Overview of Nuclear Beta Decay
Tests of Fundamental Symmetries

CIPANP—2018

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University of Washington
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 $L$:

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

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

Yang                 Gell-Mann
Lee                          Feynman
Marshak

Sudarshan

Chien-Shiung Wu (b. 1912) Nuclear Physicist
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

Predicted by Supersymmetric Theories

Or maybe something not considered so far...

Profumo, Ramsey-Musolf, Tulin

Vos, Wilschut, Timmermans,

Bhattacharya et al.
Type of experiments that determined $V$-$A$ structure have been recently improved using ion and atom traps.

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

$\beta$ asymmetry from polarized $^{37}\text{K}$
(Fenker et al., Phys. Rev. Lett. 120, 062502 (2018))
Limit on Tensor Currents from $^8$Li $\beta$ 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 S. Caldwell, 1,2 A. Chaudhuri, 2,7 J. E. Crawford, 6 C. M. Deibel, 8,9 J. Greene, 2 S. Gulick, 6 D. Lascar, 2,‡ A. F. Levand, 2 G. Li, 6,2,10 A. Pérez Galván, 2 K. S. Sharma, 7 J. Van Schelt, 1,2 R. M. Yee, 11,5 and B. I. Zabransky, 2

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8 Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA
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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 $\beta$ decay are dominated by a single measurement of the $\beta-\bar{\nu}$ correlation in $^6$He $\beta$ decay dating back over a half century. In the present work, the $\beta-\bar{\nu}-\alpha$ correlation in the $\beta$ decay of $^8$Li and subsequent $\alpha$-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 ($C_T = -C_A$) limits the tensor fraction to $|C_T/C_A|^2 < 0.011$ (95.5% 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.
\[ \beta - \nu \text{ correlation from for } A=8 \]

The \( \alpha \)'s can't carry ang. momentum along their path, so only \( M_f=0 \):

<table>
<thead>
<tr>
<th>Mi</th>
<th>Mf</th>
<th>SM Correlation</th>
<th>Clebsch</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2</td>
<td>+2</td>
<td>1 - \cos \theta</td>
<td>1/2</td>
</tr>
<tr>
<td>+1</td>
<td>+1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>+1</td>
<td>1 + \cos \theta</td>
<td>0</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>1 - \cos \theta</td>
<td>1/2</td>
</tr>
<tr>
<td>-2</td>
<td>-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2</td>
<td>-2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The effective correlation is then

1 - \( \frac{p}{E}\) cos \( \theta \) for the standard model

1 + \( \frac{p}{E}\) cos \( \theta \) for purely tensor

The non-flip transition does not contribute

\[ <\{2,0\}|\{1,0\}|\{2,0\}> = 0 \]
Ongoing improvements in production and delivery of $^8$Li/$^8$B to BPT

Upgrades resulted in $10 \times$ increase in ion delivery to BPT

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

→ revisit $^8$Li with $10 \times$ higher statistics

• Gas target geometry better matched to reactions

• New gas catcher optimized to handle lighter masses and space-charge issues
trapped ions surrounded by DSSDs and plastic

Ion trap used to hold $A=8$ nuclei.
$\alpha$’s and $\beta$’s measured with steep Si detectors.
Hit locations allow tracking back to the emission point.

$|C_T/C_A|^2 < 0.011$

Spectrum from events with $\beta$ and $\alpha$ 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

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

\[ \langle P_{\text{nucl}} \rangle = 99.13(7)(5)\% \]

- 0.1% precision better than needed for $A_\beta$ measurement

From D. Melconian, J. Behr.
The $\beta$ 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, 2\textsuperscript{nd} 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 $\nu$'s:

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

From Bhattacharya et al.
Connection to LHC data via EFT calculations

LHC (I): contact interactions

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

- The effective couplings $\varepsilon_\alpha$ contribute to the process $p p \rightarrow e \nu + X$

- No excess events in transverse mass distribution: bounds on $\varepsilon_\alpha$

Cirigliano et al. 
PPNP 71, 93 (2013)

May 2018

Fundamental symmetries and beta decay
Nuclear beta decay: beyond V-A?

We still like the parametrization of Lee and Yang.

