Spin Probes of Physics
Beyond the Standard Model

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Two Numbers
Drive new physics searches

Why is the cosmic energy budget in baryons so small? (and what is everything else?!)

And the cosmic baryon asymmetry

\[ \eta = \frac{n_{\text{baryon}}}{n_{\text{photon}}} = (5.96 \pm 0.28) \times 10^{-10} \]

so large? (And how does the neutrino get its mass?)
A Cosmic Baryon Asymmetry

[PDG, RPP, 2017]

Figure 24.1: The primordial abundances of $^4$He, D, $^3$He, and $^7$Li as predicted by the standard model of Big-Bang nucleosynthesis — the band shows the 95% CL range [5]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN $^4$He/$^3$He concordance range (both at 95% CL).

Predictions and thus in the key reaction cross sections. For example, it has been suggested [31,32] that $d(p,\gamma)^3$He measurements may suffer from systematic errors and inferior to

December 1, 2017 09:35

BAU from BBN & observed D/H & $^4$He/H concordance

[Both @ 95% CL]
A Cosmic Baryon Asymmetry

Confronting the observed D/H abundance with big-bang nucleosynthesis yields a baryon asymmetry: [Steigman, 2012]

\[ \eta = \frac{n_{\text{baryon}}}{n_{\text{photon}}} = (5.96 \pm 0.28) \times 10^{-10} \]

**By initial condition?**

We interpret the CMB in terms of an inflationary model, so that this seems unlikely. [Krnjaic, PRD 96 (2017)]

**From particle physics?**

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, 1967]

Non-equilibrium dynamics are required to avoid “washout” of an asymmetry by back reactions
The Puzzle of the Missing Antimatter

The baryon asymmetry of the universe (BAU) derives from physics beyond the standard model!

The SM almost has the right ingredients:

B? Yes, at high temperatures
C and CP? Yes, but CP is “special”

Note BAU estimates even with a light Higgs are much too small

[Farrr and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.]

Non-equilibrium dynamics? No. (!)

The discovered Higgs particle is of 125 GeV in mass;
for this mass lattice simulations reveal there is no
electroweak phase transition. [e.g., Aoki, Csikor, Fodor, Ukawa, 1999]

So that the SM mechanism fails altogether

Recipes for a Baryon Asymmetry?

New ν physics might operate!

η<10^{-26}
Our dark-dominated universe and its baryon asymmetry speaks to possible hidden (or visible?!)
particles, interactions, symmetries and more that we may yet discover

Such new physics could arise at either
i) high energies with $\mathcal{O}(1)$ couplings to SM particles

Here low energy & collider studies are complementary – or –

ii) low energies with very weak couplings to SM particles

Largely unexplored! Low energy studies have unique discovery potential!
Symmetry Tests with Spin
“Windows” on New Physics

Some examples...

- Searches for new sources of CP violation: 
  *permanent electric dipole moments (EDMs)*;
  *time-dependent “EDMs” to probe ultralight (axion-like) dark matter*

  Note plenary: F. Rathmann

- Precision measurements of magnetic moments (esp. $\mu g$-2) and of $\sin^2\theta_W$ (PVES)

  Note plenary: D. Hertzog and G. Smith

- Searches for baryon number violation: 
  *esp. quark probes of Majorana dynamics*

- Searches for BSM physics in beta-decay
Suppose new physics enters at an energy scale $E > \Lambda$

Then for $E < \Lambda$ we can extend the SM as per

$$\mathcal{L}_{SM} \Rightarrow \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^{D-4}} O_i^D,$$

Symmetries guide their construction [Weinberg, 1979]

Here assume SM electroweak symmetry [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010]

New physics can enter as (i) new operators or as (ii) modifications of $c_i$ for operators in the SM cf. non-V-A tests with tests of CKM unitarity

Can also break SM symmetries & have new operators only

But what if we introduce new degrees of freedom?
New High or Low Energy Physics?

With new low energy degrees of freedom (dof) new dimension 4 operators appear….

