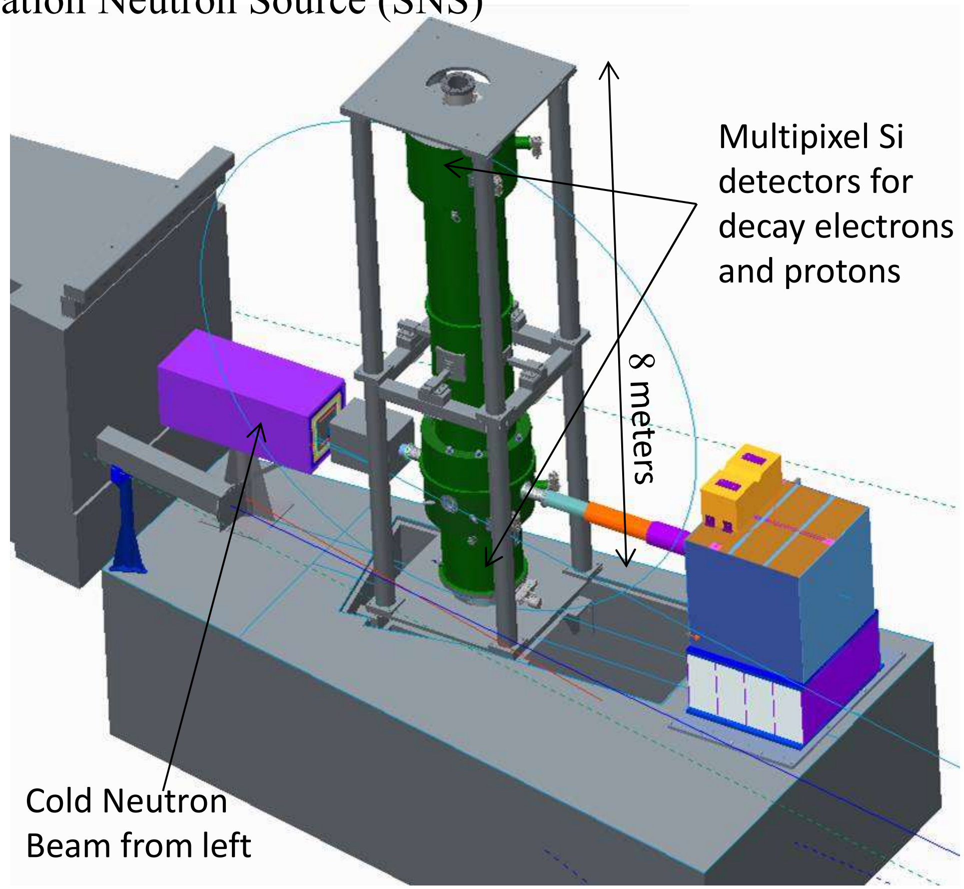
$$E_\nu = E_{e,max} - E_e$$

- Momentum Conservation:

$$p_p^2 = p_e^2 + p_\nu^2 + 2p_e p_\nu \cos\theta_{e\nu}$$

(p_p is inferred from proton time-of-flight)

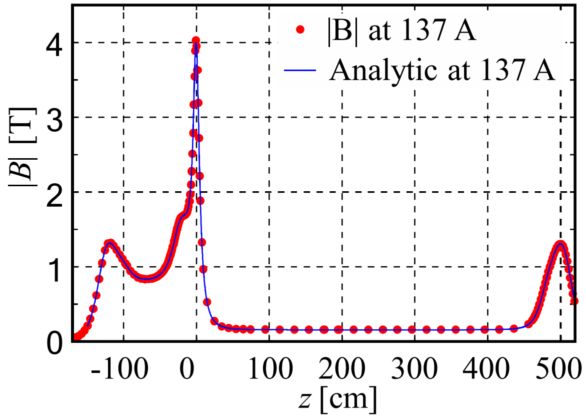
Nab @ Fundamental Neutron Physics Beamline (FNPB) @ Spallation Neutron Source (SNS)



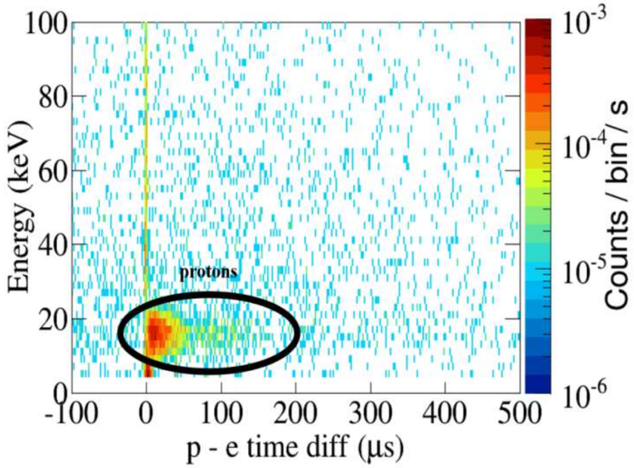
General Idea: J.D. Bowman, Journ. Res. NIST 110, 40 (2005)
Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
Asymmetric configuration: S. Baeßler et al., J. Phys. G 41, 114003 (2014)

Status of Nab

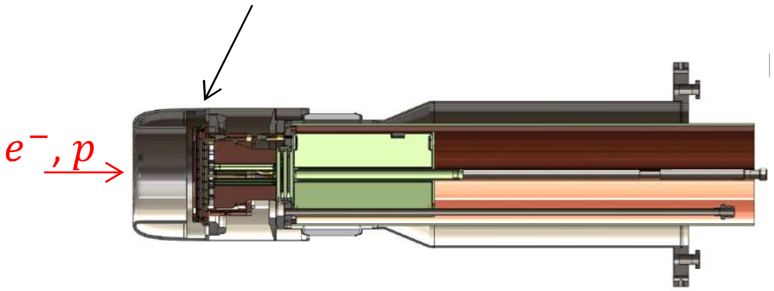
After long delays, the custom-built spectrometer **magnet** has been **tested successfully** at the manufacturer and is now at beamline.



Detector prototype testing in UCNB: Shown are decay electrons and protons from UCN decay.

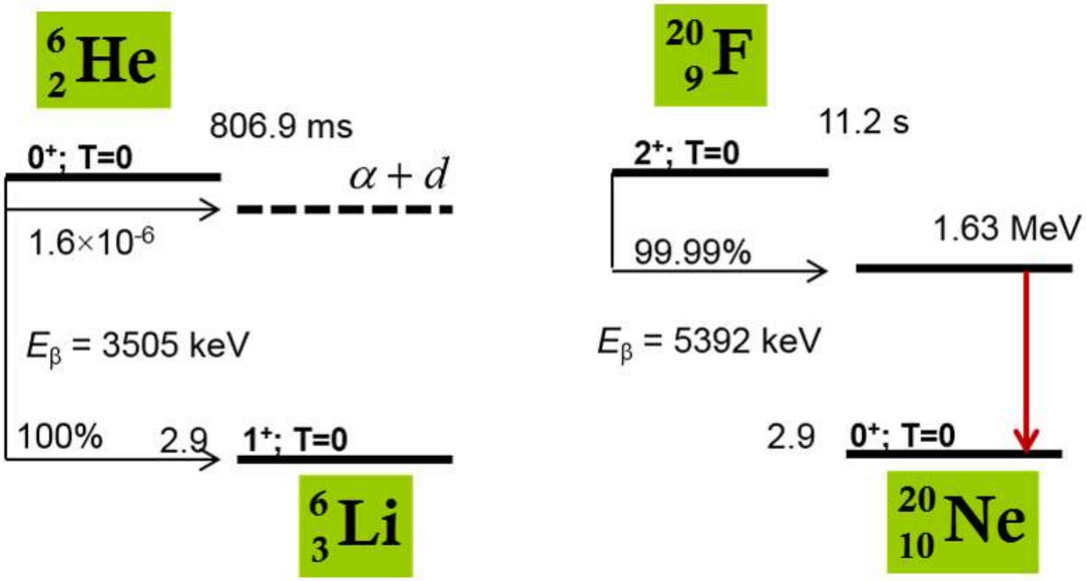


Silicon detector in mount



Commissioning and data taking is expected to start in late 2018.

Selection of Sensitive Transitions to b_{GT}

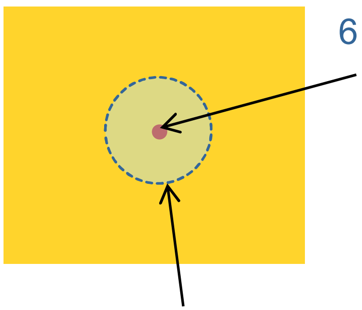


M. Gonzalez-Alonso and O. N.-C
Phys. Rev. C **94** (2016) 035503

- Effects of *induced weak currents* are well under control and serve as sensitivity test of the experimental technique.

- Implement a calorimetric technique using a radioactive beam, which eliminates the effect of electron backscattering on detectors.

