Weak (and ridiculously weak) interactions as tests of fundamental physics

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Presentation for REUs — July 25, 2012
1. Fundamental symmetries
   - what is our current understanding?
   - what lies beyond?

2. Tools of the trade
   - trapping short-lived neutral atoms
   - polarizing the atom cloud

3. Angular correlations using laser-cooled atoms
   - angular correlations of polarized $^{37}\text{K}$
   - expected limits on right-handed currents
Scope of fundamental physics

nucleons

quarks

the atom

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

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

**THE new STANDARD MODEL**
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THE new STANDARD MODEL

- quantum + special rel $\Rightarrow$ quantum field theory
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- \textbf{quantum} + \textbf{special rel} $\Rightarrow$ \textbf{quantum field theory}
- Noether’s theorem: symmetry $\iff$ conservation law
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Maxwell’s eqns invariant under changes in vector potential $\Leftrightarrow$ conservation of electric charge, $q$
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Maxwell’s eqns invariant under changes in vector potential $\Leftrightarrow$ conservation of electric charge, $q$

and there’s other symmetries too:

- time $\Leftrightarrow$ energy
- space $\Leftrightarrow$ momentum
- rotations $\Leftrightarrow$ angular momentum

\ldots
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
- $SU(3) \times SU(2)_L \times U(1)$
- Electroweak
- Strong
- Weak
- E&M
- Gravity
- Classical general rel
All of the *known* elementary particles and their interactions are described within the framework of

THE **new** STANDARD MODEL

- **quantum** + **special rel** $\Rightarrow$ quantum field theory
- Noether’s theorem: symmetry $\Leftrightarrow$ conservation law
- $SU(3) \times SU(2)_L \times U(1)$: strong + electroweak
- 12 elementary particles and 4 fundamental forces

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That’s all fine and dandy, but…

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

\[
a_\mu(\text{exp}) = 11659208(6) \times 10^{-10}
\]

\[
a_\mu(\text{SM}) = 11659181(8) \times 10^{-10}
\]

$\pm 1$ part-per-million!!

(PRL 92 (2004) 161802)
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    \pm 1 \text{ part-per-million}!!
\end{align*}
\]

![Graph showing experimental and theoretical values of $a_\mu$]

Wow ... this is the most precisely tested theory ever conceived!
But there are still questions . . .

- **values of parameters**: 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?
- **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?
- **EW symmetry breaking**: how do the fermions acquire mass? Mass hierarchy?
- **gravity**: of course can’t forget about a quantum description of gravity!
At our energy scales, we see four distinct forces . . .
But these coupling ‘constants’ aren’t really constant: $\alpha_i \rightarrow \alpha_i(Q)$

- electromagnetic and weak strengths equal at $\approx 10^{13}$ GeV
- strong force gets weaker, but doesn’t unify with EW...
Beyond the Standard Model

But what if there is **new physics** we haven’t seen yet?

the running of the coupling constants would be affected; maybe they converge at some GUT scale?

Are the three theories of **E & M**, **weak** and **strong** interactions all **low-energy limits** of **one unifying** theory?
How do we test the SM?

colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, ... direct search of particles

“go big or go home”

- large multi-national collabs
- billion $ price-tags

Dan Melconian
How do we test the SM?

**nuclear physics**: radioactive ion beam facilities (ISOL/frag)

**indirect** search via precision measurements
nuclear physics: radioactive ion beam facilities (ISOL/frag) **indirect** search via precision measurements
**How do we test the SM?**

**nuclear physics**: radioactive ion beam facilities (ISOL/frag) **indirect** search via precision measurements

- smaller collaborations
- contribute to all aspects
- “table-top” physics 😄
How we all test the SM

- **colliders**: CERN, SLAC, FNAL, BNL, KEK, DESY . . .
- **nuclear physics**: traps, exotic beams, neutron, EDMs, $0\nu\beta\beta$, . . .
- **cosmology & astrophysics**: SN1987a, Big Bang nucleosynthesis, . . .
- **muon decay**: Michel parameters: $\rho$, $\delta$, $\eta$, and $\xi$
- **atomic physics**: anapole moment, spectroscopy, . . .

All of these techniques are **complementary** and important.

- different experiments probe different (new) physics
- if signal seen, cross-checks crucial!

