Fundamental Symmetries: Highlights

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• Motivation

• An interdisciplinary Field
  – Atomic, High-Energy, Astro- and Nuclear Physics communities

• Priorities in this Presentation
  – Recent findings
  – Major efforts on the horizon
  – Chapters in this Talk
    1. EDMs
    2. PVES
    3. Neutrons
    4. Muons
    5. Pions and Photons

DNP FS/Neutrino Pre-Town Meeting 2012
Motivation: I

- **Establish SM parameters and laws.** Examples:
  - Masses $M_Z$, $M_W$, $M_H$, $m_b$, $m_t$, $m_e$, $m_u$, $m_v$, ...
  - Couplings: $\alpha_{\text{QED}}$, $\alpha_{\text{Strong}}$, $G_F$, $G_{\text{grav}}$
  - Structure of interactions $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Broad issues
    - Numbers of generations
    - Mixing angles, quarks and neutrinos
    - Lepton number conservation
      - Majorana or Dirac neutrinos
    - CP violation parameters

- **The Standard Model as we know it has been built on an enormous experimental foundation involving Precision and Energy frontier efforts**

- And, some exquisite Theory!
Motivation: II  The burning issues

• Can we sensitively test the SM limitations to help answer key questions:
  – Baryon Asymmetry of the Universe
  – EW symmetry breaking
  – ...

• Are the Standard Model predictions complete?
  – What is missing?
  – What extensions are needed?
Chapter 1: Electric Dipole Moments

EDM violates $T \rightarrow$ violates CP

New sources of $CP \rightarrow BAU$?

Experiments are largely the same:
Precess spin in $B$ field with parallel and anti-parallel $E$
Measure the frequency difference
The Seattle $^{199}$Hg (atomic) EDM Measurement

- Number of $^{199}$Hg atoms: $10^{14}$
- Leakage currents at 10 kV: 0.5 – 1 pA
- N$_2$ + CO buffer gas (500 Torr)
- Paraffin wall coating
- Spin relaxation time: 100 – 200 sec

4 mercury vapor Cells:
- 2 with opposite E fields
- 2 for B field normalization

C. Griffith
The Seattle $^{199}$Hg (atomic) EDM Measurement

Shielding reduces the effect of the nuclear dipole:

$$d_{\text{atom}} \propto d_{\text{nuc}} \left[ Z^2 \left( \frac{r_n}{a_0} \right)^2 \right]$$

$$\approx 10^{-3}$$

Limits and Sensitivities

- Current: $< 0.3 \times 10^{-28}$ e-cm  
- Next 5 years: $0.03 \times 10^{-28}$ e-cm
- 2020 and beyond: $0.006 \times 10^{-28}$ e-cm

World’s best (absolute) limit

C. Griffith
World-wide intense effort on nEDM

<table>
<thead>
<tr>
<th>Exp</th>
<th>UCN source</th>
<th>cell</th>
<th>Measurement techniques</th>
<th>( \sigma_d ) ((10^{-28}) e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL CryoEDM</td>
<td>Superfluid (^4)He</td>
<td>(^4)He</td>
<td>Ramsey technique for (\omega) External SQUID magnetometers</td>
<td>Phase 1 (\sim) 50 Phase 2 &lt; 5</td>
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<tr>
<td>PNPI – ILL</td>
<td>ILL turbine</td>
<td>Vac.</td>
<td>Ramsey technique for (\omega) (E=0) cell for magnetometer</td>
<td>Phase 1 &lt; 100 &lt; 10</td>
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<tr>
<td>ILL Crystal</td>
<td>Cold n Beam</td>
<td>solid</td>
<td>Crystal Diffraction</td>
<td>&lt; 100</td>
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<tr>
<td>PSI EDM</td>
<td>Solid (D_2)</td>
<td>Vac.</td>
<td>Ramsey for (\omega), external Cs &amp; (^3)He magnetometer. Possible Xe or Hg comagnetometer</td>
<td>Phase 1 (\sim) 50 Phase 2 &lt; 5</td>
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<tr>
<td>Munich FRMII</td>
<td>Solid (D_2)</td>
<td>Vac.</td>
<td>Under Construction (similar to PSI)</td>
<td>&lt; 5</td>
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<tr>
<td>SNS EDM</td>
<td>Superfluid (^4)He</td>
<td>(^4)He</td>
<td>(^3)He capture for (\omega) (^3)He comagnetometer SQUIDS &amp; Dressed spins</td>
<td>&lt; 5</td>
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<tr>
<td>TRIUMF</td>
<td>Superfluid (^4)He</td>
<td>Vac.</td>
<td>Phase 1 @ RCNP</td>
<td>&lt; 10</td>
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<td>JPARC</td>
<td>Solid (D_2)</td>
<td>Vac.</td>
<td>Under Development</td>
<td>&lt; 5</td>
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<tr>
<td>NIST</td>
<td>Crystal</td>
<td>Solid</td>
<td>R &amp; D</td>
<td>~ 5 ?</td>
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</table>