Active detector

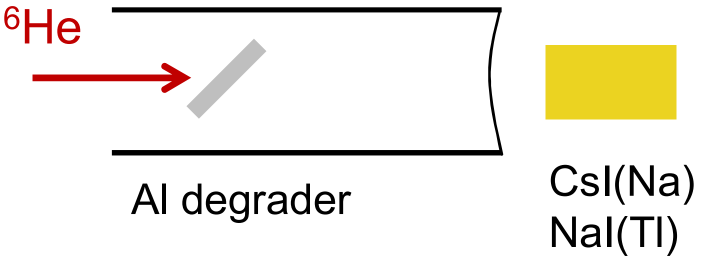


^{6}He source

Range of β particles

Measurement with ^{6}He

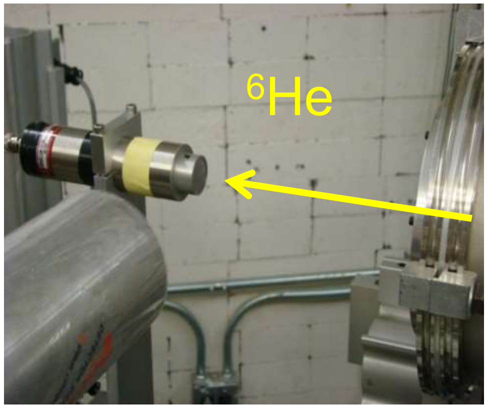
^{6}He beam: 46 MeV/nucleon after degrader



^{6}He

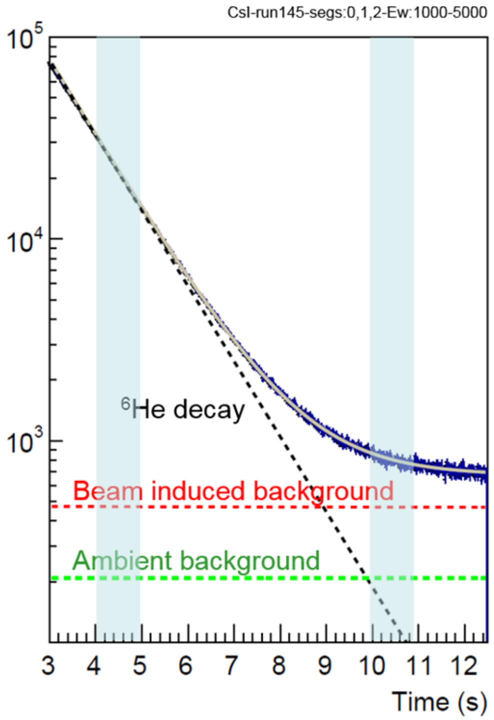
Al degrader

CsI(Na)
NaI(Tl)

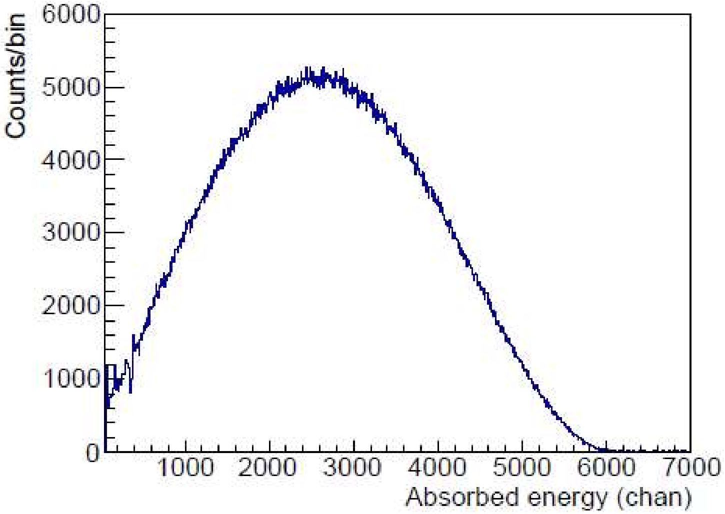


Detectors:

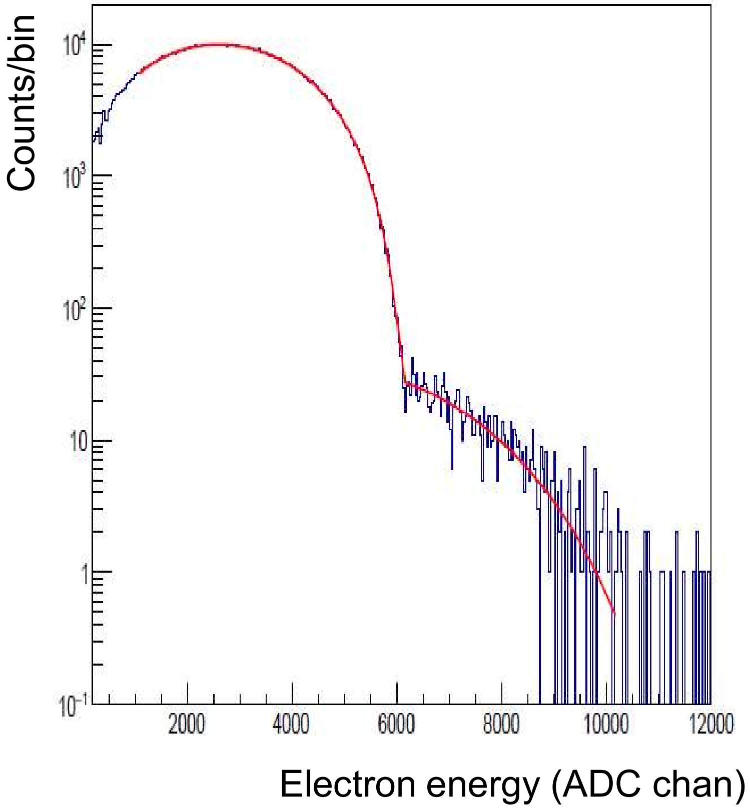
- CsI(Na) (2"×2"×5")
- NaI(Tl) (Ø3"×3")
- (Ø1"×1") CsI(Na)
- (Ø1"×1") NaI(Tl)



Background subtracted spectrum



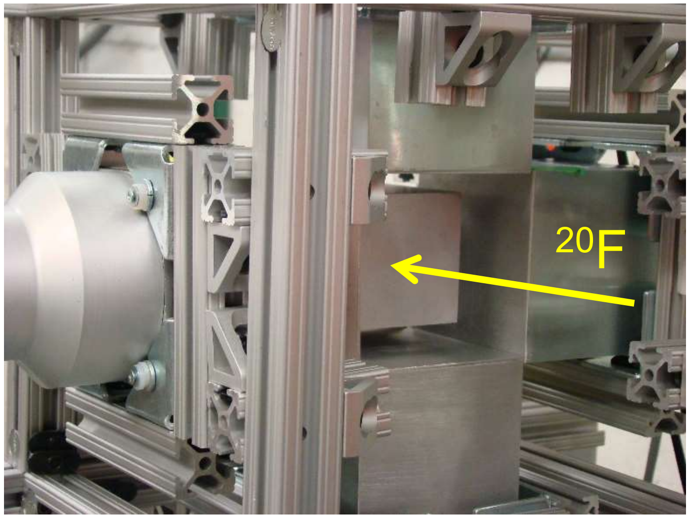
Data analysis and status (^{6}He)



- Analysis of spectra by a Monte-Carlo fit.
- Systematic effects associated with difference in Geant-4 for the description of Bremsstrahlung escape has been studied in detail: X. Huyan et al., NIMA **879** (2018) 134
- Calibration and non-linearity effects have been studied by Monte-Carlo: X. Huyan et al., Acta Phys. Pol. B **49** (2018) 249
- The “classical” radiative correction of the β particle energy requires special consideration for a calorimetric technique: X. Huyan et al., in preparation

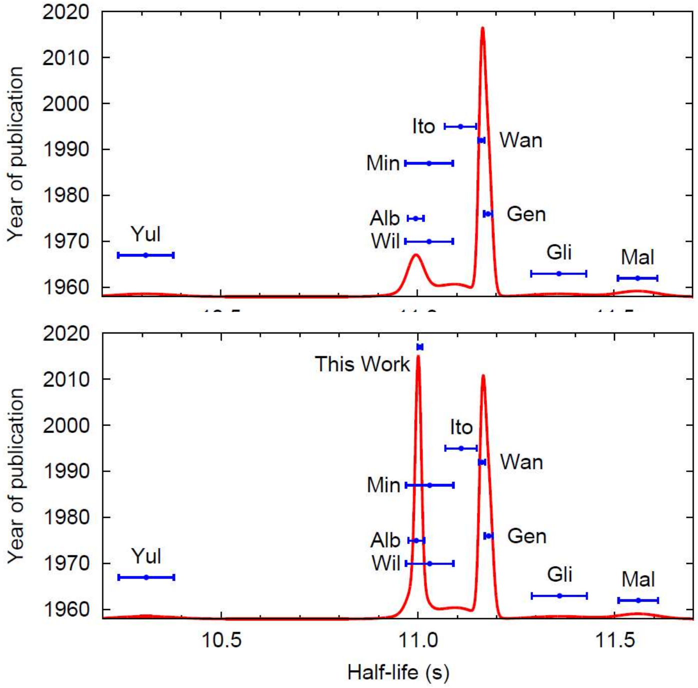
- For each of the two large sets of collected data, the experiment has reached a statistical precision of:
    - 6% on the Weak Magnetism form factor
    - 2.6×10^{-3} on the Fierz term