Often they are **interdisciplinary**

(fun and a great basis for graduate students!)
1768: Kant debates nature of incongruent counterparts
History up to 1957

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\[ \mathbf{V} = (x_\circ, y_\circ) \]

\[ \hat{P}\mathbf{V} = -\mathbf{V} \]
History up to 1957

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\[
A = \text{M.C. Escher reptiles} \\
\hat{P}A = +A
\]
**History up to 1957**

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- 1848: Pasteur *observes* optical rotation in chemical isomers
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**intrinsic parity \iff helicity or “handedness”**

\[ r \times p \rightarrow (-r) \times (-p) = r \times p \]

*spin is an *axial* vector*
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- 1927: Wigner shows Maxwell’s equations conserve parity
- 1934: Fermi’s theory of $\beta$ decay:

\[
\frac{dW}{dE_e} = \frac{G_F^2}{(2\pi)^5} p_e E_e (E_e - A_0)^2 |\mathcal{M}_{fi}|^2 \\
\mathcal{M}_{fi} = \int \psi^* \Gamma_i \psi, \quad \Gamma_i = (S, P, V, A, T)
\]
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  $\theta^+ \rightarrow \pi^0\pi^+$ and $\tau^+ \rightarrow \pi^+\pi^+\pi^-$
  (but same lifetime, mass, . . . )
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- 1956: prompted Lee and Yang to question current convention.

...existing experiments do indicate parity conservation in strong and electromagnetic interactions, but that for weak interactions
...parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence.

(Feynman bets parity is conserved)
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  \[ K^+ \rightarrow \pi^0\pi^+ \text{ and } K^+ \rightarrow \pi^+\pi^+\pi^- \]
  (same particle; parity not conserved)
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(Feynman loses $50$)
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$K^+ \rightarrow \pi^0 \pi^- \pi^+$ (parity not conserved)

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$\beta$ decay has a long history of developing our understanding of fundamental symmetries.
The **Electroweak Interaction**: \( \text{SU}(2)_L \times \text{U}(1) \Rightarrow W^+_L, Z^0, \gamma \)

Built upon **maximal** parity violation:

Vector: \( \hat{P} |\Psi\rangle = - |\Psi\rangle \)

Axial−vector: \( \hat{P} |\Psi\rangle = + |\Psi\rangle \)

\[
H_{SM} = G_F V_{ud} \left[ \bar{e} (\gamma_\mu - i \gamma_5) e \right] \left[ \bar{u} (\gamma^\mu - i \gamma_5) d \right]
\]
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\[
H_{\text{SM}} = G_F V_{ud} \bar{e}(\gamma_\mu - i\gamma_5) \nu_e \bar{u}(\gamma^\mu - i\gamma_5) d
\]

**low-energy limit of a deeper** \( \text{SU}(2)_R \times \text{SU}(2)_L \times \text{U}(1) \) theory?
The Standard Model (and beyond)

The **Electroweak Interaction**: $SU(2)_L \times U(1) \Rightarrow W_L^\pm, Z^0, \gamma$

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Low-energy limit of a deeper $SU(2)_R \times SU(2)_L \times U(1)$ theory?

$\Rightarrow$ 3 more vector bosons: $W_R^\pm, Z'$

Simplest extensions: “**manifest left-right symmetric**” models

$\sim$ only 2 new parameters: $W_2$ mass and a mixing angle, $\zeta$

\[
\ket{W_L} = \cos \zeta \ket{W_1} - \sin \zeta \ket{W_2} \\
\ket{W_R} = \sin \zeta \ket{W_1} + \cos \zeta \ket{W_2}
\]
RHCs would affect correlation parameters

\[ A_\beta = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} - \frac{\rho}{5} \right) \]
\[ B_\nu = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} + \frac{\rho}{5} \right) \]

and \[ R_{\text{slow}} = 0 \]
RHCs would affect correlation parameters

In the presence of new physics, the angular distribution of $\beta$ decay will be affected.

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

\[
B_\nu = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} + \frac{\rho}{5} \right) \to \frac{-2\rho}{1+\rho^2} \left[ (1-xy) \sqrt{\frac{3(1+x^2)}{5(1+y^2)}} + \frac{\rho(1-y^2)}{5(1+y^2)} \right]
\]

and

\[R_{\text{slow}} = 0 \to y^2\]

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

are RHC parameters that are zero in the SM.
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In the presence of new physics, the angular distribution of $\beta$ decay will be affected.

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

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where $x \approx (M_L/M_R)^2 - \zeta$ and $y \approx (M_L/M_R)^2 + \zeta$

are RHC parameters that are zero in the SM.

$\Rightarrow$ Precision measurements test the SM

Goal must be $\lesssim 0.1\%$

(see Profumo, Ramsey-Musolf and Tulin, PRD 75 (2007))
The Gameplan:

\[ \frac{Z_A X}{\rightarrow} Z^{\pm 1}_A Y + e^{\pm} + \nu_e \]

- perform a $\beta$ decay experiment on short-lived isotopes
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- perform a $\beta$ decay experiment on short-lived isotopes
- make a precision measurement of the angular correlation parameters
The Gameplan:

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- perform a $\beta$ decay experiment on short-lived isotopes
- make a precision measurement of the angular correlation parameters
- compare the SM predictions to observations
The Gameplan:

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- 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
Fig. 1. Schematic drawing of the lower part of the cryostat.
Wu’s experiment

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

Fig. 1. Schematic drawing of the lower part of the cryostat.
Many groups around the world realize the potential of using traps for precision weak interaction studies.

