Precision $\beta$-decay Studies using Trapped Atoms and Ions
1. Fundamental symmetries

- what is our current understanding?
- how do we test what lies beyond?

2. TAMU Penning Trap

- physics of superallowed $\beta$ decay
- ion trapping of proton-rich nuclei at T-REX

3. TRIUMF Neutral Atom Trap

- angular correlations of polarized $^{37}$K
- preliminary results of a recent run
Scope of fundamental physics

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

from the very smallest scales . . .
All of the *known* elementary particles and their interactions are described within the framework of

The Standard Model
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The Standard Model

量子 + 特殊相对论 $\Rightarrow$ 量子场理论
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 \(\iff\) conservation law
All of the **known** elementary particles and their interactions are described within the framework of

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Maxwell’s eqns invariant under changes in vector potential $\Leftrightarrow$ conservation of electric charge, $q$
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**The Standard Model**

- **quantum** + **special rel** ⇒ **quantum field theory**
- Noether’s theorem: symmetry ⇔ conservation law

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

and there are other symmetries too:

- time ⇔ energy
- space ⇔ momentum
- rotations ⇔ angular momentum
- :
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**
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\[
SU(3) \times \overbrace{SU(2)_L \times U(1)}^{\text{electroweak}} + \overbrace{\text{(classical general rel)}}^{\text{gravity}}
\]
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
- $SU(3) \times SU(2)_L \times U(1)$: strong + electroweak
- 12 elementary particles, 4 fundamental forces

<table>
<thead>
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<th>1st</th>
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- 12 elementary particles, 4 fundamental forces
  and (at least) 1 Higgs boson

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That’s all fine and dandy, but…

does the Standard Model work??
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✔ it predicted the existence of the \( W^\pm, Z^0, g, c \) and \( t \)

\( \rightsquigarrow \) and now the Higgs!

✔ is a renormalizable theory

✔ GSW ⇒ unified the weak force with electromagnetism

✔ QCD explains quark confinement
That’s all fine and dandy, but...

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- it **predicted** the existence of the $W^\pm$, $Z_0$, $g$, $c$ and $t$
- $\rightsquigarrow$ and now **the** Higgs!
- is a **renormalizable** theory
- GSW $\Rightarrow$ **unified** the strong force with **electromagnetism**
- QCD **explains** quark confinement

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

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

(PRL 92 (2004) 161802)
That’s all fine and dandy, but...

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(PRL 92 (2004) 161802)

$\mu^+\mu^-$

$e^+e^-$

$\tau$

Experiment Theory

Wow . . . this is

the most precisely tested theory ever conceived!
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 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!
At our energy scales, we see four distinct forces . . .

\[ \alpha_s \]

\[ \frac{\alpha_w}{\sin^2 \theta_w} \]

\[ \frac{5\alpha_{EM}}{3 \cos^2 \theta_w} \]
But these coupling ‘constants’ aren’t really constant: $\alpha_i \rightarrow \alpha_i(Q)$

\[ \alpha_i \rightarrow \alpha_i(Q) \]

\[ \rightarrow \text{electromagnetic and weak strengths equal at } \approx 10^{13} \text{ GeV} \]

\[ \rightarrow \text{strong force gets weaker, but doesn’t unify with EW} \ldots \]
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 . . .
- **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, . . .
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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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All of these techniques are **complementary** and **important**

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Often they are **interdisciplinary**

(fun and a great basis for graduate students!)
How does high-energy test the SM?

colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, . . . .
direct search of particles
How does high-energy 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
How do we test the SM?

**nuclear physics**: radioactive ion beam facilities

**indirect** search via precision measurements

---

**Nuclear Landscape**

- less than 300 stable
- terra incognita
- known nuclei

![Diagram showing the nuclear landscape with proton number Z and neutron number N axes.](image)
How do we test the SM?

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**indirect** search via precision measurements
How do we test the SM?

**nuclear physics**: radioactive ion beam facilities

**indirect** search via precision measurements

---

Dan Melconian

Nov 20, 2013

NSCL
How do we test the SM?

**nuclear physics**: radioactive ion beam facilities

*indirect* search via precision measurements

- ✔ smaller collaborations
- ✔ contribute to all aspects
- ✔ “table-top” physics
How specifically do I plan to test the SM?