Including SM dof act as “portals” to a hidden sector

\[
\mathcal{L}_{\text{dim} \leq 4} = \frac{\kappa}{2} V^{\mu \nu} F'_{\mu \nu} - H^\dagger H (A S + \lambda S^2) - Y_N L H N
\]

[Batell, Pospelov, and Ritz, 2009; Bjorken, Essig, Schuster, Toro, 2009]

- Vector Portal
- Higgs Portal
- Neutrino Portal

Hunting Hidden Forces….

Much focus on the dark photon \( A' \) & the vector portal… note impact on \( \mu \) g-2 (only simple \( A' \) excluded) [Pospelov, 2009]
Gauge Theories of the Hidden Sector

Dark gauge bosons can also couple directly to fermions

Consider the dark photon...

\[ \mathcal{L}_{A'} = \frac{\varepsilon}{2} F^Y_{\mu\nu} F'_{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'_\mu \]

Diagonalization and field definition yields

\[ A^\mu \rightarrow A^\mu - \varepsilon A'^\mu \text{ but } Z - A' \text{ mixing } \mathcal{O}(\varepsilon m_{A'}^2 / M_Z^2) \]

[Bjorken, Essig, Schuster, and Toro, 2009...]

Thus the \( A' \) couples to SM fermions.

Now w/ an extended Higgs sector...

\[ \mathcal{L}_{\text{dark}Z} = - (\varepsilon e J_{\text{em}}^\mu + \varepsilon Z \frac{g}{2 \cos \theta_W} J_{\text{NC}}^\mu) Z d_\mu \]

[Davoudiasl, Lee, Marciano, 2014]
BSM Sessions at SPIN 18

Note, too, talks in other sessions

- Searches for new sources of CP violation
  [Franke, Dietrich, Fierlinger, Franke, Gupta, Kirch, Ruiz Vidal, Yamanaka, Zimmer; Paradisi; Stadnik; Kononov, Nass, Nikolaev]

- Searches for novel spin-dependent interactions
  [Heil, Rong]

- Measurements of PVES [Gal, Baunack]

- Searches for new S, T degrees of freedom & … in beta-decay

- Searches for baryon number violation: esp. quark probes of Majorana dynamics
Operator Analysis of EDMs

Connecting from high to low scales

A single TeV scale CPV source may give rise to multiple GeV scale sources

Explicit studies of operator mixing & running effects are now available

[Chien et al., arXiv:1510.00725, JHEP 2016; Cirigliano, Dekens, de Vries, Merenghetti, 2016 & 2016]

Lattice QCD studies of single-nucleon matrix elements also exist

Enter isoscalar & isovector tensor charges...

[Bhattacharya et al., 2015 & 2016; Gupta et al., arXiv:1801.03130]

Determining the parameters of the low energy effective Lagrangian experimentally is a distinct problem

Can all the low-energy CPV sources be determined?

Need to interpret EDM limits in complex systems: atoms, molecules, and nuclei
Some Thoughts on the Strong CP Problem

The SM has other “fine-tuning” problems

The following term can appear within QCD

\[ \mathcal{L}_\theta = \frac{g^2}{32\pi^2} \theta_{\text{QCD}} F^{\mu \nu}_a \tilde{F}_{\mu \nu a} \]

as can a similar term from the quark masses, so that

\[ \theta_{\text{QCD}} \implies \bar{\theta} = \theta_{\text{QCD}} + \theta_{\text{Yukawa}} \]

Neither term needs to be small but
the experimental limit on the n EDM implies

\[ \bar{\theta} \ll 10^{-10} \]

Why is “\( \delta \) ~ 1"?!

Many discussed resolutions… note Peccei-Quinn…
Direct Detection: Ultralight Dark Matter

A new paradigm: axion-like dark matter

The axion originally appears as a solution to the strong CP violation (in QCD) and emerges from spontaneously broken Peccei-Quinn symmetry [Weinberg 1977, Wilczek 1977]

Can consider an axion-like particle which is not tied to that origin

An ultralight axion can induce time-varying T, P odd interactions!

(Axions possess a vast parameter space....)