B. Filippone
Status & Timeline for nEDM@SNS

NSAC Subcommittee on Fundamental Nuclear Physics with Neutrons Report (12/2011)

- Motivation remains strong
- Sensitivity remains compelling

- Focus now on R&D
- Construction after with 4 – 5 year timeline and ~$30M capital
- 2 minutes to show you why the US idea is special

Aim: 2 orders of magnitude improvement to < 5 x 10^{-28} level
Cold polarized neutrons enter superfluid helium vessel, and get stopped & trapped.

Incident neutrons have the same energy \emph{and} momentum as phonons in superfluid helium: they interact \emph{and} stop.

So clever, it’s worth a moment: S. K. Lamoreaux and R. Golub,
Neutron spins precess because of the external magnetic field.

\[ f = -2\mu_n B_0 / h \]

Superfluid helium
So do spins of polarized $^3$He, which are also brought into the same vessel.

$^3$He atoms precess slightly faster* than neutrons (nearly same magnetic moment).

Superfluid helium
When neutrons and $^3$He collide, interaction depends on relative spin orientations.

$^3$He, n spins parallel: “no” interaction

Superfluid helium
When neutrons and $^3$He collide, interaction depends on relative spin orientations.

$p$ and $^3$H give off scintillation light.

$^3$He, n spins anti-parallel – large reaction probability $\rightarrow p + ^3$H

Superfluid helium
Now, add external electric field: spin rate of neutrons affected if EDM is non-zero

\[ f = \left( -2 \mu_n B_0 \pm 2 d_n E_0 \right) / h \]
A new idea: pEDM in all-electric storage ring and, to a precision of $10^{-29}$!

Freeze Magnetic Moment

Momentum

Spin

At the magic momentum

$$p = \frac{m}{\sqrt{a}}$$

the spin and momentum vectors precess at same rate in an E-field

$\sim$100 M effort, but very exciting limit

Electronic supplementary information available at ScienceDirect
Chapter 2: Parity-Violating $e^-$ Scattering

A Broad Community Example

![Diagram showing experimental data and theoretical predictions for parity-violating $e^-$ scattering, with labels for various experiments and energy scales.]

- SM
- published
- ongoing
- proposed

- Atomic
- Nuclear
- High Energy

Labels include:
- $Q_W(Cs)$ Boulder
- $Q_W(e)$ SLAC E158
- NuTeV $v$-DIS
- LEP
- Tevatron
- SLC
- CMS
The precision measurement of the Higgs mass updates the story, fixing central value of $\sin^2\theta_W$

**Summer 2012**

![Graph showing allowed and excluded regions for Higgs mass](image)

- **Allowed Higgs Mass**
- **Excluded**
- **Excluded**
- **E158**
- **Proposed JLab Moller experiment**

J. Erler: arXiv:1209.3324v2
Next-Generation experiments will Probe for New Physics

Many new physics models require new, heavy, neutral current interactions

Sensitivity to TeV-scale contact interactions if:

\[ \delta(\sin^2 \theta_W) \leq 0.5\% \]

