Fundamental symmetries studies with electron spectroscopy at FRIB

- Chirality flipping interactions
  - Axial and tensor
  - Fermi and scalar
  - Tools: $R \times B$ spectrometer
  - Cyclotron Radiation Emission Spectroscopy

- Examples of other uses of beta spectroscopy:
  - Nuclear structure for $2\beta$ decays
  - Efficiency of some neutrino detectors

Alejandro Garcia
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Fundamental symmetries studies with $^6$He

- Simple decay (~100% to ground state)
- Pure Gamow-Teller decay
- Half-life ~1 sec → appropriate for trapping
- Large $Q$-value → good for seeing effects of n
- Noble gas → no worries about chemistry
- Light nucleus → ab-initio calculations

Compare to neutron:
- No backgrounds from neutron captures
- Pure GT transition (simpler decay, no polarization)

$^6$He “little a”

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*Argonne National Lab*

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*LPC, CAEN, France*

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A. Knecht,  
*PSI, Switzerland*

Y. Bagdasarova, A. Garcia, R. Hong, M. Sternberg, D. Storm, H.E. Swanson, F. Wauters, D. Zumwalt  
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$^6$He “little b”

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Y. Bagdasarova, A. Garcia, D. Hertzog, R. Hong, P. Kammel, J. Kofron, G. Rybka,  
*M. Sternberg,*

D. Storm, H.E. Swanson, F. Wauters, D. Zumwalt  
*University of Washington*
Now \( \sim 10^{10} \) atoms of \(^6\text{He}/s\) at Seattle via \(^7\text{Li}(d,^3\text{He})^6\text{He}\)

Most intense source of \(^6\text{He}\) in the world here at CENPA.

Typical decay density is about \(10^9\) decays/s cm\(^3\)...

(Good neutron decay density is \(1\) decay/s cm\(^3\))

Fundamental symmetries at FRIB
$^6$He lifetime, ab-initio calculations, $g_A$(nuclear)

With calculated $\langle f | \hat{O} | i \rangle$ and lifetime can extract $g_A$

$$\frac{1}{f(E)t} = \frac{(G_F V_{ud})^2}{K} g_A^2 \left| \langle f | \hat{O} | i \rangle \right|^2$$

Several `ab-initio’ calculations show agreement on matrix element at the few percent level:

Schiavilla & Wiringa, PRC 65, 054302 (2002)
Previn et al., PRC 76, 064319 (2007)
Vaintraub et al., PRC 79, 065501 (2009)

But experimental situation was unclear.
\( ^6 \text{He} \) lifetime, ab-initio calculations, \( g_A(\text{nuclear}) \)


- We resolved the discrepancy.

Our result in combination with ab-initio calculations shows that extraneous quenching is at most about 2%.

Now limited by theoretical uncertainty.

Fundamental symmetries at FRIB
Searches for Tensor currents.

Are nuclear weak decays carried only by W's?

\[ H = \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_i \begin{pmatrix} 2C_A e^L \gamma_\mu \gamma_5 \nu_e^L \\ \overline{\Psi}_f \sigma^{\mu\nu} \Psi_i \left[ (C_T - C'_T) e^L \sigma_{\mu\nu} \nu_e^R + (C_T + C'_T) e^R \sigma_{\mu\nu} \nu_e^L \right] \end{pmatrix} \]

Finding these would be a big deal

Decay rate:

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

\[ b \approx \frac{\text{Re} \left[ 2C_A (C_T + C'_T) \right]}{2 |C_A|^2 + |C_T|^2 + |C'_T|^2} \]

\[ a \approx -\frac{1}{3} \frac{2 |C_A|^2 - |C_T|^2 + |C'_T|^2}{2 |C_A|^2 + |C_T|^2 + |C'_T|^2} \]

Fundamental symmetries at FRIB
6He “little a”

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University of Washington

- Electron and $^6$Li detected in coincidence
- $\Delta E-E$ scintillator system for electron (energy, start of time-of-flight)
- Micro-channel plate for $^6$Li (position, TOF)

Fundamental symmetries at FRIB
Magneto-Optical Trap

- RF discharge in xenon/krypton to excite into metastable state
- Cycling on 1083 nm transition to slow down and magneto-optically trap
- Based on experience from $^6$He, $^8$He charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL 93, 142501 (2004)

Fundamental symmetries at FRIB
Precision beta decay versus others:
Can “precision” compete with “energy”? Yes.

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

Fundamental symmetries at FRIB
Is it possible to break the “$b \sim 10^{-3}$ barrier” and reach into really interesting terrain?