Via the angular distribution of the 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
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$$+ \frac{\langle \hat{I} \rangle}{I} \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_{\nu}} \right]$$

where

- $\theta_{e,i}$ and $\theta_{\nu,i}$ are the angles of the outgoing particles.
- $\vec{p}_e$ and $\vec{p}_\nu$ represent the momenta of the outgoing particles.
- $A_{\beta}$, $B_{\nu}$, and $D$ are parameters associated with $\beta$-asymmetry, $\nu$-asymmetry, and $T$-violating terms, respectively.

The diagram illustrates the angular distribution with outgoing particles $\vec{p}_e$ and $\vec{p}_\nu$ and the angles $\theta_{e,i}$ and $\theta_{\nu,i}$.
How specifically do I plan to test the SM?

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\]

- \( \beta \)-decay parameters depend on the currents mediating the weak interaction
  ⇒ sensitive to **new physics** ⇐
How to achieve our goal?

- perform a $\beta$ decay experiment on short-lived isotopes
How to achieve our goal?

- perform a β decay experiment on short-lived isotopes
- make a precision measurement of the angular correlation parameters
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- perform a $\beta$ decay experiment on **short-lived** isotopes
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- compare the SM predictions to observations
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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
- perform a nuclear measurement 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.
Many groups around the world realize the potential of using traps for precision weak interaction studies.

- **atom traps**
- **ion traps**
1. Fundamental symmetries
   - what is our current understanding?
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   - physics of superallowed $\beta$ decay
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$T = 2$ superallowed decays

- $\beta - \nu$ correlations
- model-dependence of $\delta_C$ calcs seem to depend on $T \ldots$
- new cases for $V_{ud}$
\( T = 2 \) superallowed decays

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

\[
p_e E_e (A_0 - E_e)^2 \xi \left( 1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b_F \frac{\Gamma_{m_e}}{E_e} \right)
\]

- \( \beta - \nu \) correlations
- model-dependence of \( \delta_C \) calcs seem to depend on \( T \ldots \)
- new cases for \( V_{ud} \)
Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of $^{32}\text{Ar}$


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 $^{32}\text{Ar}$ 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.

Doppler shape of delayed proton depends on $\vec{p}_e \cdot \vec{p}_\nu$!
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Doppler shape of delayed proton depends on $p_e \cdot p_\nu$!
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(Received 24 February 1999)

Neutrino correlation in the $0^+ \rightarrow 0^+$ decay of $^{32}\text{Ar}$ depends on the effect of lepton recoil on the shape of the Doppler shape of delayed proton. It is consistent with the standard model predictions, $m_e = 0.0052 \pm 0.0039$, which yields $a_{\nu}/H = 0.9989 \pm 0.0032$. This result provides improved constraints on scalar weak interactions.
But why throw away useful information??

We can improve the correlation measurement by retaining information about the $\beta$.
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utilize technology of Penning traps to provide a backing-free source of localized radioactive ions!!
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---

Diagram of Penning trap system with labels for Position-sensitive detector, End Cap, Compensation Electrode, Ring Electrode, Compensation Electrode, and magnetic field lines.
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utilize technology of Penning traps to provide a **backing-free** source of localized radioactive ions!!
A Penning trap at T-REX CI/TAMU

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

ECR ION SOURCE
K500 CYCLOTRON
RADIATION EFFECTS FACILITY 1994, 2000, 2005
BEAM ANALYSIS SYSTEM 1994
MARS Recoil SPECTROMETER 1992
CB-ECR SOURCE
HEAVY ION GUIDE
LLNL LINE 2011
MARS SPECTROMETER 1999
Q^3 SPECTROMETER 2012
NIMROD 1999
MDM SPECTROMETER 1993, 2000
TAPE TRANSPORT & PRECISION DECAY FACILITY 1999
LIGHT ION GUIDE
will be the **world’s most open-geometry** ion trap!

- uniquely suited for studying $\beta$-delayed proton decays: 
  \[\beta - \nu\text{ correlations, } f_t \text{ values}/V_{ud}\]
- mass measurements, EC studies, laser spectroscopy, . . .
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The Texas A&M University Penning Trap

 пеннинг трап, уникально пригоден для изучения
β-распадов протонов, β-ν корреляций, ft значений / V_{ud}, массовых измерений, исследований EC, лазерной спектроскопии, …

Mehlman et al., NIM A712, 9 (2013)

ρ₀ = 90 mm

Position-sensitive detector

End Cap  Compensation Electrode  Ring Electrode  Compensation Electrode  End Cap
Current status (come visit and see!)
Current status (come visit and see!)