Measurement with ^{20}F



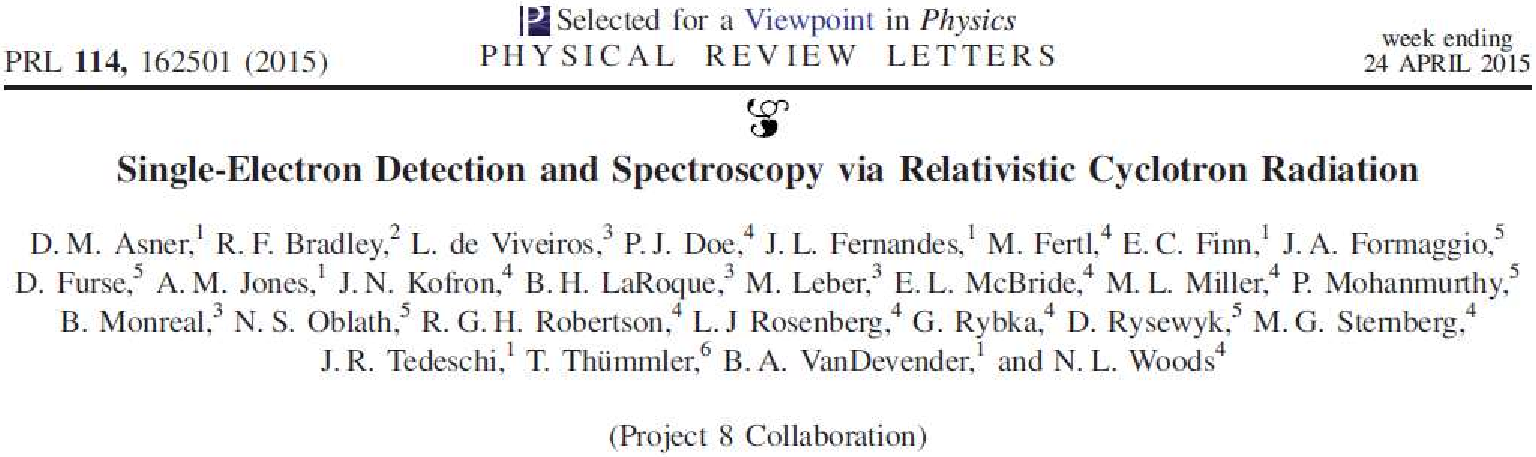
- ^{20}F beam: 132 MeV/nucleon before implantation
- Detectors: (2”x2”x4”) CsI(Na) for implantation and β detection; 4 (3”x3”x3”) CsI(Na) for γ ray.
- Data analysis proceeds similarly to ^{6}He. The Monte-Carlo of summing effects and the cuts on spectra are more complicated due to the γ ray.

- During the data analysis, we have reported a new value of the ^{20}F half-life.
- The value is at variance by 17 standard deviations from the literature value and adds new tension to the current data set.
- M. Huges et al., [arxiv:1805.05800] accepted for publication in PRC.



O. Naviliat-Cuncic: naviliat@nscl.msu.edu

New idea: CRES technique



Selected for a Viewpoint in *Physics*

PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

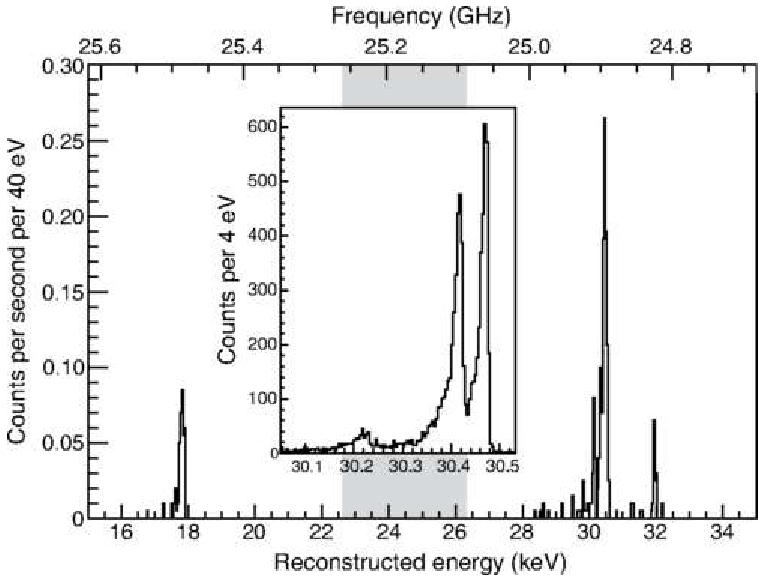
Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

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 ?

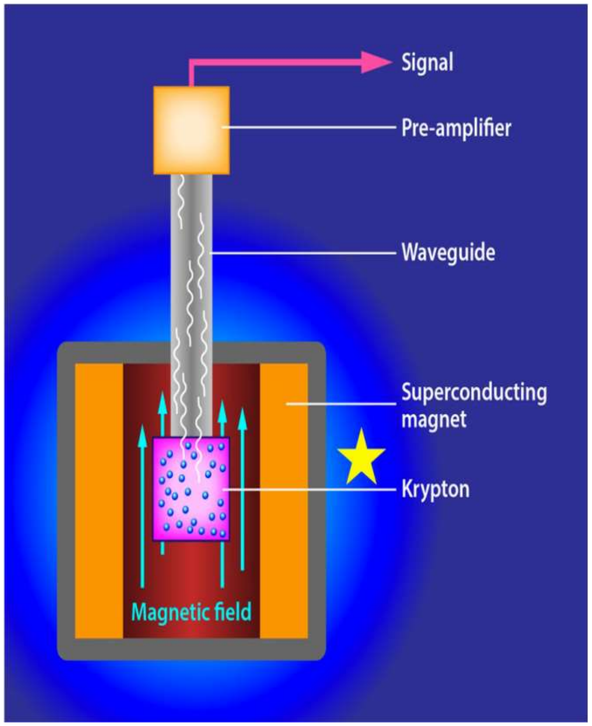


New idea: CRES technique

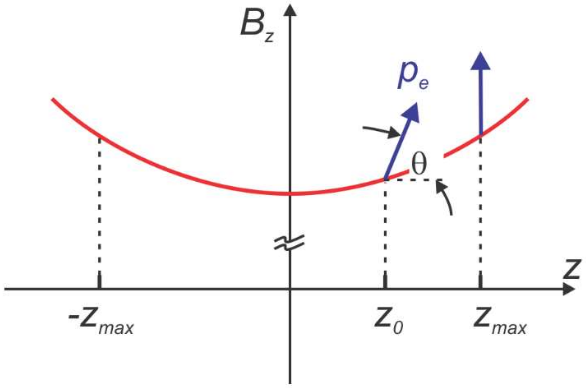
Project 8 in a nutshell

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 additional coils to set up a *magnetic trap*:



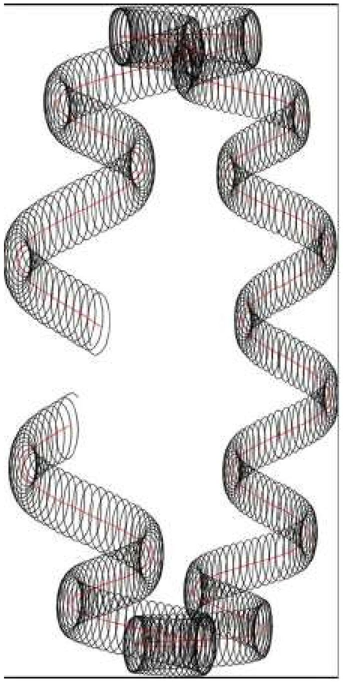
Longitudinal comp. of momentum decreases as *B* increases up to return point, z_{max}. Axial oscillations with ω_z.

New idea: CRES technique

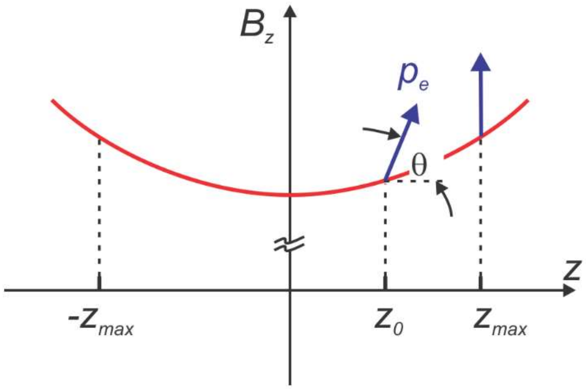
Some details

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

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



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*:



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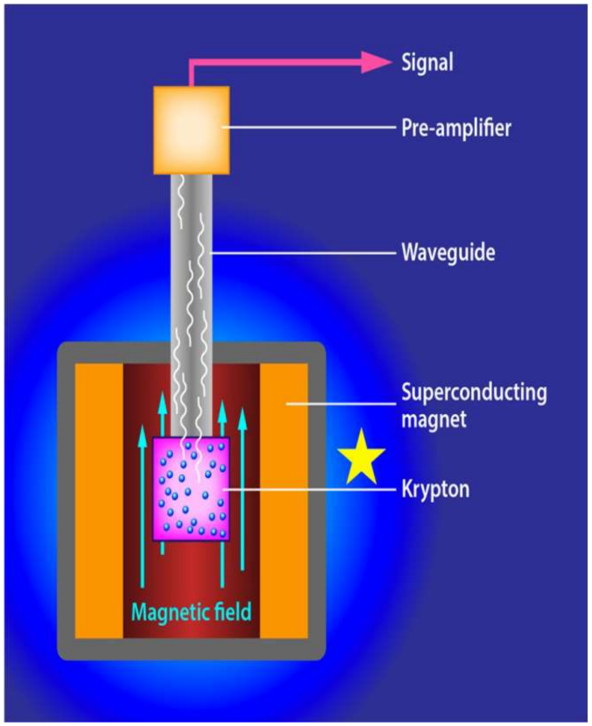
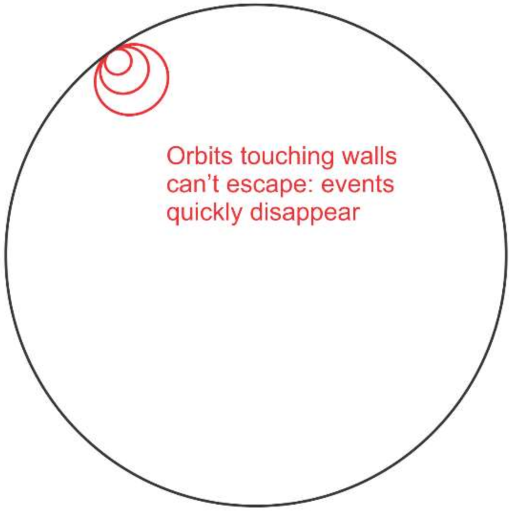