Note Stadnik talk
Direct Detection: Ultralight Dark Matter

![Graph showing constraints on axion interactions](image)

### Supernova energy loss

### Big bang nucleosynthesis

### QCD axion

### CASPER (projected)

### Storage ring EDMs: Rathmann, plenary, this AM! (see ref)

**Figure 4. Limits on the interactions of an axion with the gluons**

C. Abel

Direct Detection:

Axion-nucleon coupling in Eq.

Axion-wind effect would manifest itself through

Angular frequencies:

Time-dependent shifts in

Oscillating neutron EDM as limits on the axion-gluon

**V. CONCLUSIONS**

In summary, we perform a search for a time-oscillating

Following Eq.

None of the significant excesses pass our discovery criteria.

With the short-time-base analysis, we are most sensitive to

To be 0.05. The limit is shown as the blue curve in Fig.

None of the limits have significant excesses.

Secondly, the signals must be in antiphase in the parallel and

Lastly, we require high coherence (a

Define strict requirements for an excess to be considered as

With opposite phase in the two subsets. We find two overlapping

Opposite phase in the two subsets. We find two overlapping

We deliver a limit on the oscillation amplitude similarly

We present these limits in Fig.

**Axion mass (eV)**

**Oscillation frequency (Hz)**

**Direct Detection: Ultralight Dark Matter**

**Supernova energy loss**

**Big bang nucleosynthesis**

**QCD axion**

**CASPER (projected)**

**Storage ring EDMs: Rathmann, plenary, this AM! (see ref)**

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Theoretical Framework for $\beta$ Decay

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda_i^2} O_i \implies \mathcal{L}_{\text{SM}} + \frac{1}{\nu^2} \sum_i \hat{\alpha}_i O_i,$$

with $\hat{\alpha}_i = \nu^2 / \Lambda_i^2$. [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010; Cirigliano, Jenkins, González-Alonso, 2010; Cirigliano, González-Alonso, Graesser, 2013]

Radiative correction*!

$$\mathcal{L}^{\text{eff}} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \left[ (1 + \delta_\beta) \bar{e}_\gamma \mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d \right. + \epsilon_L \bar{e}_\gamma \mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d + \tilde{\epsilon}_L \bar{e}_\gamma \mu (1 + \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d \\
+ \epsilon_R \bar{e}_\gamma \mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d + \tilde{\epsilon}_R \bar{e}_\gamma \mu (1 + \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d \\
+ \epsilon_S \bar{e} (1 - \gamma_5) \nu_\ell \cdot \bar{u} d + \tilde{\epsilon}_S \bar{e} (1 + \gamma_5) \nu_\ell \cdot \bar{u} d \\
- \epsilon_P \bar{e} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d + \tilde{\epsilon}_P \bar{e} (1 + \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d \\
+ \epsilon_T \bar{e} \sigma_{\mu \nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu \nu} (1 - \gamma_5) d + \tilde{\epsilon}_T \bar{e} \sigma_{\mu \nu} (1 + \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu \nu} (1 + \gamma_5) d \\
+ \text{h.c.} \]

[Note Gorchtein talk]


Note right-handed neutrinos appear explicitly

QCD (hadron matrix elements) play a key role!
The terms appear in a one-to-one map....

The "QCD parts" are now clearly identified; note, e.g., in n decay

$$\langle p(p_p) | \bar{u} d | n(p_n) \rangle = g_S(q^2) \bar{u}_p(p_p) u_n(p_n)$$

Enter lattice QCD....

[Bhattacharya et al., 2012]
Recent $g_A$ result of 1% precision in agreement w/ expt!
“Deep dive” by PNDME ’18 reveals no serious disagreements
Act to sharpen constraints on non-V-A currents from decay correlation measurements (esp. b)

Phenom Forecasts ($g_T$; SoLID) have much higher precision

[Ye et al., PLB 2017 arXiv: 1609.02449]
\[
\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \left\{ 1 + b \frac{m_e}{E_e} + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{J} \rangle \left[ A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] + \ldots \right\}
\]

[Jackson, Treiman, Wyld, 1957]

