Nuclear $\beta$ Decay: Using the Atomic Nucleus to Probe Symmetries of the Weak Interaction

Dan Melconian
March 24, 2018
Overview

Introduction

- Fundamental symmetries
- What is our current understanding?
- How do we test what lies beyond?

The TRIUMF Neutral Atom Trap

- Angular correlations of polarized $^{37}$K
- Recent results
- Looking forward
the atom

From the very smallest scales . . .
Scope of fundamental physics

nucleons

quarks

electrons

the atom

From the very smallest scales . . .

. . . to the very largest
All of the *known* elementary particles and their interactions are described within the framework of

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- Noether’s theorem: symmetry \(\Leftrightarrow\) conservation law

Maxwell’s eqns invariant under changes in vector potential \(\Leftrightarrow\) conservation of electric charge, \(q\)

and there are other symmetries too:

- time \(\Leftrightarrow\) energy
- space \(\Leftrightarrow\) momentum
- rotations \(\Leftrightarrow\) angular momentum

\[\vdots\]
All of the *known* elementary particles and their interactions are described within the framework of

The Standard Model

- Quantum + special rel $\Rightarrow$ quantum field theory
- Noether’s theorem: symmetry $\Leftrightarrow$ conservation law
- 12 elementary particles, 4 fundamental forces

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<th>leptons</th>
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- **quantum** + special rel $\Rightarrow$ quantum field theory
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$
\begin{align*}
\text{leptons} & : (\nu_e, \nu_\mu, \nu_\tau) \\
\text{quarks} & : (u, d, s, c, t, b)
\end{align*}$
That’s all fine and dandy, but...

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✔ It **predicted** the existence of the $W^\pm$, $Z_0$, $g$, $c$ and $t$
  ~⇒ and now **the Higgs**!
✔ It is a **renormalizable** theory
✔ GSW ⇒ **unified** the **weak** force with **electromagnetism**
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(see 2017 PDG)

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Wow ... this is

the most precisely tested theory ever conceived!

Dan Melconian

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Joint APS/AAPT Meeting
March 23, 2018
But there are still questions . . .

- **parameters values**: Does our “ultimate” theory really need 25 arbitrary constants? Do they change with time?
- **dark matter**: SM physics makes up less than 5% of the energy-matter of the universe!
- **baryon asymmetry**: Why more matter than anti-matter?
- **strong CP**: Do axions exist? Fine-tuning?
- **neutrinos**: Dirac or Majorana? Mass hierarchy?
- **fermion generations**: Why three families?
- **weak mixing**: Is the CKM matrix unitary?
- **parity violation**: Is parity maximally violated in the weak interaction? No right-handed currents?
- **gravity**: Of course, we can’t forget about a quantum description of gravity!
How we **all** test the SM

- **colliders**: CERN, SLAC, FNAL, BNL, KEK, DESY . . .
- **nuclear physics**: traps, exotic beams, neutron, EDMs, $0\nu\beta\beta$, . . .
- **neutrinos**: sterile $\nu$ vs, oscillations, coherent scattering, . . .
- **cosmology & astrophysics**: SN1987a, Big Bang nucleosynthesis, . . .
- **muon decay**: Michel parameters: $\rho$, $\delta$, $\eta$, and $\xi$
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All of these techniques are **complementary** and **important**

- different experiments probe different (new) physics
- if signal seen, cross-checks crucial!
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**often they are interdisciplinary**

(which makes it extra *fun!*
How does high-energy physics test the SM?

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direct search of particles

27 km

Compact Muon Solenoid
How does high-energy physics test the SM?

Colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, ….

**direct** search of particles

- large multi-national collabs
- *billion* $ price-tags
How does nuclear physics test the SM?
Overcoming temptation, David opted against the obvious, unsportsmanlike cheap shot.
How does nuclear physics test the SM?

Nuclear physics: radioactive ion beam facilities

indirect search via precision measurements
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How does nuclear physics test the SM?