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

\[
a \approx -\frac{1}{3} \frac{2|C_A|^2 - |C_T|^2 + |C'_T|^2}{2|C_A|^2 + |C_T|^2 + |C'_T|^2}
\]

\[
b \approx \frac{\text{Re}\left[2C_A(C_T + C'_T)\right]}{2|C_A|^2 + |C_T|^2 + |C'_T|^2}
\]

\[
E_{\text{thres}} = 200 \text{ keV}
\implies \Delta b \approx 10 / \sqrt{N}
\]

Can get stats with rates of about $10^4$ Hz.

Fundamental symmetries at FRIB
Detect little $b$

Typical beta spectrometers work best with a `point' source

From Knutson et al. submitted to PRC (Recent work on the shape of the beta spectrum of $^{14}$O.)

Hard to apply this technique for $^{6}$He: presently we can load only $\sim 1000$ atoms in laser trap

Fundamental symmetries at FRIB
$R \times B$ spectrometer for $^6$He (similar to idea being pursued by PERC):

\[
\bar{D} = \pi R_{\text{max}} (p) \frac{\cos^2 \theta + \frac{\sin^2 \theta}{2}}{3(B/\text{Tesla})} \approx 1
\]

Existing device at PSI

Fundamental symmetries at FRIB
Comparison of neutron to 6He shape measurement with $R \times B$ spectrometer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Neutron (PERC)</th>
<th>6He (CENPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{e\text{Max}}$ (MeV)</td>
<td>0.97</td>
<td>3.5</td>
</tr>
<tr>
<td>B3 (Tesla)</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Effective decay rate (1/s)</td>
<td>$10^6$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Trappable</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Image size at $p=0$</td>
<td>1×1 cm$^2$</td>
<td>0.3×0.3 cm$^2$</td>
</tr>
</tbody>
</table>

Systematic uncertainties:
- Singles measurement: backgrounds? **Looks ok.**
- Effects from unobserved backscattering? **Looks ok.**
- Non-trapped 6He? **Looks manageable.**
- Trajectories in realistic configuration: any surprises? Needs more study
$^6$He “little $b$”: Project 8 collaboration is aiming at detecting electrons from $^3$H decay.

P8 idea: Pick up cyclotron radiation

- None of the usual problems of calorimetry: scattering, dead layers, low resolution, etc…
- Good linearity between cyclotron frequency and energy.
- Excellent resolution
\( ^{6}\text{He} \) “little \( \beta \)”: Project 8 collaboration is aiming at detecting electrons from 3H decay.

Project 8 recently showed impressive results from a conversion electron source (Asner et al. arXiv:1408.5362)

**P8 idea:** Pick up cyclotron radiation

**FIG. 2:** A typical signal from the decay of \(^{85m}\text{Kr}\) characterized by an abrupt onset of narrowband power over the thermal noise of the system. The measured frequency reflects the kinetic energy of the electron, in this case 30 keV. The frequency

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**Fundamental symmetries at FRIB**
$^6\text{He}$ “little $b$”: aiming for $10^{-4}$ with Project-8 like system

Intense production at CENPA (decay density up to about $10^9$ decays/s cm$^3$!) and $^6\text{He}$ as gas make it well suited for P8-like approach.

Need larger guide (58x29 mm$^2$ vs. 11x4 mm$^2$)
--loose power prop to area $P \propto 1/A \approx 1/40$
--but compensate due to higher energies $P \propto (\gamma^2 - 1)B^2$
--many alternative schemes to be considered

Next: test with conversion lines at energies closer to $^6\text{He}$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Decay</th>
<th>$t_{1/2}$ (days)</th>
<th>$E_e$(keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{131}\text{mXe}$</td>
<td>IT</td>
<td>12</td>
<td>129,158,163</td>
</tr>
<tr>
<td>$^{133}\text{mXe}$</td>
<td>IT</td>
<td>2.2</td>
<td>233</td>
</tr>
<tr>
<td>$^{133}\text{Xe}$</td>
<td>$\beta^-$</td>
<td>5.3</td>
<td>346</td>
</tr>
</tbody>
</table>
$^6$He “little $b$”: aiming for $10^{-4}$ with Project-8 like system

What’s different about measuring $^6$He spectrum?

Cyclotron Radius

$$R_c = \frac{\gamma \beta m_e c}{qB}$$

R = 1.2 cm @ 1 T
R = 0.6 cm @ 2T
(For 3.5 MeV $\beta$)

Radiated Power

Frequency Range

Fundamental symmetries at FRIB
\(^6\)He at CENPA summary:

Present and near future work (little a):
- Several ongoing upgrades. Expect trapping about 1000 atoms with little bkgd.
- Determination of apparatus parameters: E field, geometry, efficiencies, instabilities.