- Atom traps: He, K, Na, Rb
- Ion traps: Na, Fr, planned
Any type of trap requires a velocity-dependent force to cool an object.
Any type of trap requires a velocity-dependent force to cool an object ... as well as a position-dependent force that defines $x = 0$. 

![Diagram of a trap with forces applied](image-url)
Any type of trap requires a velocity-dependent force to cool an object . . . as well as a position-dependent force that defines $x = 0$
Any type of trap requires a velocity-dependent force to cool an object ... as well as a position-dependent force that defines $x = 0$.
How can light seriously affect a thermal atom?

\[ \hbar c \cdot \frac{2\pi}{\lambda} = (197.3 \text{ MeV fm}) \left( \frac{6.28}{770 \text{ nm}} \right) \]
\[ = 1.6 \times 10^{-6} \text{ MeV} \]
\[ \Rightarrow \hbar k \sim 1.6 \text{ eV/c} \]

\[ \frac{1}{2} Mv^2 = k_B T \]
\[ M v = \left[ \frac{2(40 \times 10^6 \text{ keV/c}^2)}{(8.62 \times 10^{-8} \text{ keV/K})(295 \text{ K})} \right]^{1/2} \]
\[ \Rightarrow M v \sim 45 \text{ keV/c} \]
Cycling Transitions!

\[ \hbar k \times 30,000 \approx M v \]
However.

cycling transition $\Rightarrow$ not everything trappable
However....

cycling transition ⇒ not everything trappable

and *still* the trap is shallow...
Still, gotta love it!!

Raab PRL 59 (1987)

- isomerically selective!
Still, gotta love it!!

- isomerically selective!
- point-like source! (\(\lesssim 1 \text{ mm}^3\) FWHM)

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- cold atoms! ($\lesssim 1 \text{ mK}$)
- backing-free source!

Raab PRL 59 (1987)
Still, gotta love it!!

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- cold atoms! ($\lesssim 1$ mK)
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Raab PRL 59 (1987)

an ideal source of radioactives for $\beta$-decay experiments!
Coupling a MOT to ISAC-I

$\sigma^+ \sigma^- \sigma^+ \sigma^-$

$Zr$ neutralizer

$K^+$ ion beam

$^{37}K$ yield with 40 $\mu$A on TiC #1: $6 \times 10^7$/s
Double-MOT system

 Ion beam
 Push beam
 Neutralizer
 Collection chamber

 15 cm
 MCP
 Electrostatic hoops
 DSSSD
 BC408
 β detector
 Detection chamber
Traps provide a backing-free, cold ($\lesssim 1$ mK), localized ($\lesssim 1$ mm$^3$) source of short-lived radioactive atoms.

Detect $p_\beta$ and $p_{\text{recoil}} \Rightarrow$ deduce $p_\nu$!
The TRINAT lab
The TRINAT lab
The new chamber

- Shake-off $e^-$ detection
- Better control of OP beams
- $B_{\text{quad}} \rightarrow B_{\text{OP}}$ quickly: AC-MOT
  
  (Harvery & Murray, PRL 101 (2008))

- Increased $\beta$/recoil solid angles
- Stronger $E$-field
- ...
The new chamber

- Shake-off detection
- Better control of OP beams
  \( B_{\text{quad}} \rightarrow B_{\text{OP}} \) quickly: AC-MOT (Harvey & Murray, PRL 101 (2008))
- Increased \( \beta / \text{recoil solid angles} \)
- Stronger \( E \)-field
- ...
Outline of polarized experiment

\[ F = I + J \]

\[ I = \frac{3}{2} J \]

\[ F = \sigma \pm S \]

355 nm
Outline of polarized experiment

\[ F = I + J \]

\[ I = \frac{3}{2} J \]

\[ J = \frac{1}{2} 0^2 - 2 = m F \]

\[ \sigma \pm \frac{S_1}{2} \]

355 nm

D\textsubscript{2} trapping light

anti-Helmholtz
Outline of polarized experiment

\[ F = I + J \]

\[
I = \frac{3}{2} \\
J = \frac{1}{2}
\]

\[ m_F = \begin{array}{c}
-2 \\
-1 \\
0 \\
1 \\
2
\end{array} \]

Helmholtz (2 G)

D\subscript{1} pumping light

355 nm light pumping
Outline of polarized experiment

E-field

MCP

K+

photoionization

D1

light

Helmholtz (2 G)

