A new correlation Penning trap for fundamental physics at Texas A&M

Dan Melconian
Dec 5, 2014
1. Fundamental symmetries
   - brief motivation
   - game plan for testing the SM

2. Cyclotron Institute upgrade project
   - overview
   - expected RIB production

3. TAMU Penning Trap (being built)
   - physics of superallowed $\beta$ decay
   - ion trapping of proton-rich nuclei at T-REX
We all know the SM works stubbornly well

✔ it **predicted** the existence of the $W^\pm$, $Z_0$, $g$, $c$ and $t$

$\implies$ and now the Higgs!

✔ is a **renormalizable** theory

✔ GSW $\Rightarrow$ **unified** the weak force with **electromagnetism**

✔ QCD explains quark confinement

\[ a_\mu \equiv \frac{1}{2}(g - 2) \]

\[ \Delta a_\mu = 288(80) \times 10^{-11}!! \]

(PDG 2013)
We all know the SM works stubbornly well

- It predicted the existence of the $W^\pm$, $Z_0$, $g$, $c$ and $t$
- and now the Higgs!
- It is a renormalizable theory
- GSW $\Rightarrow$ unified the weak force with electromagnetism
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$$a_\mu \equiv \frac{1}{2}(g - 2)$$

$$\Delta a_\mu = 288(80) \times 10^{-11}!$$

(PDG 2013)

Wow ... this is the most precisely tested theory ever conceived!
But we also know there’s more to discover

.parameters values:. does our “ultimate” theory really need 25 arbitrary constants? Do they change with time?

dark matter:. SM physics makes up only 4% 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 can’t forget about a quantum description of gravity!
How do many of us plan to test the SM?

- perform a $\beta$ decay experiment on short-lived isotopes
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- perform a $\beta$ decay experiment on **short-lived** isotopes
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How do many of us plan to test the SM?

- perform a $\beta$ decay experiment on **short-lived** isotopes
- make a **precision measurement** of the angular correlation parameters
- **compare** the SM predictions to observations
- look for **deviations** as an indication of **new physics**
- try to convince HEP community when you see something! 😊
Test SM via the **angular distribution** of $\beta$ decay: the often-quoted Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)

\[
\frac{d^5 W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_o - E_e)^2 \xi \left( 1 + b \frac{\Gamma m_e}{E_e} \right)
\]
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\]

**vector**

\[
a_{\beta\nu} = \frac{|C_V|^2 + |C_V'|^2}{|C_V|^2 + |C_V'|^2}
\]
Test SM via the **angular distribution** of $\beta$ decay: the often-quoted Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)

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\]

**vector**

\[
a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2}{|C_V|^2 + |C'_V|^2}
\]

**scalar**

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

\[
a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}
\]
A little more specifically...

Test SM via the **angular distribution** of $\beta$ decay: the often-quoted Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_0 - E_e)^2 \xi \left( 1 + \frac{A_{\beta\nu}}{E_e E_{\nu_e}} \right) \frac{p_e \cdot p_{\nu_e}}{E_e} + \frac{b}{E_e} \Gamma m_e$$

$$+ \frac{\langle I \rangle}{I} \cdot \left[ A_\beta \frac{p_e}{E_e} + B_\nu \frac{p_\nu}{E_\nu} + D \frac{p_e \times p_\nu}{E_e E_\nu} \right] + \ldots$$
A little more specifically...

Test SM via the **angular distribution** of $\beta$ decay: the often-quoted Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)

$$
\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \text{basic decay rate} \left( 1 + \frac{a_{\beta\nu}}{E_e E_{\nu_e}} \right) + \frac{b}{E_e} \frac{\Gamma m_e}{E_e} + \ldots
$$

where

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

and

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

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

are right-handed current parameters that are zero in the SM.
A little more specifically...