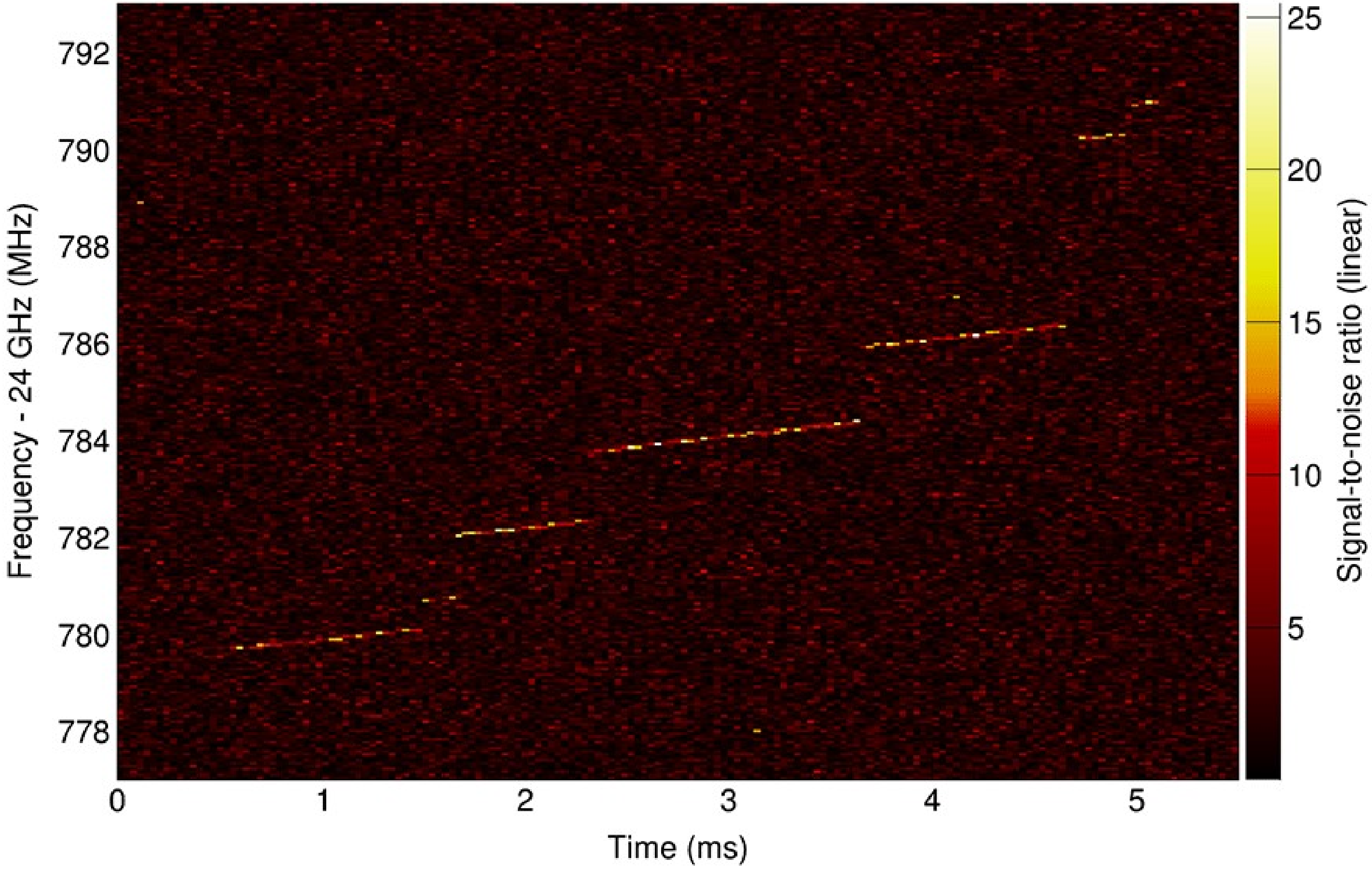
Advantage

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.

Project-8 data

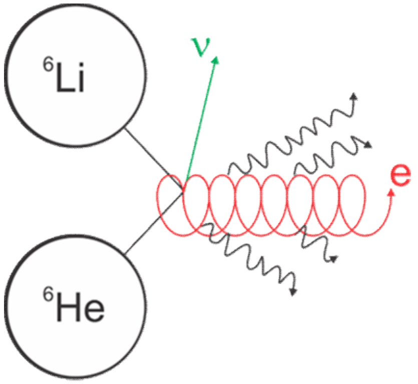


Power from a single electron orbiting in a magnetic field versus time and the frequency of the electron's orbit. The straight streaks correspond to the electron losing energy (and orbiting faster) as it radiates. The jumps correspond to the loss of energy when the electron collides with an atom or molecule.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

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

W. Byron[1], M. Fertl[1], A. Garcia[1], G. Garvey[1], B. Graner[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

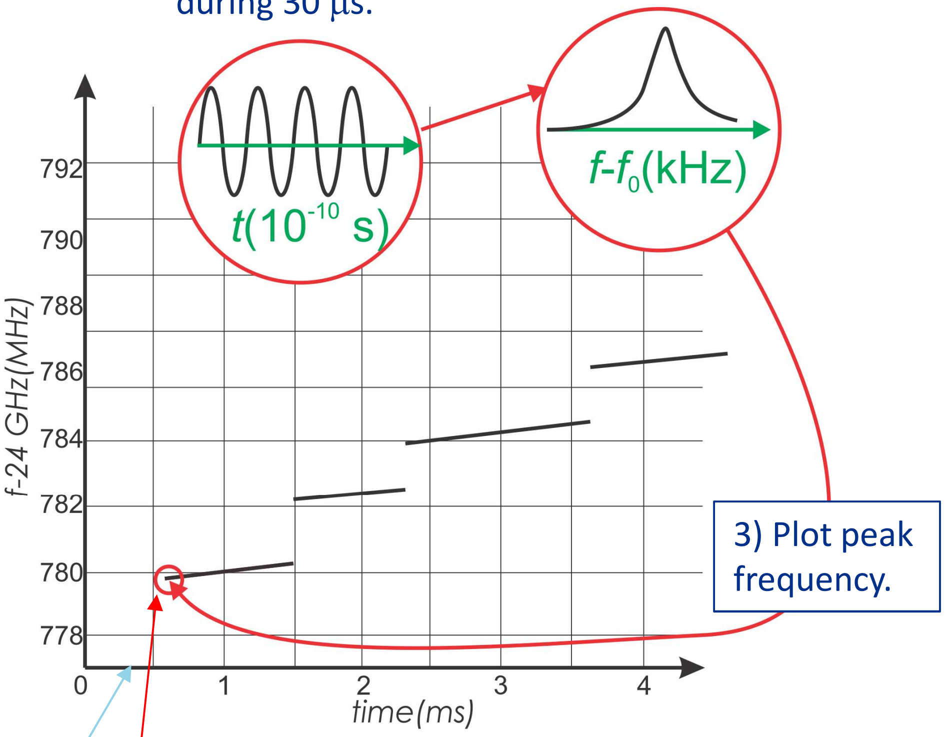
- **Technique**
  - Use Cyclotron Radiation Emission Spectroscopy. Similar to Project 8 setup for tritium decay.
  - Need to extend the technique to higher energy betas and to a precision determination of a continuum spectrum.

Advantages of the CRES technique

- **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.

1) Take a wave during 30 μs.

2) Fourier analysis.

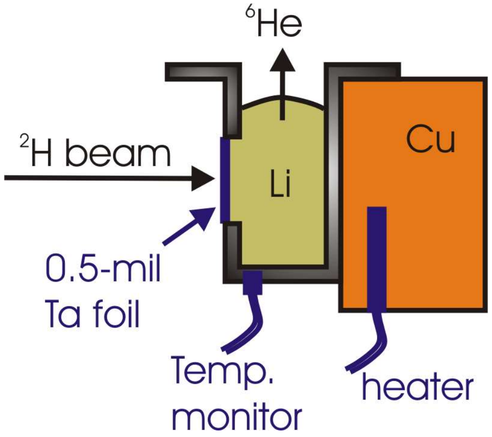


3) Plot peak frequency.

Initial frequency → *E*

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

Time bins ~ 30 μs.



^{6}He source at Seattle

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.