F = I + J
I = \frac{3}{2}
J = \frac{1}{2}

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

σ±

355 nm

Dan Melconian

July 25, 2012
REU presentation
Atomic measurement of $P$

$P_{1/2}$

$S_{1/2}$

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

deduce $P$ based on a model of the excited state populations:

$$
\frac{S}{\sigma} \pm 2 = -1.1
$$

deduce $P_{\text{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$

$I = 124 \pm 22 \mu W/cm^2$

$B_{\text{bad}} = 210.3 \pm 40.5 \text{ mG}$

$\Delta = -4.50 \text{ MHz}$

$b = 0.085 \text{ counts}/10 \mu \text{s}$

$\chi^2/128 = 1.362$

$C.L. = 0.4\%$

$\Rightarrow \langle P \rangle = -97.0 \pm 0.9\%$

$\Rightarrow P_{\text{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$
for MOT currents rapidly switched to zero, the induced eddy currents continue to produce $B$ fields until they too reduce to zero.

In practice the $B$ field due to the MOT takes $\sim 10$ ms to reduce to $<10^{-7}$ T, this time depending on the proximity of conductors to the coils, their shape, and resistivity. During this time, a large fraction of trapped atoms escape, resulting in a cold atom density that rapidly falls to zero. Losses can be reduced by leaving the cooling lasers on to create an optical molasses (if this does not interfere with the experiment); however, the loss problems remain. The comparatively long time taken for the $B$ field to decay also reduces data accumulation rates, since the repetition rate is then only $\sim 50$ Hz.

It is clearly advantageous to eliminate these constraints. Several methods have been attempted, including shaping the dc MOT driving current at switchoff to try to cancel fields due to eddy currents [10]. This technique is complicated and requires different currents when spectrometer
Asymmetry = \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) - N(\sigma^-)} 
\sim PA_\beta \left\langle \frac{p_e}{E_e} \right\rangle

A = 81.3(1.0)\% 
P = (0.28 \pm 0.49)\% 
\text{finite vacuum}

A = -79.2(1.5)\%

P = 0.967
Measuring $B_\nu$ (and $D$)

\[ dW \sim PB_\nu \hat{p}_\nu \cdot \hat{i} + PD \frac{\hat{i} \cdot (p_\beta \times \hat{p}_\nu)}{E_\beta} \]

\[ \hat{p}_\beta \approx \hat{z} \Rightarrow p_\nu \approx -p_{Ar} \]
Measuring $B_\nu$ (and $D$)

\[ dW \sim P B_\nu \hat{p}_\nu \cdot \hat{i} + P D \frac{\hat{i} \cdot (p_{\beta} \times \hat{p}_\nu)}{E_\beta} \]

$\hat{p}_\beta \approx \hat{z} \Rightarrow p_\nu \approx -p_{Ar}$
Measuring $B_\nu$ (and $D$)

\[ dW \sim PB_\nu \hat{p}_\nu \cdot \hat{i} + PD \frac{\hat{i} \cdot (p_\beta \times \hat{p}_\nu)}{E_\beta} \]

\[ \hat{p}_\beta \approx \hat{z} \Rightarrow p_\nu \approx -p_{Ar} \]

\[ \hat{x} \text{ asymmetry } \sim PB_\nu \]
\[ \hat{y} \text{ asymmetry } \sim PD \]
The neutrino asymmetry measurement

1\textsuperscript{st}: \( \langle B_\nu \rangle = (0.995 \pm 0.040)B_{\nu}^{\text{SM}} \) (stat)

2\textsuperscript{nd}: \( \langle B_\nu \rangle = (0.975 \pm 0.031)B_{\nu}^{\text{SM}} \) (stat)

\Rightarrow \quad B_\nu = 0.981(26)(17)B_{\nu}^{\text{SM}}

(Melconian, PLB 649 (2007) 370)
**Goal, in terms of RHCs**

Expected limits if $A_\beta$, $B_\nu$ and $R_{\text{slow}}$ all measured to 0.1%

see Profumo, Ramsey-Musolf and Tulin, PRD 75 (2007) 075017
Beyond the minimal L-R symmetric model

(adapted from Thomas et al., Nucl Phys A 694; see also Severijns, Beck and Naviliat-Cuncic, Rev Mod Phys 78 (2006))

different experiments are complementary
Summary

- SM is fantastic, but incomplete
- many exciting avenues to find more complete model
- needed: precision measurement of correlation parameters
- (AC-)MOT + opt. pumping = cool physics
Summary

- SM is fantastic, but **incomplete**
- many **exciting avenues** to find more complete model
- **needed**: precision measurement of correlation parameters
- **(AC-)MOT + opt. pumping = cool** physics

Don’t get married five days before you’re supposed to give a talk! ;-)
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