Nuclear physics: radioactive ion beam facilities

- indirect search via precision measurements
- smaller collaborations
- contribute to all aspects
- “table-top” physics
Initially quite a mystery:

- why does the “β” particle have a continuous energy spectrum? is angular momentum not conserved?
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A primer in $\beta$ decay

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Revolutionary idea and discovery: Unlike the other forces, parity is **not** conserved by the weak interaction!

Now understood as a \((V - A)\) interaction at the quark level mediated by the \(W^\pm\) boson:

\[
\frac{A}{Z} X \rightarrow \frac{A}{Z-1} Y + e^+ + \nu_e
\]
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![Diagram of $\beta$ decay process]

$\frac{A}{Z}X \rightarrow \frac{A}{Z-1}Y + e^+ + \nu_e$

But is it completely left-handed...?
The **electroweak interaction**: $\text{SU}(2)_L \times U(1) \implies W_L^\pm, Z^°, \gamma$
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Built upon **maximal** parity violation:

$$H_{\text{SM}} = G_F V_{ud} \bar{e} \left( \gamma_\mu - \gamma_\mu \gamma_5 \right) \nu_e \bar{u} \left( \gamma^\mu - \gamma^\mu \gamma_5 \right) d$$
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$A = \text{M.C. Escher reptiles}$

$\hat{P}A = +A$

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$\vec{A} = M \cdot C \cdot \text{Escher reptiles}$

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\( \Rightarrow \) 3 more vector bosons: \( W^\pm_R, Z' \)

Simplest extensions: "**manifest left-right symmetric**" models

\( \Rightarrow \) only 2 new parameters: \( W_2 \) mass and a mixing angle, \( \zeta \):

\[
|W_L\rangle = \cos \zeta |W_1\rangle - \sin \zeta |W_2\rangle \\
|W_R\rangle = \sin \zeta |W_1\rangle + \cos \zeta |W_2\rangle
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The existence of RHCs would affect the values of $\beta$ decay parameters
**How do I test the SM?**

Begin by looking at the rate for $\beta$ decay

\[
\frac{dW}{dE_e} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_0 - E_e)^2
\]

![Graph showing the intensity of $\beta$ decay against kinetic energy](image)
Expand to the often-quoted **angular distribution** of the decay:

(Jackson, Treiman and Wyld, Phys Rev 106 and Nucl Phys 4, 1957)

\[
\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_0 - E_e)^2 \xi \left( 1 + a_{\beta \nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_{\nu_e}} + b \frac{\Gamma m_e}{E_e} \right)
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\[
a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2}{|C_V|^2 + |C'_V|^2}
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\]

**Scalar**

\[
a_{\beta\nu} = -\frac{|C_S|^2 - |C'_S|^2}{|C_S|^2 + |C'_S|^2}
\]

**Vector**

\[
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\]

\[
a_{\beta\nu} = \frac{-|C_S|^2 - |C'_S|^2}{|C_S|^2 + |C'_S|^2}
\]

\[
a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} = 1 ??
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\]

\[
+ \frac{\langle \vec{I} \rangle}{I} \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_{\nu}}{E_{\nu}} + D \frac{\vec{p}_e \times \vec{p}_{\nu}}{E_e E_{\nu}} \right] + \ldots
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\]

E.g. \( A_\beta = \frac{-2\rho}{1+\rho^2} \left[ (1-x)y \sqrt{3(1+x^2)(1+y^2)} - \frac{\rho(1-y^2)}{5(1+y^2)} \right] \)

where \( x \approx (M_L/M_R)^2 - \zeta \)

and \( y \approx (M_L/M_R)^2 + \zeta \)

are right-handed current parameters that are zero in the SM, and \( \rho \equiv \frac{C_A M_{GT}}{C_V M_F} \)
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\beta \text{-asy} \quad \nu \text{ asym} \quad T\text{-violating}
\]

- \(\beta\)-decay parameters depend on the currents mediating the weak interaction
- sensitive to **new physics**

E.g. \(A_\beta = \frac{-2\rho}{1+\rho^2} \left[ (1-xy) \sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)} \right] \)

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$$\frac{d^5 W}{dE_e d\Omega_e d\Omega_{\nu e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\beta - B_\beta) E_\nu + \ldots$$

- **basic decay rate**
- **$\beta-\nu$ correlation**
- **Fierz term**

$\beta$-decay parameters depend on the currents mediating the weak interaction
⇒ sensitive to **new physics**

Goal must be \( \lesssim 0.1\% \) to complement LHC

Cirigliano, González-Alonso and Graesser, JHEP 1302, 046 (2013)
Vos, Wilschut and Timmermans, RMP 87, 1483 (2015)

zero in the SM, and $\rho \equiv \frac{C_A M_G T}{C_V M_F}$
How to achieve our goal?