Test SM via the **angular distribution** of $\beta$ decay: the often-quoted Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)

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

**$\beta$-decay parameters** depend on the currents mediating the weak interaction

$\Rightarrow$ sensitive to **new physics**

Goal must be **0.1%** to complement LHC

Overview

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The Cyclotron Institute at Texas A&M

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE
The T-REX Upgrade Project

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE

- ECR ION SOURCE
- K500 CYCLOTRON
- BEAM ANALYSIS SYSTEM 1994
- LIGHT ION GUIDE
- CB-ECR SOURCE
- HEAVY ION GUIDE

- RADIATION EFFECTS FACILITY 1994, 2000, 2005
- MARS RECOIL SPECTROMETER 1992
- Q^2 SPECTROMETER 2012
- NIMROD 1999
- TAPE TRANSPORT & PRECISION DECAY FACILITY 1999
- MDM SPECTROMETER 1993, 2000
- LLNL LINE 2011

K150 (88°) CYCLOTRON

36 FEET
### K500 primary beams

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy [MeV/u]</th>
<th>Intensity [$\mu A$]</th>
<th>Isotope</th>
<th>Energy [MeV/u]</th>
<th>Intensity [$\mu A$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>55</td>
<td>27</td>
<td>$^{20}$Ne</td>
<td>28</td>
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</tr>
<tr>
<td>$d$</td>
<td>35</td>
<td>21</td>
<td>$^{22}$Ne</td>
<td>29</td>
<td>0.5</td>
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<tr>
<td>$^3$He</td>
<td>45</td>
<td>11</td>
<td>$^{34}$S</td>
<td>20</td>
<td>0.7</td>
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<tr>
<td>$^4$He</td>
<td>35</td>
<td>10</td>
<td>$^{40}$Ar</td>
<td>17</td>
<td>1.4</td>
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<tr>
<td>$^6$Li</td>
<td>35</td>
<td>7</td>
<td>$^{40}$Ca</td>
<td>17</td>
<td>1.5</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>25</td>
<td>7</td>
<td>$^{59}$Co</td>
<td>11</td>
<td>0.9</td>
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<tr>
<td>$^{10}$B</td>
<td>35</td>
<td>4</td>
<td>$^{78}$Kr</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>29</td>
<td>4.7</td>
<td>$^{86}$Kr</td>
<td>8.3</td>
<td>0.6</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>35</td>
<td>2.3</td>
<td>$^{129}$Xe</td>
<td>5.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>
The Light Ion Guide

- mainly \((p, n)\), \((d, p)\) and \((\alpha, n)\) reactions, based on JYFL design
- also light-ion induced fission with heavy targets
The Light Ion Guide

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35 FEET

Dan Melconian

Dec 5, 2014
TCP2014
Takamatsu
heavy ion deep inelastic collisions and fragmentation
fusion evapouration reaction
The Heavy Ion Guide

- heavy ion deep inelastic collisions and fragmentation
- fusion reactions
Projected intensities after K500 (based on JYFL experience)

<table>
<thead>
<tr>
<th>$(p, n)$ product</th>
<th>Max energy [MeV/u]</th>
<th>Intensity [pps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{27}$Si</td>
<td>57</td>
<td>$6 \times 10^3$</td>
</tr>
<tr>
<td>$^{50}$Mn</td>
<td>45</td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td>$^{54}$Co</td>
<td>45</td>
<td>$6 \times 10^3$</td>
</tr>
<tr>
<td>$^{64}$Ga</td>
<td>45</td>
<td>$4 \times 10^4$</td>
</tr>
<tr>
<td>$^{92}$Tc</td>
<td>35</td>
<td>$4 \times 10^4$</td>
</tr>
<tr>
<td>$^{106}$In</td>
<td>28</td>
<td>$4 \times 10^4$</td>
</tr>
<tr>
<td>$^{108}$In</td>
<td>28</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>$^{110}$In</td>
<td>26</td>
<td>$6 \times 10^4$</td>
</tr>
</tbody>
</table>
### Expected RIB Production – HIG

Projected intensities after K500 (calc by G. Souliotis)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$^9$Li</td>
<td>45</td>
<td>$3 \times 10^6$</td>
<td>$^7$Li</td>
<td>60</td>
</tr>
<tr>
<td>$^{11}$Be</td>
<td>45</td>
<td>$1 \times 10^6$</td>
<td>$^8$Be</td>
<td>70</td>
</tr>
<tr>
<td>$^{22}$O</td>
<td>40</td>
<td>$4 \times 10^4$</td>
<td>$^{11}$O</td>
<td>63</td>
</tr>
<tr>
<td>$^{24}$Ne</td>
<td>40</td>
<td>$1 \times 10^4$</td>
<td>$^{14}$Ne</td>
<td>70</td>
</tr>
<tr>
<td>$^{32}$Mg</td>
<td>40</td>
<td>$2 \times 10^4$</td>
<td>$^{22}$Mg</td>
<td>57</td>
</tr>
<tr>
<td>$^{38}$S</td>
<td>36</td>
<td>$4 \times 10^5$</td>
<td>$^{23}$S</td>
<td>60</td>
</tr>
<tr>
<td>$^{42}$Ar</td>
<td>39</td>
<td>$5 \times 10^5$</td>
<td>$^{27}$Ar</td>
<td>62</td>
</tr>
<tr>
<td>$^{62}$Fe</td>
<td>38</td>
<td>$3 \times 10^4$</td>
<td>$^{62}$Fe</td>
<td>47</td>
</tr>
<tr>
<td>$^{60}$Cr</td>
<td>32</td>
<td>$1 \times 10^3$</td>
<td>$^{65}$Ga</td>
<td>45</td>
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$T = 2$ superallowed decays