- Built, but not yet installed
- Installed and tested

Dan Melconian

Nov 20, 2013

NSCL
Current status (come visit and see!)

Begin trapping RIB soon after K150 commissioned (by 2016)

**Installed and tested**
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Overview

1. Fundamental symmetries
   - what is our current understanding?
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Almost as simple as $0^+ \rightarrow 0^+$:

- **Isobaric analogue** decay
- **Strong** branch to g.s.

### Decay Scheme

- **$^{37}_{19}K$**
  - $3/2^+$: $1.225(7)$ s
  - Transition: $3/2^+ \rightarrow 3/2^+$ (1.225(7) s)
  - Branching ratios:
    - $3/2^+ \rightarrow 3/2^+$: $97.99(14)$% (strong)
    - $3/2^+ \rightarrow 3/2^+$: $0.022$% (isobaric analogue)
    - $3/2^+ \rightarrow 5/2^+$: $2.07(11)$% (isobaric analogue)
Almost as simple as $0^+ \rightarrow 0^+$:

- **Isobaric analogue** decay
- **Strong** branch to g.s.
- **Polarization/alignment**
- **Mixed** Fermi/Gamow-Teller

$$\Rightarrow \text{need } \rho \equiv \frac{G_A M_{GT}}{G_V M_F} \text{ to get SM prediction for correlation parameters}$$
Almost as simple as $0^+ \rightarrow 0^+$:

- **isobaric analogue decay**
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$\Rightarrow$ need $\rho \equiv G_A M_{GT}/G_V M_F$

to get SM prediction for correlation parameters

\[
\rho^2 = \frac{2\mathcal{F}t_{0^+ \rightarrow 0^+}}{\mathcal{F}t} - 1
\]
Almost as simple as $0^+ \rightarrow 0^+$:

- Isobaric analogue decay
- Strong branch to g.s.
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⇒ 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:

$$\rho^2 = \frac{2\mathcal{F} t^{0^+ \rightarrow 0^+}}{\mathcal{F} t} - 1$$

$Q_{EC}$: ±0.003%
$BR$: ±0.14%
$t_{1/2}$: ±0.57%
The \( \beta^+ \)-decay of \( ^{37}K \)

*Almost as simple as* \( ^0_1 + \rightarrow ^0_1 + \):

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

\[
\begin{array}{c|c}
\text{37}^\beta_1 & 1.225(7) \text{s} \\
\text{19}^\beta_1 & 3/2^+ \\
\text{37}^+_1 & 3/2^+ \\
\text{19}^+_1 & 0.022\% \\
\text{5/2^+} & 2.07(11)\% \\
\text{3/2^+} & 97.99(14)\% \\
\text{37}^+_1 & 3/2^+ \\
\text{18}^+_1 & 0.022\% \\
\end{array}
\]

The **lifetime** limits the \( \mathcal{F}_t \) value and hence precision of \( \rho \) and hence the SM predictions of the correlation parameters.

\[ \mathcal{F}_t = 4562(28) \Rightarrow \rho = 0.5874(71) \]
Measuring the lifetime at the CI

$^{38}\text{Ar} (p, 2n)^{37}\text{K}$
Improving the lifetime

Set #9: $t_{1/2} = 1238.8 \pm 1.8$ ms; $\chi^2/488 = 1.05$

Set #9: $t_{1/2} = 1238.2 \pm 2.0$ ms; $\chi^2/10288 = 1.03$
Improving the lifetime

nearly a $10 \times$ improvement: $t_{1/2} = 1236.51 \pm 0.47 \pm 0.83$ ms

$\Rightarrow \Delta F t = 0.62\% \rightarrow 0.18\%$

and $\Delta \rho = 1.2\% \rightarrow 0.4\%$

P. Shidling et al., in preparation
Branching ratio — going on now!

$^{38}\text{Ar} (p, 2n)^{37}\text{K}$
Angular distribution of a $^{3\frac{1}{2}}_2^+ \rightarrow ^{3\frac{1}{2}}_2^+$ decay

$$dW \sim 1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \frac{\vec{I}}{I} \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right]$$