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

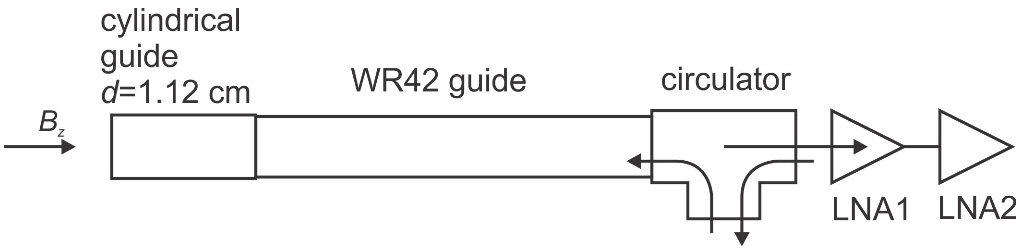
Phase I: proof of principle
- 2 GHz bandwidth.
- Show detection of cycl. radiation from 6He.
- Study power distribution.

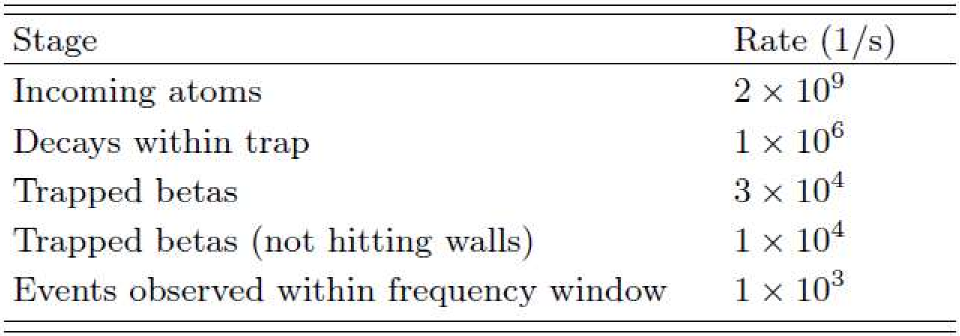
$\}$ Mission for next three years

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

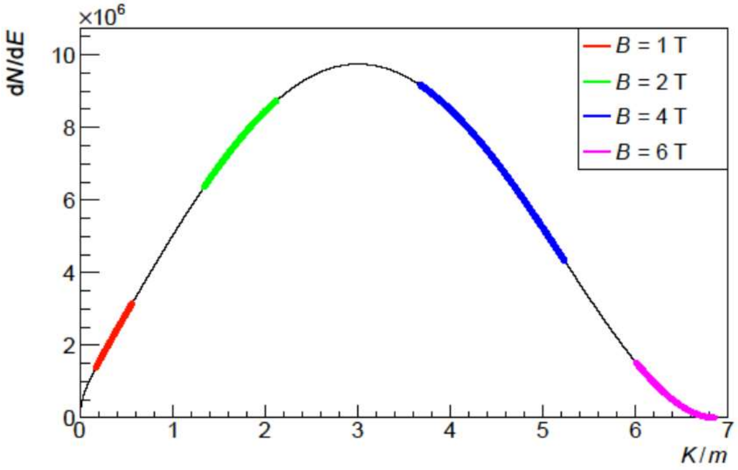




Stage	Rate (1/s)
Incoming atoms	2×10^9
Decays within trap	1×10^6
Trapped betas	3×10^4
Trapped betas (not hitting walls)	1×10^4
Events observed within frequency window	1×10^3

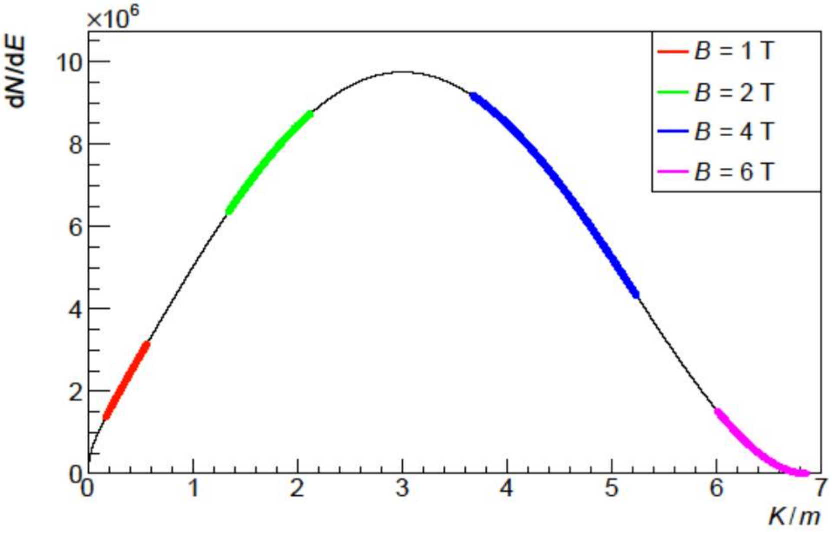
Frequency band: *f*=18-24 GHz.

Monte Carlo simulation of observation in Few days of running

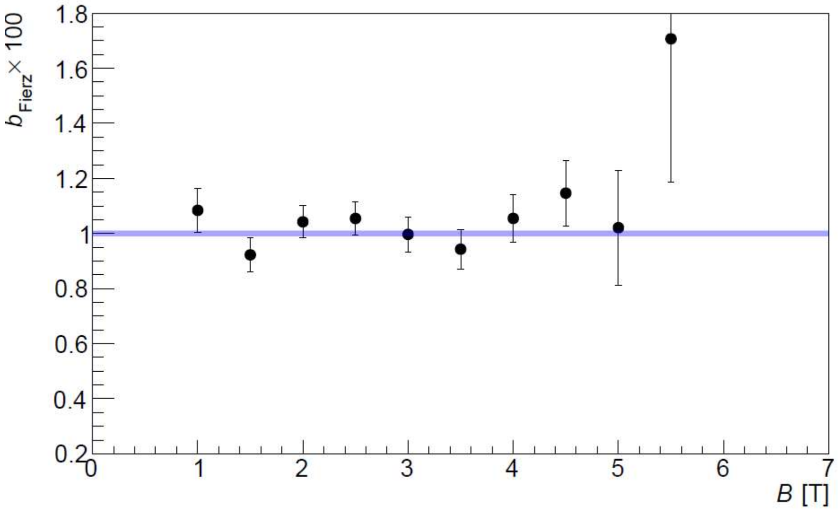


^{6}He little-b measurement at Seattle

Monte Carlo simulation of observation in
Few days of running

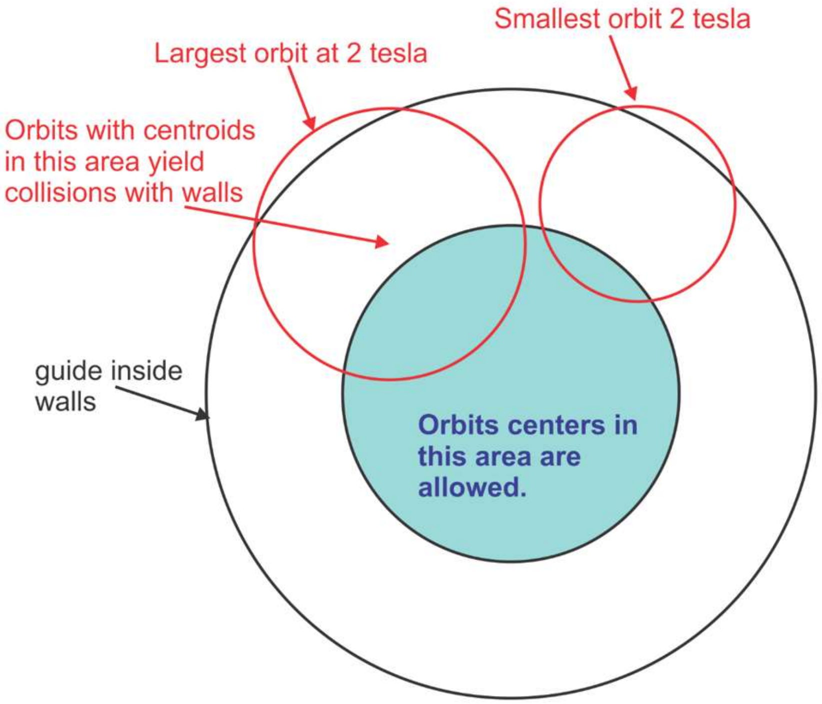


Extracting little b vs. B field
Few days of running each point
(assumed $b_{MC} = 0.01$)



^{6}He little-b measurement at Seattle

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.

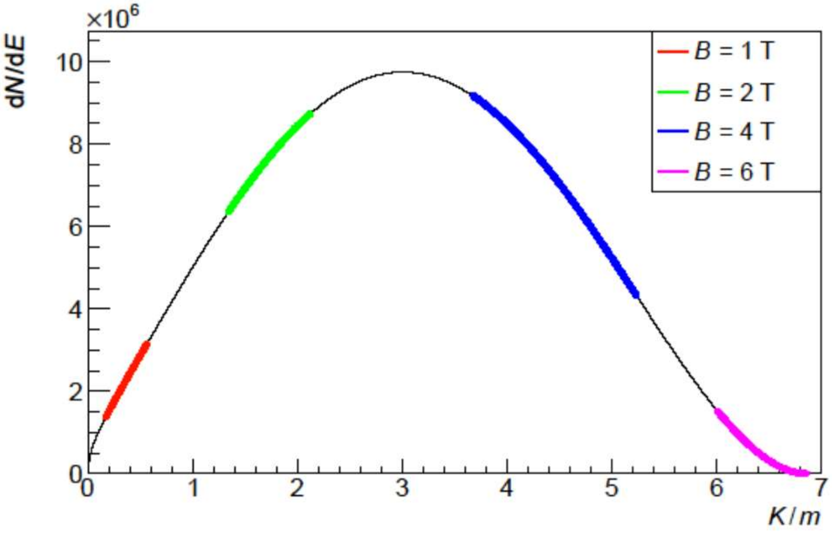
Since blue area depends on energy there is a systematic distortion of the spectrum

Can be studied by varying the B field.