\[ \beta^+ \quad 0^+, T=2 \]

$p \quad \gamma$

\[ T = 1 \quad T = 2 \]

\[ 44^{\text{Cr}} \quad 40^{\text{Ti}} \]

\[ 36^{\text{Ca}} \quad 32^{\text{Ar}} \]

\[ 24^{\text{Si}} \quad 28^{\text{S}} \]

\[ 20^{\text{Mg}} \]

\[ \text{Stable} \]

\[ T = 1 \]

\[ T = 2 \]
\[ T = 2 \text{ superallowed decays} \]

\[ \begin{align*}
0^+, T &= 2 \\
\beta^+ \\
\beta^- + \nu + 0^+, T &= 2 \\
\gamma \\
p \\
\end{align*} \]

- \( \beta^- - \nu \) correlations
- ft values: test \( \delta_C \); \( V_{ud} \) (?)
- spectroscopy of proton-rich nuclei

\[ \begin{array}{c}
\text{Stable} \\
T = 1 \\
T = 2 \\
\end{array} \]
\[ T = 2 \] superallowed decays

pure Fermi decay \( \Leftrightarrow \) minimal structure effects; decay rate simply given by:

\[
d W_0 \left( 1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b_F \frac{\Gamma m_e}{E_e} \right)
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\[ \beta^- \nu \] correlations

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spectroscopy of proton-rich nuclei
\( T = 2 \) superallowed decays

\[ dW_0 \left( 1 + \alpha_{\beta \nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b_F \frac{\Gamma m_e}{E_e} \right) \]

pure Fermi decay \( \iff \) minimal structure effects; decay rate simply given by:

\[ \beta - \nu \] correlations

\[ f^t \text{ values: test } \delta_C; V_{ud} (\?) \]

spectroscopy of proton-rich nuclei

\( 44^{20} \text{M} \)

Proton energy [MeV]
Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of $^{32}$Ar

E. G. Adelberger,¹ C. Ortiz,² A. García,² H. E. Swanson,¹ M. Beck,¹ O. Tengblad,³ M. J. G. Borge,³ I. Martel,⁴ H. Bichsel,¹ and the ISOLDE Collaboration⁴

¹Department of Physics, University of Washington, Seattle, Washington 98195-1560
²Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556
³Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain
⁴EP Division, CERN, Geneva, Switzerland CH-1211

(Received 24 February 1999)

The positron-neutrino correlation in the $0^+ \rightarrow 0^+$ $\beta$ decay of $^{32}$Ar was measured at ISOLDE by analyzing the effect of lepton recoil on the shape of the narrow proton group following the superallowed decay. Our result is consistent with the standard model prediction. For vanishing Fierz interference we find $a = 0.9989 \pm 0.0052 \pm 0.0039$, which yields improved constraints on scalar weak interactions.
But why throw away useful information?

⇝ increase sensitivity and solid angle using a Penning trap to observe $e - p$ coincidences!
But why throw away useful information?

$$\beta - \nu$$ correlation from $^{32}\text{Ar}$

But why throw away useful information?