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

**Standard Model**

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

**Right-handed**

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

** chirality flipping**

\[
O_i = \begin{cases} 
1 & i = S \\
\sigma^{\mu\nu} & i = T 
\end{cases}
\]
Nuclear beta decay: beyond V-A?

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

\[ C_i = \frac{G_F}{\sqrt{2}} V_{ud} \tilde{C}_i \]

\[ \tilde{C}_V = g_V(1 + \epsilon_L + \epsilon_R) \]

\[ \tilde{C}_A = -g_A(1 + \epsilon_L - \epsilon_R) \]

\[ \tilde{C}_S = g_S \epsilon_S \]

\[ \tilde{C}_T = 4g_T \epsilon_T, \]

We still like the parametrization of Lee and Yang.

From Gonzalez-Alonso et al. arXiv:1803.08732v1

<table>
<thead>
<tr>
<th>Charge</th>
<th>Value</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_A )</td>
<td>1.278(33)</td>
<td>33</td>
</tr>
<tr>
<td>( g_T )</td>
<td>0.987(55)</td>
<td>32</td>
</tr>
<tr>
<td>( g_S )</td>
<td>1.02(11)</td>
<td>24</td>
</tr>
<tr>
<td>( g_P )</td>
<td>349(9)</td>
<td>24</td>
</tr>
</tbody>
</table>
Precision beta decay versus others:
Can “precision” compete with “energy”?

Bhattacharya et al.

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

\[ H_A = \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_0 \left[ (2C_A) \bar{e}^L \gamma_\mu \gamma_5 \nu_e^L \right] + \bar{\Psi}_f \sigma^{\mu\nu} \Psi_0 \left[ (C_T + C_T') \bar{e}^R \sigma_{\mu\nu} \nu_e^L + (C_T - C_T') \bar{e}^L \sigma_{\mu\nu} \nu_e^R \right] \]

Decay rate:

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

\[ a \approx -\frac{1}{3} \left( 1 - \frac{C_T^2 + C_T'^2}{2 C_A^2} \right) \]

\[ b \approx \pm \frac{(C_T + C_T')}{C_A} \]

\[ \beta-\nu \text{ correlation} \]

\[ \text{Fierz interference} \]

May 2018

Fundamental symmetries and beta decay
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)

\[ dw = dw_0 \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_v}{E_e E_v} + b \frac{\Gamma m_e}{E_e} \right] \]

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
First direct constraints on Fierz interference in free-neutron $\beta$ decay

UCNA collaboration

FIG. 1. Schematic diagram of the UCNA spectrometer.
UCNA collaboration

\[ b_n = 0.067 \pm 0.005^{+0.090}_{-0.061} \text{stat.} \]

~8 % accuracy over ~1 MeV
Magnetic spectrometer produced at Madison

L. D. Knutson et al.  

$^{14}$O branch  
P. A. Voytas et al.  

$^{14}$O spectrum  
E. A. George et al.  

$^{66}$Ga spectrum  
G. W. Severin et al.  
Magnetic spectrometer produced at Madison

$^{14}$O spectrum
E. A. George et al.

$^{66}$Ga spectrum
G. W. Severin et al.

~1% accuracy over few MeV’s

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 $2.9 \times 10^{10}$ decays, while the 16 A data in panel (b) correspond to $3.1 \times 10^{10}$ decays.
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 \( \propto p_b \)
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.

UCNA (2017)
aCORN (2017)
PERKEO II (2013)
PERKEO I (1986)
Liaud (1997)
Stratowa (1978)

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

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

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

\[
d\Gamma \propto g(E_e) \left( 1 + a \frac{p_e}{E_e} \cos \theta_{ev} + b \frac{m_e}{E_e} \right)
\]

Kinematics in Infinite Nuclear Mass Approximation:

• Energy Conservation:
  \[ E_v = E_{e,max} - E_e \]

• Momentum Conservation:
  \[ p_p^2 = p_e^2 + p_{\nu}^2 + 2p_e p_{\nu} \cos \theta_{ev} \]

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

Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
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.

Commissioning and data taking is expected to start in late 2018.
Selection of Sensitive Transitions to $b_{GT}$

- 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.