Perform a $\beta$ decay experiment on short-lived isotopes
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- **Compare** the SM predictions to observations
- Look for **deviations** as an indication of new physics
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Perform a nuclear measurement — often using atomic techniques — to test high-energy theories
Fig. 1. Schematic drawing of the lower part of the cryostat.
C.S. Wu’s experiment – Parity violation

- so much scattering!
- low polarization
- short relaxation time
- poor sample purity
- pain to flip the spin
- need long $t_{1/2}$

Fig. 1. Schematic drawing of the lower part of the cryostat.
Fast-forward 70 yrs . . .

Measure same correlation, $A_\beta$, in $^{37}$K at TRIUMF using modern techniques
The $\beta^+$-decay of $^{37}\text{K}$

Almost as simple as $0^+ \rightarrow 0^+$:

<table>
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<tr>
<th>Decay Path</th>
<th>Branching</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{37}_{19}\text{K}$ $\beta^+$</td>
<td>$3/2^+$ 1.225(7) s</td>
</tr>
<tr>
<td>$^{37}_{18}\text{Ar}$ $3/2^+$</td>
<td>97.99(14)%</td>
</tr>
<tr>
<td>$^{37}_{19}\text{K}$ $5/2^+$</td>
<td>0.022%</td>
</tr>
<tr>
<td>$^{37}_{18}\text{Ar}$ $5/2^+$</td>
<td>2.07(11)%</td>
</tr>
</tbody>
</table>

- isobaric analogue decay
- strong branch to g.s.
Almost as simple as $^0_+ \rightarrow ^0_+$:

- **isobaric analogue** decay
- **strong** branch to g.s.
- **polarization/alignment**
- **mixed** Fermi/Gamow-Teller

$\Rightarrow$ need $\rho \equiv G_A M_{GT}/G_V M_F$ to get SM prediction for correlation parameters

Get $\rho$ from the comparative half-life:

$$\rho^2 = \frac{2\mathcal{F}t^{0+\rightarrow0+}}{\mathcal{F}t} - 1$$
The $\beta^+$-decay of $^{37}$K

Almost as simple as $0^+ \rightarrow 0^+$:

<table>
<thead>
<tr>
<th>State</th>
<th>3/2$^+$</th>
<th>5/2$^+$</th>
<th>3/2$^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{37}$K</td>
<td>1.225(7) s</td>
<td>0.022%</td>
<td>97.99(14)%</td>
</tr>
<tr>
<td>$^{37}$Ar</td>
<td>2.07(11)%</td>
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<td></td>
</tr>
</tbody>
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- **polarization/alignment**
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$\Rightarrow$ need $\rho \equiv \frac{G_A M_{GT}}{G_V M_F}$ to get SM prediction for correlation parameters

Get $\rho$ from the comparative half-life:

$Q_{EC}$: ±0.003%

$BR$: ±0.14%

$t_{1/2}$: ±0.08%

$\mathcal{F}t = 4605(8) \Rightarrow \rho = 0.5768(21)$

$\Rightarrow A^\text{SM}_\beta = -0.5719(7)$, predicted to <0.1%
Atomic methods have opened up a new vista in precision work and provide the ability to push $\beta$ decay measurements to $\lesssim 0.1\%$.

- laser-cooling and trapping (magneto-optical traps)
- sub-level state manipulation (optical pumping)
- characterization/diagnostics (photoionization)
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Traps provide a backing-free, very cold ($\lesssim 1\ mK$), localized ($\sim 1\ mm^3$) source of isomERICALLY-selective, short-lived radioactive atoms.
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- laser-cooling and trapping (magneto-optical traps)

Traps provide a backing-free, very cold ($\lesssim 1$ mK), localized ($\sim 1$ mm$^3$) source of isomerically-selective, short-lived radioactive atoms.