$\leadsto$ increase sensitivity and solid angle using a Penning trap to observe $e - p$ coincidences!
The Texas A&M University Penning Trap

- ID = 180 mm: very open-geometry ion trap for RIBs!
- uniquely suited for studying $\beta$-delayed proton decays:
  $\beta-\nu$ correlations, $ft$ values/$V_{ud}$
- also amendable to mass measurements, EC studies, laser spectroscopy, ... ⟨insert your idea here⟩
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# K500 production of $T = 2$ nuclei

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<tr>
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<th>Intensity</th>
<th>$E_p$ [MeV]</th>
<th>$R_L$ [mm]</th>
</tr>
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<tbody>
<tr>
<td>$^{20}\text{Mg}$</td>
<td>$1 \times 10^4$</td>
<td>4.28</td>
<td>42.7</td>
</tr>
<tr>
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<td>3.91</td>
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</tr>
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</tr>
<tr>
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<td>2.55</td>
<td>33.0</td>
</tr>
<tr>
<td>$^{40}\text{Ti}$</td>
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<td>3.73</td>
<td>22.9</td>
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Isotope Intensity $E_p$ [MeV] $R_L$ [mm]

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| $^{36}\text{Ca}$ | $2 \times 10^4$ | 2.55 | 33.0 |
| $^{40}\text{Ti}$ | $7 \times 10^5$ | 3.73 | 22.9 |

- **Black**: Stable
- **Green**: $T = 1$
- **Yellow**: $T = 2$
Efficiencies

Biggest hits/worries:

- BigSol separation: ~30%
Efficiencies

Biggest hits/worries:

- BigSol separation: ~ 30%
- gas-catcher: ~ 10%
Efficiencies

Biggest hits/worries:

- **BigSol separation:** \( \sim 30\% \)
- **gas-catcher:** \( \sim 10\% \)
- **RFQ cooler/buncher:** \( \sim 50\% \)
Efficiencies

Biggest hits/worries:

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Efficiencies

Biggest hits/worries:
- BigSol separation: $\sim 30\%$
- gas-catcher: $\sim 10\%$
- RFQ cooler/buncher: $\sim 50\%$
- purification trap (?): $\sim 50\%$

Overall efficiency expected to be $\geq 0.5\%$. 
Current status (come visit and see!)
Current status (come visit and see!)
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Current status (come visit and see!)
Begin trapping RIB soon after K150 and heavy ion guide commissioned (by 2016)

Installed and tested
Built, but not yet installed/tested
This is a great conference!!

 Beef up the RFQ driver (thanks Peter!)
This is a great conference!!

- Beef up the RFQ driver (thanks Peter!)
- Need a purification trap? (thanks Ryan!)
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Burning questions
- Detectors in or out of 7T magnet...?
  - particle trajectories more normal to detector surface if out; and easier to get ions into trap?
  - if in, excite to higher radius to avoid $e^+$ losses?
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  - for $f_t$ value measurements
  - daughter nuclei also $\beta^+$ decays
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  - if in, excite to higher radius to avoid $e^+$ losses?
- Any good way to count (precisely) the number of trapped ions...?
  - for $ft$ value measurements
  - daughter nuclei also $\beta^+$ decays
- A million other smaller things that we’ve probably not considered...
Arigatou Gozaimasu

TAMU members: Mike Mehlman, Praveen Shidling, Yakup Boran; Eames Bennett

This community must be the friendliest in all of science...!

Many thanks to all who have helped:
- Sage advice/drawings from TITAN (Dilling, Kwiatkowski, Good), CPT (Savard, Clark), LEBIT (Ringle, Bollen)
- Local support from the Cyclotron Institute (Tabacaru, Chubaryan, ...)

Also, thank$ to
- DOE DE-FG02-93ER40773, Early Career ER41747
- TAMU/Cyclotron Institute
Angular correlations in $\beta$ decay can be used to probe physics beyond the standard model to be competitive, precision must be 0.1%
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Upgraded Cyclotron Institute offers a unique niche for RIB experiments:
- K500 and K150 – coupled or in parallel
- No PAC!!; flexible scheduling and beamtime availability
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TAMUTRAP: unique facility to study $\beta$-delayed proton decays
- scalar currents through $a_{\beta\nu}$: enhanced sensitivity
- $ft/V_{ud}$ and other applications
Angular correlations in $\beta$ decay can be used to probe physics beyond the standard model
  
  - to be competitive, precision must be 0.1%

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  - K500 and K150 – coupled or in parallel
  - No PAC!!; flexible scheduling and beamtime availability

TAMUTRAP: unique facility to study $\beta$-delayed proton decays
  
  - scalar currents through $a_{\beta\nu}$: enhanced sensitivity
  - $ft/V_{ud}$ and other applications

Happy to collaborate — let’s trade beamtime for expertise!