Present and near future work (little b):
- Test “Project8-like” setup with higher energy conversion sources.
- Put together similar system to detect betas in 200-900 keV range.
- We would consider again the “\(R\times B\) Spectrometer” idea if the above fails.

Goals 3 years:
Determination of \(a\) to \(\sim 0.1\%\); R&D to determination of \(b\).
Determine \(b\) to \(\sim 10^{-3}\).

Goals 6 years:
Determine \(b\) to \(\sim 10^{-4}\).
Examples of other applications of electron spectroscopy

Benchmarks for \(2\nu - 2\beta\) decays nuclear structure:

- \(2\nu - 2\beta\) 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...)*

We developed a device to determine the tiny EC branches.
We developed a device to determine the tiny EC branches using the radioactive beams available at IGISOL (JYFLTRAP).

Use ion trap for clean activity
High-resolution Ge for x rays
Scintillator for vetoing beta-decays
$^{100}$Tc EC decay:
$\text{BR(EC)} = (2.6\pm0.4)\times10^{-5}$

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

S. Sjue, Thesis 2008;
Sjue et al.,
PRC 87, 032501 (2013).

Both of our results are consistent with complete ground state dominance: just using the ground state accounts for the measured 2$\nu$-2$\beta$ decay rate.
Comparison with 2 different QRPA calculations

O. Moreno, R. Alvarez-Rodriguez, P. Sarriguren, E. Moya de Guerra, F. Simkovic, A. Faessler

Suhonen & Civitarese

Our measurements

Fundamental symmetries at FRIB
High resolution Auger spectroscopy would determine the efficiencies of solar pp neutrino detectors
High-resolution beta spectroscopy

Perhaps FRIB would be the place for the most intense production of some gaseous molecular species or trapped ions that could be used for cyclotron-radiation detection in pure axial and pure Fermi decays to search for tensor and scalar currents.

High-resolution Auger spectroscopy with ions of choice could help with spectroscopy relevant for neutrino physics (double beta decay, solar neutrinos).
Backup slides
The Influence of MEC

<table>
<thead>
<tr>
<th>Calculation</th>
<th>$M_G (\text{no MEC})$</th>
<th>Change from $g_A(n)$</th>
<th>$M_G (\text{incl. MEC})$</th>
<th>Change from $g_A(n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schiavilla/Wiringa</td>
<td>$2.254(5) (\psi_1)$, $2.246(10) (\psi_2)$</td>
<td>-3.9%, -3.6%</td>
<td>$2.284(5) (\psi_1)$, $2.278(10) (\psi_2)$</td>
<td>-5.2%, -5.0%</td>
</tr>
<tr>
<td>Vaintraub/Barnea/Gazit</td>
<td>$2.225(2)$</td>
<td>-2.7%</td>
<td>$2.198(7)$</td>
<td>-1.5%</td>
</tr>
</tbody>
</table>

- Free low-energy constant in calculation of meson-exchange currents: fixed by $^3\text{H}$ half-life.
- Influence of MEC different in the two calculations.
- Vaintraub et al. argue that this is an effect of the correct modeling of the underlying currents in $\chi$PT.

Fundamental symmetries at FRIB
6He:
“recoil order”

\[ C_V \int \vec{\alpha} \times \vec{r} \rightarrow \frac{f_V}{M} \left[ \int \tau^+ \vec{\sigma} + \int \tau^+ \vec{r} \times \vec{p} \right] - 2f_{WM} \int \tau^+ \vec{\sigma} \]

\[ C_A i \int \gamma_5 \vec{r} \rightarrow g_A i \int \tau^+ \vec{\sigma} \times \vec{l} \]

Small and under control for 6He decay.

… and radiative corrections.

From theorists (Barry Holstein et al.): “no show stoppers”
We have already trapped ~500 atoms of $^6$He at UW!
Precision beta decay versus pion and “LHC”: (Wauters et al.)

FIG. 5. Limits on tensor currents from envisaged measurements of the correlation coefficient for $^6$He at 0.1% [53] or of the Fierz interference term $b_{Fierz}$ to $10^{-3}$ in $^6$He or neutron decays [54]. In the formalism of Eq. 3, the current LHC limits from Ref. [9] are $|(C_T + C_T')/C_A| < 6 \times 10^{-3}$ and $|(C_T - C_T')/C_A| < 2 \times 10^{-2}$.

FIG. 3. Limits $C_T$ and $C_S$ combining neutron and nuclear $\beta$ decay data for the 3-parameter fit. On top we show the probability distribution of the limits on $C_T$ obtained by projecting the 2D distribution and compare to the limits from pion decay data.