Detect $\vec{p}_\beta$ and $\vec{p}_{\text{recoil}}$ and deduce $\vec{p}_\nu$ event-by-event!!
The TRINAT lab
The measurement chamber

Electrostatic hoops

Laser light

Electron MCP

Recoil MCP

BC408 scintillator

40×40×0.3 mm³ Si-strip detector

re-entrant flange and collimator

Mirror with 275 µm-thick SiC substrate

229 µm-thick Be foil

90 mm

(Anti-) Helmholtz coils

Dan Melconian

Joint APS/AAPT Meeting
March 23, 2018
Outline of polarized experiment

\[ D_2 \text{ MOT} \]

anti-Helmholtz
Outline of polarized experiment

Dan Melconian

\[ \vec{F} = \vec{I} + \vec{J} \]

Helmholtz

Joint APS/AAPT Meeting
March 23, 2018
Outline of polarized experiment

- E-field
- MCP
- K⁺
- Helmholtz
- Photoionization
- D₁ OP

\[ \vec{F} = \vec{I} + \vec{J} \]

- Polarization:
  - \( P_{1/2} \)
  - \( S_{1/2} \)

- Quantum States:
  - \( m_F = -2 \)
  - \( \pm \sigma \)

355 nm
Deduce $P$ based on a model of the excited state populations.
Deduce $P$ based on a model of the excited state populations

$$P_{1/2}$$

$$S_{1/2}$$

$m_F = -2 \quad -1 \quad 0 \quad 1 \quad 2$

$$S_3 = 0.9958$$

$$B_{bad} = 0.028(6)(8)$$

$$\chi^2/781 = 1.098$$

$$\Rightarrow P_{\text{nucl}} = 0.9932^{+3}_{-5}$$
Atomic measurement of $P$

Deduce $P$ based on a model of the excited state populations

\[ \Rightarrow \langle P_{\text{nucl}} \rangle = 99.13(8)\% \]

and

\[ \langle T_{\text{align}} \rangle = -0.9767(25) \]

Fenker et al., New J. Phys. 18, 073028 (2016)
Energy Spectrum Compared to GEANT4

Note: there is no background subtraction!

\[ \chi^2/229 = 1.04 \]

CL = 31%
Asymmetry Measurement (briefly)

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Asymmetry Measurement (briefly)

\[ A_{\text{obs}}(E_e) = \frac{1 - S(E_e)}{1 + S(E_e)}, \quad \text{where} \quad S(E_e) \equiv \sqrt{\frac{r_1^-(E_e)r_2^+(E_e)}{r_1^+(E_e)r_2^-(E_e)}} \]
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\[ \chi^2/41 = 0.957 \]

CL = 55%
Asymmetry Measurement (briefly)

\[
\chi^2/41 = 0.957 \\
CL = 55\%
\]

**PHYSICAL REVIEW LETTERS** 120, 062502 (2018)

**Precision Measurement of the \( \beta \) Asymmetry in Spin-Polarized \( ^{37}\text{K} \) Decay**

B. Fenker,\(^{1,2}\) A. Gorelov,\(^{3}\) D. Melconian,\(^{1,2,*}\) J. A. Behr,\(^{3}\) M. Anholm,\(^{3,4}\) D. Ashery,\(^{5}\) R. S. Behling,\(^{1,6}\) I. Cohen,\(^{5}\) I. Craiciu,\(^{3}\) G. Gwinner,\(^{4}\) J. McNeil,\(^{7,3}\) M. Mehlman,\(^{1,2}\) K. Olchanski,\(^{3}\) P. D. Shidling,\(^{1}\) S. Smale,\(^{3}\) and C. L. Warner\(^{3}\)
## $A_\beta$ Error Budget