If \( J \neq 1/2 \)

\[
b = \frac{2\gamma}{1 + 3\lambda^2} \left[ g_S \text{Re}(\epsilon_S) - 12\lambda g_T \text{Re}(\epsilon_T) \right],
\]

\[
b_\nu = \frac{-2\gamma}{1 + 3\lambda^2} \left[ g_S \text{Re}(\epsilon_S) \lambda - 4g_T \text{Re}(\epsilon_T) (1 - 2\lambda) \right]
\]

\[
B(E_e) = B_0 + b_\nu m_e / E_e
\]

**Comparison assumes**

\( \Lambda_{BSM} > 13 \text{ TeV} \)

[Gupta et al. [PNDME], 1806.09006; current \( \beta \) decay from Gonzalez-Alonso et al, 1803.08752]

**Analysis & forecast neglect**

second class currents [SG & Plaster, 2013]
What if neutrons also decay invisibly?

[Recall early suggestion: Z. Berezhiani & “mirror neutrons”]
Possible Dark Decays
Modeled to solve the n lifetime puzzle

Thus $\tau_n^{\text{beam}} = \tau_n^{\text{bottle}} / \text{Br}(n \rightarrow p + \text{anything})$

Visible

$$\mathcal{L}_{1}^{\text{eff}} = \bar{n} \left( i\phi - m_n + \frac{g_n e}{2m_n} \sigma^{\mu \nu} F_{\mu \nu} \right) n$$
$$+ \bar{\chi} (i\phi - m_\chi) \chi + \varepsilon (\bar{n} \chi + \bar{\chi} n)$$

Invisible

Enter $\Phi = (3, 1, -1/3)$ and $\chi$ a SM singlet
Select $\chi$ mass window to avoid proton decay & nuclear constraints
Status of $V_{ud}$

$|\lambda|$ suggests no "χ" needed!

But note most recent bottle $\tau_n$

[Figure Credit: M. A. P. Brown]

[Czarnecki, Marciano, Sirlin, PRL 2018]
Dark Aftermaths?

Particular models are now excluded as explanations of the entire anomaly

[Tang et al., PRL, 2018]

These models also run afoul of the existence of 2 $M_{\odot}$ neutron stars (unless $\chi$ is self-interacting or heavy)

[McKeen et al., 2018; Baym et al., 2018, Motta et al., 2018]
B-L Violation with Quarks

in collaboration with Xinshuai Yan
Origins of the Neutrino Mass

The Majorana mass and $0 \nu \beta \beta$ decay

A neutrino can have a Majorana mass if B-L symmetry is broken

(Enter the Weinberg operator $(v_{\text{weak}}^2/\Lambda_{\text{new}}) \, v_L^T \, C \, v_L$)

Or (and) the neutrino could have a Dirac mass

(Enter the right-handed neutrino & the Higgs mechanism)

But only B-L violation permits $0 \nu \beta \beta$ decay

However, $0 \nu \beta \beta$ decay need not mediated by the exchange of a light Majorana $\nu$ (other sources could act); though its observation would show it effectively exists

[Schechter & Valle, 1982]
Mechanisms of $0\nu\beta\beta$ decay

Why the energy scale of $B-L$ violation matters

If it is generated by the Weinberg operator, then SM electroweak symmetry yields $m_\nu = \lambda v_{\text{weak}}^2 / \Lambda$. If $\lambda \sim 1$ and $\Lambda \gg v_{\text{weak}}$, then naturally $m_\nu \ll m_f$!

N.B. if $m_\nu \sim 0.2$ eV, then $\Lambda \sim 1.6 \times 10^9$ GeV!

Alternatively it could also be generated by higher dimension $|\Delta L| = 2$ operators, so that $m_\nu$ is small just because $d \gg 4$ and $\Lambda$ need not be so large. [EFTs: Babu & Leung, 2001; de Gouvea & Jenkins, 2008 and many models]

Can we establish the scale of $B-L$ violation in another way?