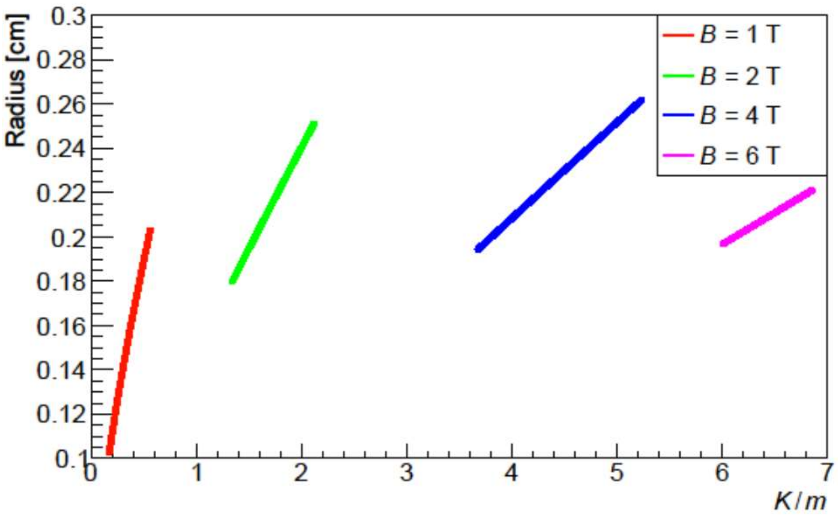
^{6}He little-b measurement at Seattle

Obvious worry: efficiency depends on energy.
Can study by varying B field.

Monte Carlo simulation of observation in
Few days of running



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



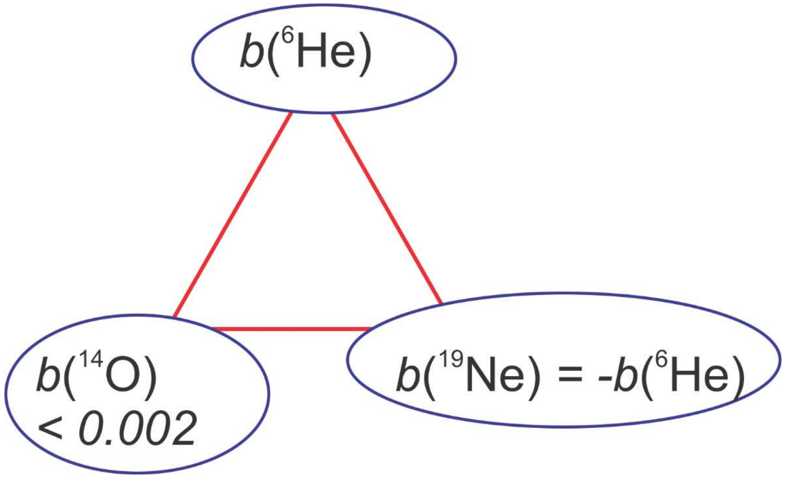
^{6}He little-*b* measurement at Seattle

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.

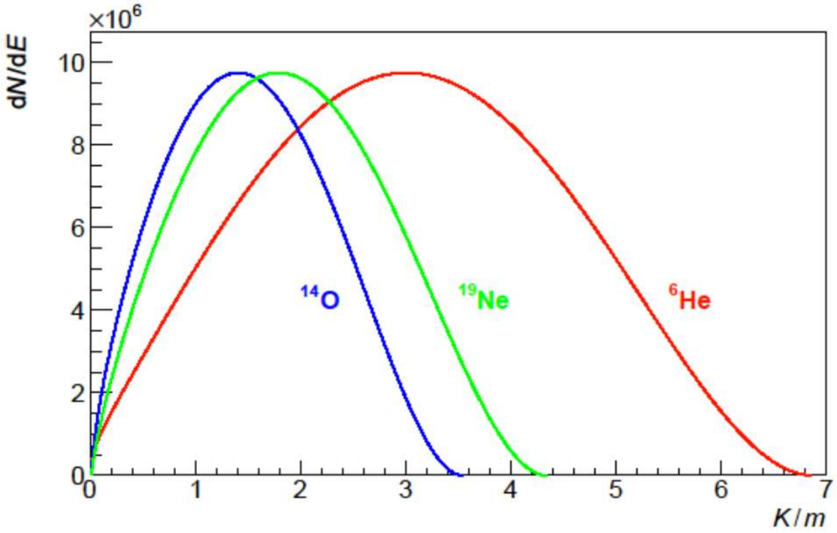
^{19}Ne source developed at Princeton appropriate.



$b(^{6}\mathrm{He})$

$b(^{14}\mathrm{O}) < 0.002$

$b(^{19}\mathrm{Ne}) = -b(^{6}\mathrm{He})$

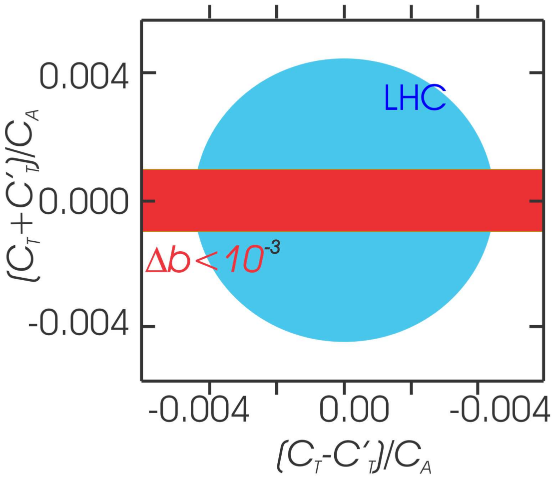


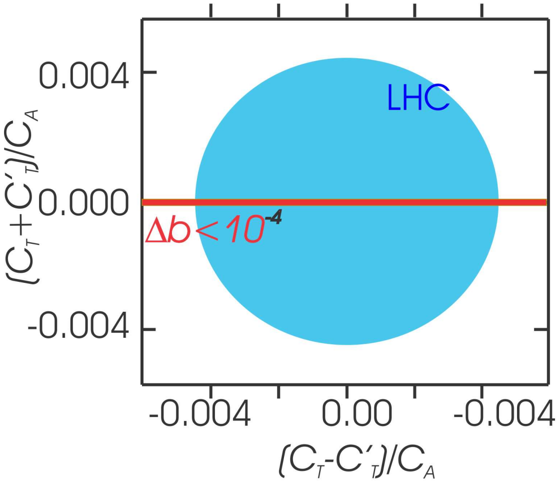
Potential reach (Monte Carlo simulations)

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

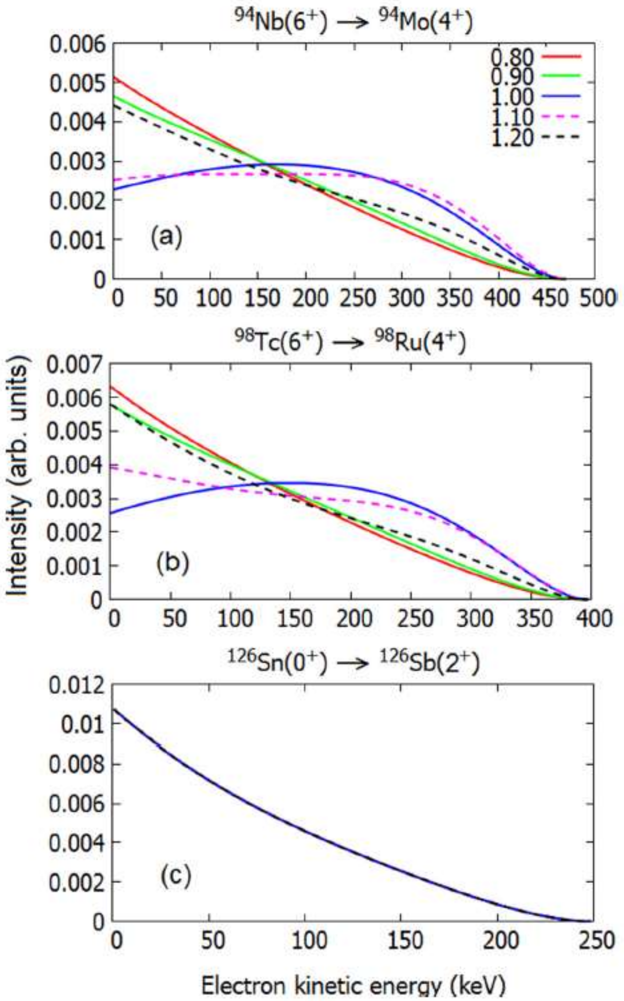


FIG. 2. Same as Fig. 1 but for the second-forbidden nonunique decays of ^{94}Nb [panel (a)], ^{98}Tc [panel (b)], and ^{126}Sn [panel (c)].

Is theory on good grounds?

- Cirigliano-Gupta et al. organizing a workshop at Amherst on neutron and nuclear beta decay

- Gazit-Phillips-et al. proposing workshop at ECT*

Is theory on good grounds?