<table>
<thead>
<tr>
<th>Source</th>
<th>Correction</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Systematics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>1.0014</td>
<td>0.0008</td>
</tr>
<tr>
<td>$\beta$ scattering$^a$</td>
<td>1.0230</td>
<td>0.0007</td>
</tr>
<tr>
<td>Trap ($\sigma^+\text{ vs }\sigma^-$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>position (typ $\lesssim \pm 20$ $\mu$m)</td>
<td></td>
<td>0.0004</td>
</tr>
<tr>
<td>sail velocity (typ $\lesssim \pm 30$ $\mu$m/ms)</td>
<td></td>
<td>0.0005</td>
</tr>
<tr>
<td>temperature (typ $\lesssim \pm 0.2$ mK)</td>
<td></td>
<td>0.0001</td>
</tr>
<tr>
<td>Si-strip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>radius$^a$ ($15.5^{+3.5}_{-5.5}$ mm)</td>
<td></td>
<td>0.0004</td>
</tr>
<tr>
<td>energy agreement ($\pm 3\sigma \rightarrow \pm 5\sigma$)</td>
<td></td>
<td>0.0002</td>
</tr>
<tr>
<td>threshold ($60 \rightarrow 40$ keV)</td>
<td></td>
<td>0.0001</td>
</tr>
<tr>
<td>Shakeoff electron TOF region ($\pm 3.8 \rightarrow \pm 4.6$ ns)</td>
<td></td>
<td>0.0003</td>
</tr>
<tr>
<td>SiC mirror$^a$ ($\pm 6$ $\mu$m)</td>
<td></td>
<td>0.0001</td>
</tr>
<tr>
<td>Be window$^a$ ($\pm 23$ $\mu$m)</td>
<td></td>
<td>0.00009</td>
</tr>
<tr>
<td>Si-strip$^a$ ($\pm 5$ $\mu$m)</td>
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<td>0.0001</td>
</tr>
<tr>
<td>Scintillator only vs $E + \Delta E^a$</td>
<td></td>
<td>0.0001</td>
</tr>
<tr>
<td>Scintillator threshold ($400 \rightarrow 1000$ keV)</td>
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<td>0.00003</td>
</tr>
<tr>
<td>Scintillator calibration ($\pm 0.4$ ch/keV)</td>
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<td>0.00001</td>
</tr>
<tr>
<td><strong>Total systematics</strong></td>
<td></td>
<td>0.0013</td>
</tr>
<tr>
<td><strong>Statistics</strong></td>
<td></td>
<td>0.0013</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>1.0088</td>
<td>0.0005</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.0338</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

$^a$Denotes sources that are related to $\beta^+$ scattering.
In terms of CKM unitarity, our $A_\beta$ result improved $V_{ud}$ for this nucleus by nearly a factor of five: $|V_{ud}| = 0.981^{+12}_{-10} \rightarrow 0.9745(25)$. 
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In terms of right-handed currents, our result is the best nuclear limit: $M_{WR} > 351$ GeV (in minimal left-right symmetric models)

Analysis of Fierz and second-class currents ($E$-dependent observables) to be finished soon
Summary

- The SM is fantastic, but **not** our “ultimate” theory. There are many exciting avenues to find more a complete model.

- **Nuclear approach:** precision measurement of correlation parameters

- (AC-)MOT + opt. pumping = *cool* physics
  - extremely precise, high nuclear polarization: $\langle P \rangle = 99.13(8)\%$
  - best nuclear limit on $M_{WR} > 351$ GeV (at $\zeta = 0$).
  - on the way to a 0.1% measurement of $A_\beta$ and other (un)polarized correlations.


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  - best nuclear limit on $M_{WR} > 351$ GeV (at $\zeta = 0$).
  
  - on the way to a 0.1% measurement of $A_\beta$ and other (un)polarized correlations

- If you’re interested in this (or other nuclear physics – structure, astro, EoS, RHIC, reactions, . . .) and considering grad school:

  Nuclear @ TAMU #12 in 2010, #13 in 2014, now tied for #7 overall and #5 among public universities
The Mad Trappers/Thanks

TAMU: B. Fenker, S. Behling, M. Mehlman, P. Shidling
 + TAMU/REU undergrads
 + ENSICAEN interns

TRINAT:

TRIUMF J.A. Behr, J. McNeil, A. Gorelov, K. Olchanski, ...

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And thank you for your attention!