• away from the Z resonance

Heavy Z’ s and neutrinos, technicolor, compositeness, extra dimensions, SUSY…
Worldwide proposed efforts
The JLab Suite

- **QWeak**
  - Completed
  - 1st result today
  - Goal: $\delta Q_W^p = \pm 4\% \Rightarrow \delta (\sin^2 \theta_W) = \pm 0.3\%$

- **MOLLER@11GeV**
  - Proposed for 2017
  - Goal: $\delta (\sin^2 \theta_W) = \pm 0.1\%$

- **SOLID**
  - Deep Inelastic Scattering from $^2H$
  - Early planning

\[
C_{1i} = 2g_A^e g_V^i
\]
\[
C_{2i} = 2g_V^e g_A^i
\]
Chapter 3: Neutrons
The Neutron as a Fundamental Laboratory

\[ n \rightarrow p^+ + e^- + \nu_e^* \]

neutron lifetime \( \tau \approx 15 \text{ min} \)

\( \beta \)-endpoint energy: \( E_{\text{max}} = 782 \text{ keV} \)

\[ dW \propto \frac{1}{\tau_n} F(E_e) \left[ 1 - a \frac{p_e \cdot p_v}{E_e \cdot E_v} + b \frac{m_e}{E_e} + A \frac{\sigma_n \cdot p_e}{E_e} + B \frac{\sigma_n \cdot p_v}{E_v} \right] \]

\( \tau_n \propto \frac{1}{(g_A^2 + 3g_V^2)} \)

\[ a = \frac{1 - \left( \frac{g_A}{g_V} \right)^2}{1 - 3 \left( \frac{g_A}{g_V} \right)} \]

\( b = 0 \)

\[ A = -2 \left( \frac{g_A}{g_V} \right)^2 + \left( \frac{g_A}{g_V} \right) \left[ 1 - 3 \left( \frac{g_A}{g_V} \right)^2 \right] \]

\[ B = 2 \left( \frac{g_A}{g_V} \right)^2 - \left( \frac{g_A}{g_V} \right) \left[ 1 + 3 \left( \frac{g_A}{g_V} \right)^2 \right] \]

Neutron beta decay measurements give:

\( \frac{g_A}{g_V} \)
Neutron Decay Correlations

\[ \frac{g_A}{g_V} \]

Nuclear \( O^+ \rightarrow O^+ \) Decays, CKM Unitarity

\[ g_V \]

Neutron Lifetime

\[ g_A^2 + 3g_V^2 \]
2007 picture: Lifetime and Correlations combine in a confused picture for the physics of $g_A$ or unitarity

$g_A$ important

$g_V \equiv G_F V_{ud} f(0)$
Significant updates

- **Big A:** \( g_A/g_V \)
  - UCNA
  - PERKEO II

- **n Lifetime Update**
  - Important to Big Bang Nucleosynthesis

- Precision of \( 0^+ \rightarrow 0^+ \) superallowed measurements for unitarity

- CVC verified
- \( V_{ud} = 0.97425(22) \)

CKM unitarity test:
\[
V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99999(6)
\]
2012: \( n \) Lifetime Update: PDG

As Kumar \( n \) Committee recommended, an improved BEAM-method at 1-s precision is very important.

PDG uses latest 7, including corrected and other newer results.
2012: PDG Big $A \rightarrow g_A/g_V$

MUND et al (2012) = $-1.2767(16)$

Not in PDG yet

$\lambda \equiv g_A / g_V$
2012 Picture: Lifetime and Correlations in better shape, but lifetime and Asymmetry still in small tension

$$\lambda \equiv \frac{g_A}{g_V}$$

**PDG:** $g_A/g_V$

**PDG: Lifetime**

$$g_V \equiv G_F V_{ud} f(0)$$

J. Nico, 2012
2015- Nab – future and beyond

- Measure the electron-neutrino parameter $a$ in neutron decay
  
  with accuracy of $\frac{\Delta a}{a} \approx 10^{-3}$ or $\sim 50 \times$ better

- Measure the Fierz interference term $b$ in neutron decay
  
  with accuracy of $\Delta b \approx 3 \times 10^{-3}$

  Never measured in n decay

NSF MRI-funded Spectrometer

- Nab will be followed by the abBA/PANDA polarized program to measure A, electron, and B/C, neutrino/proton, asymmetries with $\sim 10^{-3}$ relative precision, an independent measurement of $\lambda$. 
Chapter 4: Muons