<table>
<thead>
<tr>
<th>Correlation</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta - \nu$ correlation:</td>
<td>$a_{\beta\nu} = 0.6580(61)$</td>
</tr>
<tr>
<td>Fierz interference parameter:</td>
<td>$b = 0$ (sensitive to scalars and tensors)</td>
</tr>
<tr>
<td>$\beta$ asymmetry:</td>
<td>$A_{\beta} = -0.5739(21)$</td>
</tr>
<tr>
<td>$\nu$ asymmetry:</td>
<td>$B_{\nu} = -0.7791(58)$</td>
</tr>
<tr>
<td>Time-violating $D$ coefficient:</td>
<td>$D = 0$ (sensitive to imaginary couplings)</td>
</tr>
</tbody>
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Precision measurements of these correlations to $\lesssim 0.1\%$ complement collider experiments and test the SM

Angular distribution of a $\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$ decay

$$dW \sim 1 + a_{\beta \nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \Gamma \frac{m}{E_e} + \frac{\vec{T}}{I} \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right]$$

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<td>$\beta - \nu$ correlation:</td>
<td>$a_{\beta \nu} = 0.6580 \pm 0.061 \rightarrow 0.6668 \pm 0.018$</td>
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<tr>
<td>$\beta$ asymmetry:</td>
<td>$A_{\beta} = -0.5739 \pm 0.021 \rightarrow -0.5719 \pm 0.007$</td>
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<td>$\nu$ asymmetry:</td>
<td>$B_{\nu} = -0.7791 \pm 0.058 \rightarrow -0.7703 \pm 0.018$</td>
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Precision measurements of these correlations to $\lesssim 0.1\%$
complement collider experiments and test the SM

see Profumo, Ramsey-Musolf and Tulin, PRD 75 (2007)
and Cirigliano, González-Alonso and Graesser, JHEP 1302 (2013)
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) 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!!

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

![Diagram of the new chamber](image-url)
The new chamber

- Shake-off
- Better control of OP beams
- \( B_{\text{quad}} \)
  - (Harvery & Murray, PRL 101 (2008))
- Increased \( \beta \)/recoil solid angles
- Stronger \( E \)-field

Shake-off detection

100 \( \mu \)m thick Si-coated mirror

40x40 mm\(^2 \times 300 \mu \)m MCP

BB1 Si-strip detector
Outline of polarized experiment
Outline of polarized experiment

$D_2$ MOT

anti-Helmholtz
Outline of polarized experiment

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

\[ m_F = -2 \]

\[ P_{1/2} \]

\[ S_{1/2} \]

\[ \sigma^\pm \]

Helmholtz

D\textsubscript{1} OP
Outline of polarized experiment

355 nm

E-field

MCP

K^+

photoionization

D_1 OP

Helmholtz

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

\( m_F = -2 \)

\( \sigma^\pm \)

\( S_{1/2} \)

\( P_{1/2} \)
deduce $P$ based on a model of the excited state populations:
deduce $P$ based on a model of the excited state populations:

$$P_{\text{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$$
The cloud is better controlled now!

old system:
- retroreflected beams
- kludged “Helmholtz” coils
- eddy currents

![Graph showing cloud position and width over cycle time]
The cloud is better controlled now!

- **old system:**
  - retroreflected beams
  - kludged “Helmholtz” coils
  - eddy currents

- **Dec 2012:**
  - beams balanced
  - anti-Helmholtz $\rightarrow$ Helmholtz well-defined fields
  - ac-MOT $\Rightarrow$ fast switching and low eddy currents

much more stable! lower cloud temperature!
Just the raw data; a slight lower-energy cut to get rid of 511s
Requiring a $\Delta E$ coincidence $\Rightarrow$ remove $\gamma$s
Requiring a shake-off $e^- \Rightarrow$ decay occurred from trap!

$A_{\text{meas}} = -0.502(6)$
Put in all the basic analysis cuts ⇒ clean spectrum!!
Scintillator spectra — Fall 2012

\[ A_{\text{meas}} = -0.535(7) \]
Comparison with GEANT4 simulation is very good!
Comparison with GEANT4 simulation is very good!

Much higher asymmetry observed compared to 1st attempt!
SM is fantastic, but *not* our “ultimate” theory

many *exciting avenues* to find more a complete model
Summary

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

- **nuclear approach**: precision measurement of correlation parameters
**Summary**

- SM is fantastic, but **not** our “ultimate” theory
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**nuclear approach:** precision measurement of correlation parameters

- Penning trap + RIB CI = *cool* physics
- (AC-)MOT + opt. pumping = *cool* physics
The Mad Trappers/Thanks

TAMU: Spencer Behling, Mike Mehlman, Ben Fenker, Praveen Shidling + TAMU/REU undergrads

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D. Ashery, G. Gwinner

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