$^6\text{He}$

\[ 0^+; T=0 \rightarrow \alpha + d \]
\[ E_\beta = 3505 \text{ keV} \]
\[ 100\% \rightarrow 1^+; T=0 \]
\[ 1.6 \times 10^{-6} \text{ ms} \]

\[ ^6\text{Li} \]

$^20\text{F}$

\[ 2^+; T=0 \rightarrow 1^+; T=0 \]
\[ E_\beta = 5392 \text{ keV} \]
\[ 99.99\% \rightarrow 1.63 \text{ MeV} \]
\[ 11.2 \text{ s} \]

$^{20}\text{Ne}$


Active detector

Range of $\beta$ particles

$^6\text{He}$ source
Measurement with $^{6}\text{He}$

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

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 ($^6\text{He}$)

- 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 $\beta$ 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
- $2.6 \times 10^{-3}$ 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 $\beta$ detection; 4 (3”x3”x3”) CsI(Na) for $\gamma$ 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 $\gamma$ 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.
New idea: CRES technique

Project 8 collaboration gets FWHM/E ≈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.

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 $\omega_z$. 

\[ \omega = \frac{qB}{E} \]
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 \( \sim 30 \) 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, \( z_{\text{max}} \). Axial oscillations with \( \omega_z \).
New idea: CRES technique

Project 8 in a nutshell

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

\[ \omega = \frac{qB}{E} \]

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-\textit{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.
- $^6$He in gaseous form works well with the technique.
- $^6$He ion-trap (shown by others to work) allows sensitivity higher than any other proposed.
- Counts needed not a big demand on running time.

\[
\omega = \frac{qB}{E}
\]

1) Take a wave during 30 μs.
2) Fourier analysis.
3) Plot peak frequency.

Initial frequency \( \rightarrow E \)

Time bins \( \sim 30 \mu s \)
"Statistics for searching for new physics", compare decay densities to neutron sources:

UCN: $10^3$ UCN/cc $\rightarrow \approx 1 \text{ (decay/s)/cc}$

CN: $10^{10}$ CN/s cm$^2$ $\rightarrow 2 \times 10^5$ CN/cc $\approx 200 \text{ (decay/s)/cc}$

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

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 $^{6}\text{He}$.
- Study power distribution.

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

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

Mission for next three years
$^6$He little-$b$ measurement at Seattle

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

<table>
<thead>
<tr>
<th>Stage</th>
<th>Rate (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoming atoms</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>Decays within trap</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>Trapped betas</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>Trapped betas (not hitting walls)</td>
<td>$1 \times 10^4$</td>
</tr>
<tr>
<td>Events observed within frequency window</td>
<td>$1 \times 10^3$</td>
</tr>
</tbody>
</table>
$^6$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 $b_{MC} = 0.01$)
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
$^6\text{He}$ little-$b$ measurement at Seattle

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

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

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

$^{19}\text{Ne}$ source developed at Princeton appropriate.
Potential reach (Monte Carlo simulations)

<table>
<thead>
<tr>
<th>Effect</th>
<th>No trap</th>
<th>Ion trap</th>
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</thead>
<tbody>
<tr>
<td>Magnetic field uncertainties</td>
<td>$10^{-4}$</td>
<td>$&lt; 10^{-4}$</td>
</tr>
<tr>
<td>Wall effect uncertainties</td>
<td>$10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>RF pickup uncertainties</td>
<td>$10^{-4}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Misidentification of events</td>
<td>$10^{-4}$</td>
<td>$5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Phase III: Future development, couple to an ion trap

Phase II

May 2018 Fundamental symmetries and beta decay
Applications: coupling CRES with radioactive ion trap.
Benchmarks for nuclear structure and $2\beta$ decays

$2\beta$ 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.
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*
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High precision analytical description of the allowed $\beta$ spectrum shape

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

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

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

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

Factor determined to $\sim 2\%$ by connection to $\gamma$ decay of analogue in $6\text{Li}$.

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 $\Delta f$ 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 inhomogeneities?  
  \[ \omega_c = \frac{qB}{E} \]
  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:

\[ e^{i(\beta z - \omega t)} \]

The amplifier observes a frequency:

\[ \omega + \beta \dot{z} \omega / \omega \]

“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.