(well) Beyond Schwinger

Muon Campus @ FNAL
2010: Michel Parameter / Muon Decay: TWIST

\[ \rho = 0.74977 \pm 0.00012 \text{ (stat)} \pm 0.00023 \text{ (syst)} \]

\[ \delta = 0.75049 \pm 0.00021 \text{ (stat)} \pm 0.00027 \text{ (syst)} \]

\[ \mathcal{P}_\mu \pi \xi = 1.00084 \pm 0.00029 \text{ (stat)} \pm 0.00063 \text{ (syst)} \]

Results mostly constrain right-handed muon terms

\[ Q_{LR}^\mu = \frac{1}{4} |g_{LR}^S|^2 + \frac{1}{4} |g_{RR}^S|^2 + |g_{LR}^V|^2 + |g_{RR}^V|^2 + 3 |g_{LR}^T|^2 \]

\[ = \frac{1}{2} \left[ 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right] \]

\[ < 8.2 \times 10^{-4} \text{ (90\%!C.L.)} \]

2011: 

Muon lifetime / Fermi constant: MuLan*

\( \Delta \tau (R07 - R06) = 1.3 \text{ ps} \)

\( \tau (\text{MuLan}) = 2196980.3 \pm 2.2 \text{ ps} \ (1.0 \text{ ppm}) \)

\( G_F(\text{MuLan}) = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2} \ (0.5 \text{ ppm}) \)

The most precise particle or nuclear or atomic lifetime ever measured

Enables precision muon capture program (next)

*US led effort at PSI

2012: Muon Capture on Proton: MuCap*

Measured: $\Lambda_S = (714.9 \pm 5.4_{\text{stat}} \pm 5.0_{\text{syst}}) \text{s}^{-1}$

$g_p$ as a function of the molecular transition rate, $\lambda_{\text{op}}$.

Determined: $g_p(\text{MuCap}) = 8.06 \pm 0.56$

Compare to: $g_p(\text{Theory}) = 8.26 \pm 0.23$

First unambiguous determination of $g_p$ and clarification of long-standing puzzle between fundamental QCD-based prediction and expt.

*US led effort at PSI

Andreev et al, ArXiv:1210.6545v1; submitted to PRL (today)
2012-14: Muon Capture on Deuteron: MuSun*

Several fundamental astrophysics processes depend on weak interaction in deuterium

Basic solar fusion: $p + p \rightarrow d + e^+ + \nu$

Sudbury Neutrino Observatory: $\nu_e + d \rightarrow p + p + e^-$ (CC)
$\nu_x + d \rightarrow p + n + \nu_x$ (NC)

Tiny cross sections, predictions rely on theory

Idea: replace $e^-$ by $\mu^-$, calibrate in muon capture reaction

*US led effort at PSI

model-independent connection via EFT
Flagship efforts being mounted at the new Fermilab Muon Campus: g-2 & Mu2e

For g-2, achieves
1) Long decay channel
2) Rapid ring cycle
3) No hadronic flash

For Mu2e, achieves
1) Ideal proton bunches for mu formation
2) High intensity / Extinction
The statistically limited g-2 measurement is $3.6\sigma$ from the Standard Model

“Do it better …”
→ More Muons
→ Reduced Systematics

- Concept sound
- Relocate the storage ring to FNAL
- Build new measuring equipment (NSF & DOE Nuclear invested in this part)

E989 is approved, has CD-0, 24 Institutions, 100+ members, Start: 2016
Precision Physics and Beyond the Standard Model Exploration: An example (of course, quite speculative and not implied as true)