Fundamental symmetries with 6He
MCPPSD (micro channel plates with delay line anodes)

MCPs (micro channel plates)

Delay line anodes

5 polarization voltages: front MCP, back MCP, det. frame, anode_ref, anode_sig

5 signals: charge emitted by MCPs, charge collected on anodes (x1,x2,y1,y2)

Fundamental symmetries with 6He
X&Y calibration:
- Reconstruction with 2\textsuperscript{d} order polynomial functions

Fundamental symmetries with 6He
Detect little $b$. Betas in adiabatic motion in $B$: basic ideas

1) Flux = $B \ r_0^2 \ \sin^2 \theta = \text{constant}$

\[
r_0 = \frac{p}{qB} \quad \sin^2 \theta = \text{constant}
\]

2) Orbital magnetic moment conserved:

\[
\mu = \pi \ (r_0 \ \sin \theta)^2 \ e \ \frac{\omega}{2\pi} = \text{constant}
\]

3) A force $F$ applied perpendicular to $B$ generates a “drift velocity”:

\[
u = \frac{(\vec{F} \ / \ e) \times \vec{B}}{B^2}
\]

4) A solenoidal field with intensity varying as in the figure yields smaller pitch-angle betas, good for minimizing backscatter
Comparison of neutron to 6He shape measurement with $R \times B$ spectrometer

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Backscattering front foil of a gas counter

<table>
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<tr>
<th>Parameter</th>
<th>Backscattered fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_e$ (MeV)</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>0.2</td>
<td>0.07</td>
</tr>
<tr>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>0.5</td>
<td>0.01</td>
</tr>
<tr>
<td>1.0</td>
<td>0.002</td>
</tr>
</tbody>
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Systematic uncertainties:
- Singles measurement: backgrounds?
- Effects from unobserved backscattering?
- Non-trapped 6He?
- Trajectories in realistic configuration: any surprises?
Fundamental symmetries with 6He
Trapping of $^{6}\text{He}$

- RF discharge in xenon/krypton to excite into metastable state
- Cycling on 1083 nm transition to transversely cool, slow down and trap magneto-optically
- Trapped atoms transferred to detection chamber with 2nd MOT
- Based on experience from $^{6}\text{He}$, $^{8}\text{He}$ charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL 93, 142501 (2004)

Fundamental symmetries with $^{6}\text{He}$
Detection systems

$\Delta E-E$ scintillator system for electron detection (energy, start of time-of-flight)

Micro-channel plate detector for detection of $^6$Li recoil nucleus (position, time-of-flight)

Fundamental symmetries with $^6$He
Systematic uncertainties on little a (from MC simulations).

<table>
<thead>
<tr>
<th></th>
<th>$\Delta a/\Delta x$</th>
<th>$(\Delta a/\Delta x)/a$</th>
<th>$\Delta x$</th>
<th>$\Delta a/a$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Z-Position</strong></td>
<td>$&lt;-3e-4/0.1\text{mm}$</td>
<td>$&lt;0.1%/0.1\text{mm}$</td>
<td>$\delta z = 0.1\ \text{mm}$</td>
<td>$0.1%$</td>
</tr>
<tr>
<td><strong>Timing (res)</strong></td>
<td>$-7e-4/1\text{ns}$</td>
<td>$0.2%/1\text{ns}$</td>
<td>$\delta \sigma = 1.0\ \text{ns}$</td>
<td>$0.2%$</td>
</tr>
<tr>
<td><strong>MCP: mask for radius cut</strong></td>
<td>$-0.02/\text{mm}$</td>
<td>$6.5%/\text{mm}$</td>
<td>$\delta r = 15\ \mu\text{m}$</td>
<td>$0.1%$</td>
</tr>
<tr>
<td><strong>MCP: position</strong></td>
<td>$1.5e-3/\text{mm}$</td>
<td>$0.3%/\text{mm}$</td>
<td>$\delta \text{pos} = 0.3\ \text{mm}$</td>
<td>$0.1%$</td>
</tr>
<tr>
<td><strong>Beta threshold</strong></td>
<td>$2e-4/10\ \text{keV}$</td>
<td>$0.065%/10\ \text{keV}$</td>
<td>$\delta \text{Th} = 15\ \text{keV}$</td>
<td>$0.1%$</td>
</tr>
<tr>
<td><strong>E-Field Stability</strong></td>
<td>$1e-4/\text{V}$</td>
<td>$0.03%/\text{V}$</td>
<td>$\delta \text{V} = 1\ \text{V}$</td>
<td>$0.03%$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>$0.3%$</td>
</tr>
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Fundamental symmetries with 6He