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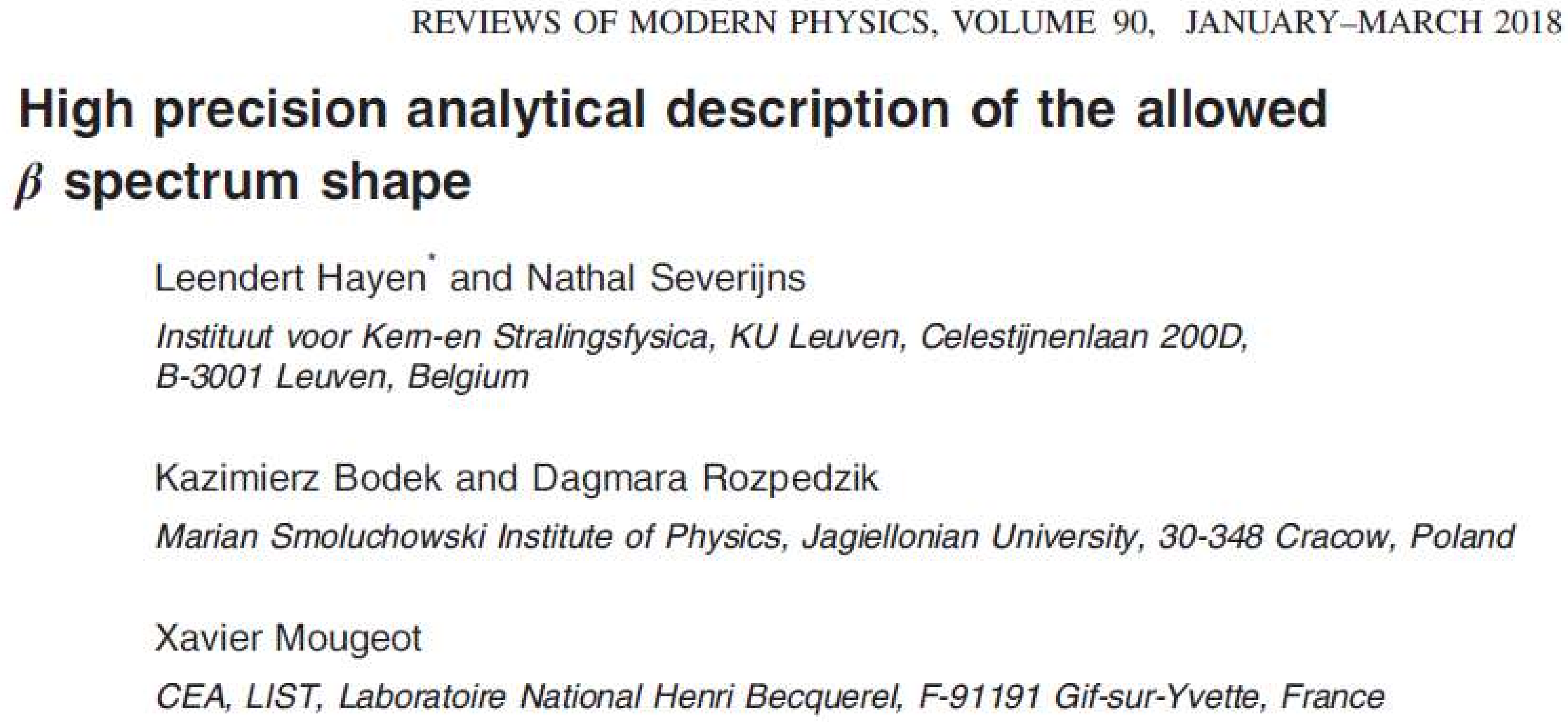

REVIEWS OF MODERN PHYSICS, VOLUME 90, JANUARY–MARCH 2018

High precision analytical description of the allowed β spectrum shape

Leendert Hayen* and Nathal Severijns

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B-3001 Leuven, Belgium

Kazimierz Bodek and Dagmara Rozpedzik

Marian Smoluchowski Institute of Physics, Jagiellonian University, 30-348 Cracow, Poland

Xavier Mougeot

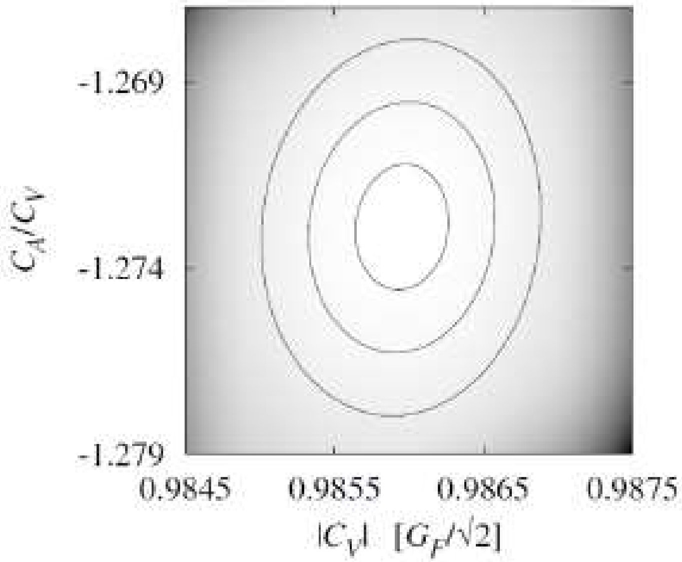
CEA, LIST, Laboratoire National Henri Becquerel, F-91191 Gif-sur-Yvette, France

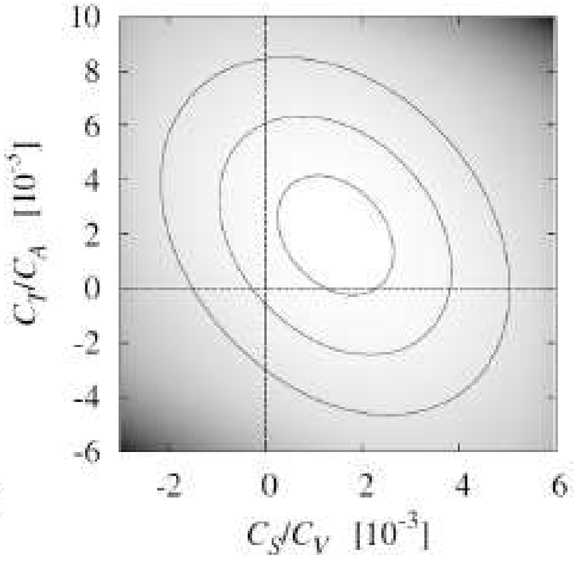
Conclusions

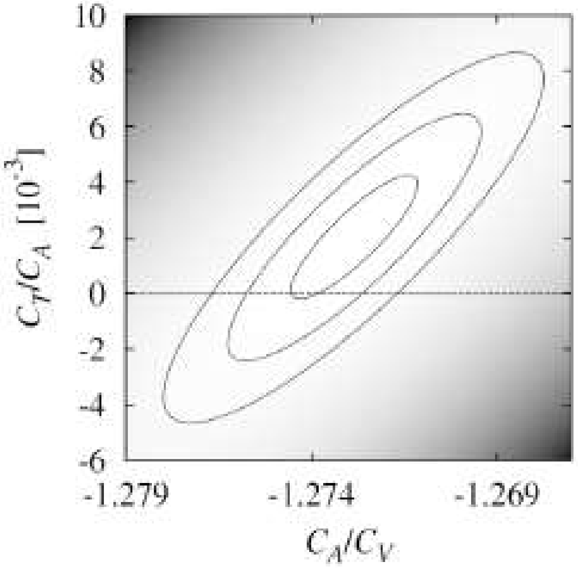
- Trapping techniques applied to nuclear beta decay have yielded fruits recently.
- Most sensitive way forward seems Fierz interference.
- Direct effect on shape of beta spectra. Difficult to measure without distortions. Many techniques being pursued.
- Calculating SM contributions to allow most sensitive searches is non trivial. Work under way.