- We often claim the low-energy observables (both limits and signals) will be part of the conversation and interpretation of, say, LHC results

**Correlation between the Higgs Decay Rate to Two Photons and the Muon $\mu - 2$**

Gian F. Giudice\textsuperscript{a}, Paride Paradisi\textsuperscript{b} and Alessandro Strumia\textsuperscript{a,b}

arXiv:1207.6393v1

Post Higgs paper (others exist too)

- Observations at the LHC
  - $h \rightarrow \gamma\gamma$ production rate is too high by $\sim 40-50\%$
  - Higgs rates in $ZZ^*$ and $WW^*$ are consistent with the SM

- Theoretical SUSY model that fits observations
  - light stau with large left-right mixing
  - light Bino
  - heavy higgsinos

- Other consequences
  - Predicts Muon Anomaly exactly
  - Compatible with thermal dark matter
  - Predicts small deviations in $h \rightarrow \gamma Z$ and $h \rightarrow \tau\tau$
  - Predicts measurable violations of Lepton Non-Universality in $\tau - \mu$ and $\tau - e$
  - Predicts NO violation in the $\mu - e$ sector
Muon-to-Electron Conversion: Mu2e*

The SM theory is clear: It won’t happen

\[ \mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L) \]

*Nuclear / Particle / Accelerator collaboration at Fermilab
How it is done

- Make muonic Al atoms.
  - 40% will decay “in orbit”;
  - 60% will capture (junk emitted)
- Look for mono-energetic $e^-$, at muon mass (~104 MeV)

This experiment is in R&D and Pre-Construction Mode with CD1 approval

Start date close to 2020
Chapter 5: Pions & Photons

Silicon strip tracker inside an evacuated dipole for excellent vtx & mom resolution
2012+ $\pi \rightarrow e\nu$: Lepton Universality: PEN*, PiENu**

$$B_{\text{calc}} = \frac{\Gamma(\pi \rightarrow e\bar{\nu}(\gamma))}{\Gamma(\pi \rightarrow \mu\bar{\nu}(\gamma))} = \begin{cases} 1.2352 (5) \times 10^{-4} \\ 1.2354 (2) \times 10^{-4} \\ 1.2352 (1) \times 10^{-4} \end{cases}$$

Current Expt. World Avg. = $(1.230 \pm 0.004) \times 10^{-4}$

PEN, PiENu aim at: $$\frac{\delta B}{B} \simeq 5 \times 10^{-4}$$ x 10 improvement

PEN data taking complete. Analysis in progress

PiENu data taking ends in December

*at PSI  **at TRIUMF
A’, a massive neutral vector boson
- kinematically mixes with $\gamma$
- $\alpha' = \varepsilon \alpha_{\text{e.m}}$, $\varepsilon = 10^{-2} - 10^{-6}$
- Mass in the MeV-GeV region

- Can explain g-2 discrepancy
- Can explain cosmic positron data

Dark Photon searches: @JLab

2010 $\Rightarrow$ ...
Method: Produce $A'$ with electron beam
Detect pair decays (narrow peak above background)

APEX in Hall A

Simplest using existing spectrometers

Heavy Photon Search @ Hall B

Physics reach: $\epsilon < 10^{-4}$; mass 20-800 MeV
Parasitic test run complete 2012
Plan for physics run in 12 GeV era

DarkLight @ the JLab FEL

- FEL beam (~1mA, 100 MeV) incident on a H2 gas jet target.
- Collect 1/ab in ~ 60 days of beam time
- High acceptance detector inside a 0.5 T solenoid

Successful Test Run (July 2012)

Seeking funding
Summary: This Field is …

• Vibrant, Active, Diverse
• Discovery-oriented
• Directing larger investments to efforts with significant potential payoff
  – nEDM
  – Moller
  – Equipment request for g-2

• Incompletely summarized. I omitted:
  – npdgamma, other EDM efforts, various nuclear beta decay expts., theory efforts, n radiative decay, emiT, new n lifetime ideas, acorn, …