End

Gonzalez-Alonso, Naviliat-Cuncic, Severijns
hep-ph 1803.08732





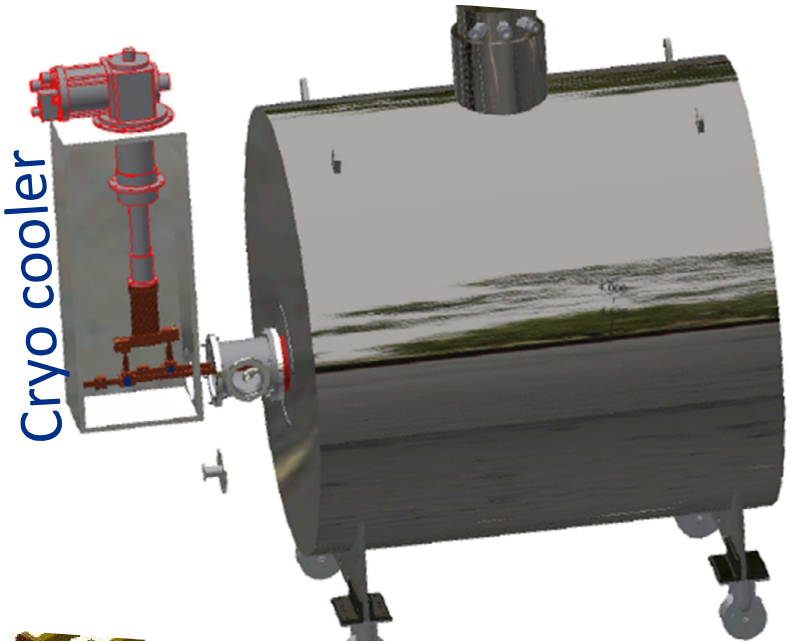


^{6}He little-b measurement at Seattle

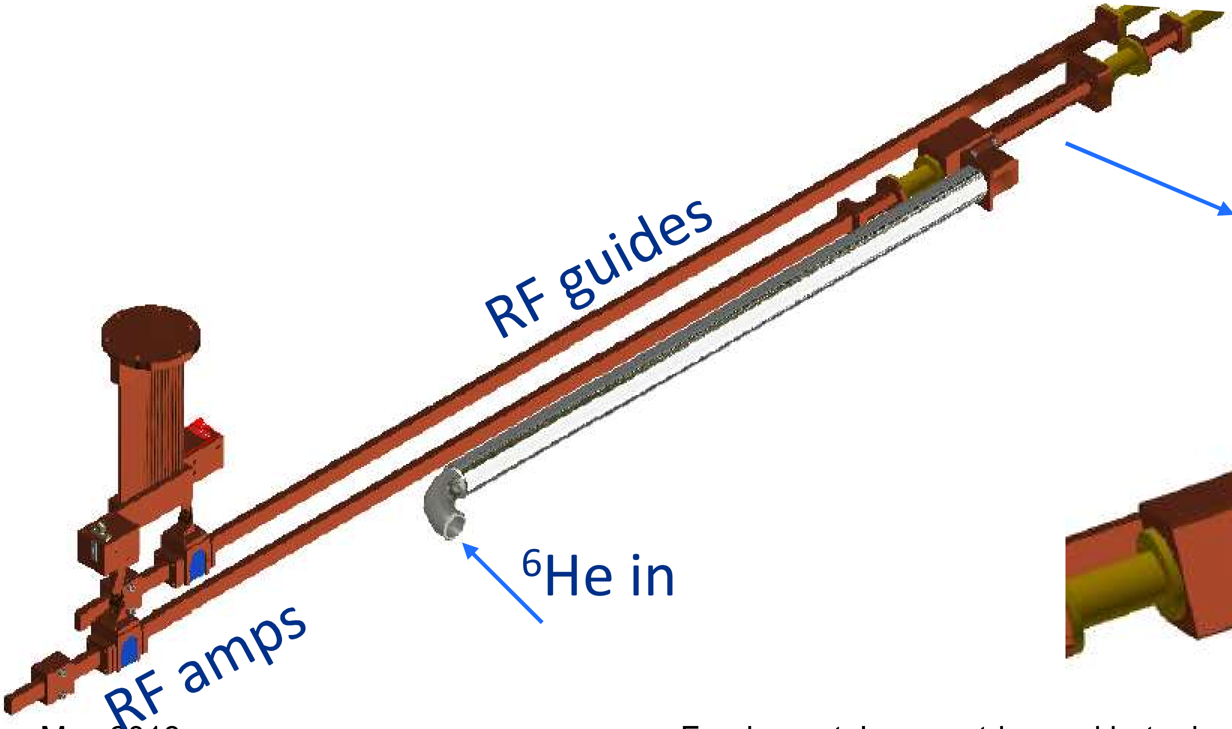
Goal: measure "little b" to 10^{-3} or better in ^{6}He

Stats not a problem.

Starting construction during summer 2018.



Cryo cooler

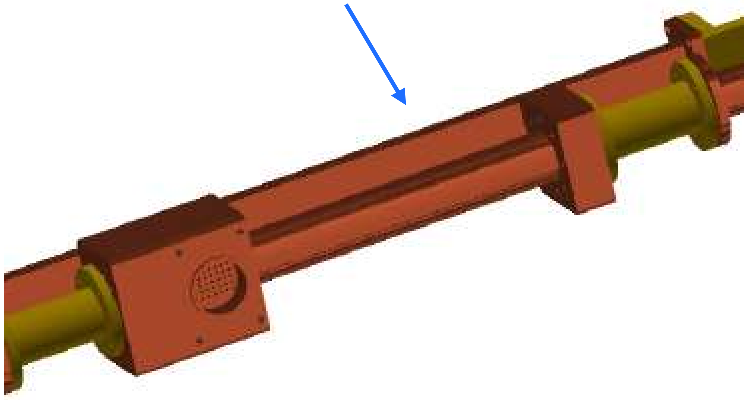


RF guides

RF amps

^{6}He in

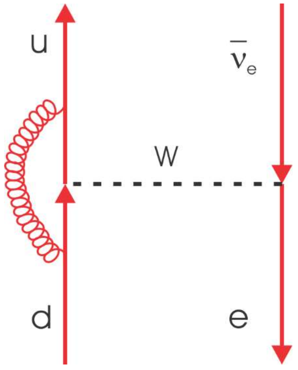
Decay volume



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

^{19}Ne?
^{14}O?

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

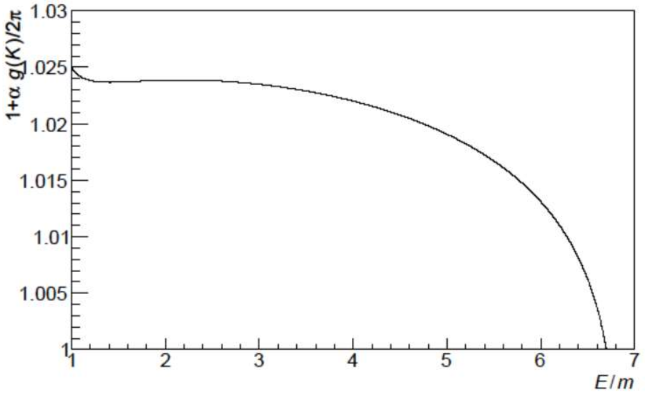


Dominant factor in recoil-order correction is interference between WM and GT:

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

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

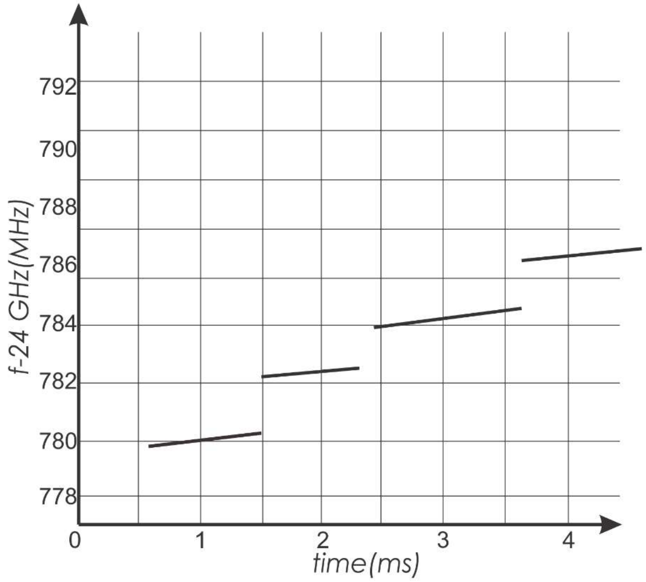
Radiative corrections



Model-independent Sirlin factor.

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

Other worries: DAQ.



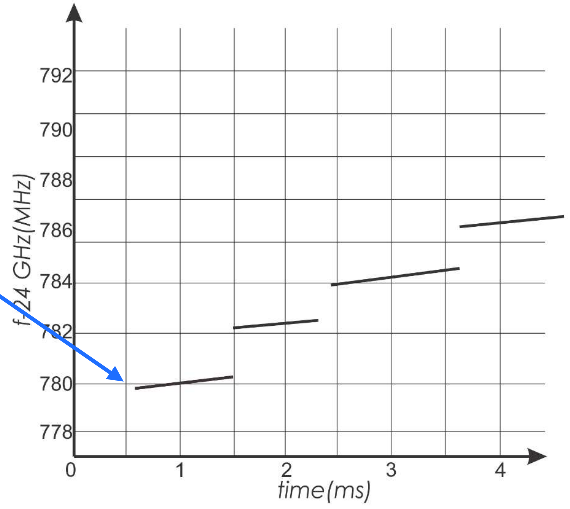
To register it all, need to take about 1 byte at 5 GHz.

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:



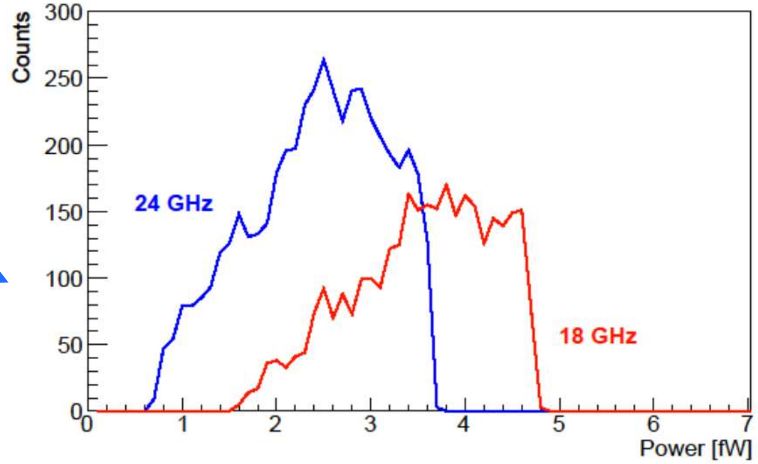
- Identify initial frequency?

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:

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

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.