N.B. searches for same sign dilepton final states at the LHC also constrain the higher dimension ("short range") operators. [Helo, Kovalenko, Hirsch, and Päs, 2013]

Here we consider $B-L$ violation in the quark sector: via $n-\bar{n}$ transitions
Neutron-Antineutron Transitions

Can be realized in different ways

Enter searches for

• neutron-antineutron oscillations (free n’s & in nuclei)

“spontaneous”

& thus sensitive to

environment

\[ M = \begin{pmatrix}
M_n - \mu_n B & \delta \\
\delta & M_n + \mu_n B
\end{pmatrix} \]

\[ P_{n \rightarrow \bar{n}}(t) \simeq \frac{\delta^2}{2(\mu_n B)^2} [1 - \cos(2\mu_n B t)] \]

• dinucleon decay (in nuclei)

(limited by finite nuclear density)

• neutron-antineutron conversion (NEW!)

Patterns of $|\Delta B|=2$ Violation?

Minimal scalar-fermion models give connections

[SG & Xinshuai Yan, arXiv: 1808.05288]

Note such models of $n \rightarrow \bar{n}$ oscillation without p decay

[Arnold, Fornal, Wise, PRD, 2013]

Enter new scalars $X_i$ that respect SM gauge symmetry and interactions $X_iX_jX_k$ or $X_iX_jX_kX_l$ — cf. “hidden sector” searches: possible masses are limited by experiment

Here products of different new scalars give $n \rightarrow \bar{n}$ oscillation and $n\bar{n}$ conversion ($e^- p \rightarrow e^+ \bar{p}, \ldots$), and thus can predict $\pi^-\pi^- \rightarrow e^-e^-$!
New Scalars in SM EFT?
Eliminating p decay gives severe constraints!

Scalar-fermion couplings

Possible SM gauge invariant models

<table>
<thead>
<tr>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
</tr>
<tr>
<td>M2</td>
</tr>
<tr>
<td>M3</td>
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<tr>
<td>M4</td>
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<tr>
<td>M5</td>
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<tr>
<td>M6</td>
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<tr>
<td>M7</td>
</tr>
<tr>
<td>M8</td>
</tr>
<tr>
<td>M9</td>
</tr>
</tbody>
</table>

TABLE I. Scalar particle representations in the SU(3)_c × SU(2)_L × U(1)_Y SM that carry nonzero B and/or L but permit no proton decay at tree level, after Ref. [4]. We indicate the possible interactions between the scalar X and SM fermions schematically. Note that the indices a, b run over three generations, that the symmetry of the associated coupling $g_i^{ab}$ under $a \leftrightarrow b$ exchange is noted in brackets, and finally that our convention for Y is $Q_{em} = T_3 + Y$. Please refer to the text for further discussion.

<table>
<thead>
<tr>
<th>Scalar SM Representation</th>
<th>B</th>
<th>L</th>
<th>Operator(s)</th>
<th>$g_i^{ab}$?</th>
</tr>
</thead>
<tbody>
<tr>
<td>X_1</td>
<td>(1, 1, 2)</td>
<td>0</td>
<td>-2 $Xe^a e^b$</td>
<td>[S]</td>
</tr>
<tr>
<td>X_2</td>
<td>(1, 1, 1)</td>
<td>0</td>
<td>-2 $XL^a L^b$</td>
<td>[A]</td>
</tr>
<tr>
<td>X_3</td>
<td>(1, 3, 1)</td>
<td>0</td>
<td>-2 $XL^a L^b$</td>
<td>[S]</td>
</tr>
<tr>
<td>X_4</td>
<td>(6, 3, -1/3)</td>
<td>-2/3</td>
<td>0 $XQ^a Q^b$</td>
<td>[S]</td>
</tr>
<tr>
<td>X_5</td>
<td>(6, 1, -1/3)</td>
<td>-2/3</td>
<td>0 $XQ^a Q^b, Xu^a d^b$</td>
<td>[A, -]</td>
</tr>
<tr>
<td>X_6</td>
<td>(3, 1, 2/3)</td>
<td>-2/3</td>
<td>0 $Xd^a d^b$</td>
<td>[A]</td>
</tr>
<tr>
<td>X_7</td>
<td>(6, 1, 2/3)</td>
<td>-2/3</td>
<td>0 $Xd^a d^b$</td>
<td>[S]</td>
</tr>
<tr>
<td>X_8</td>
<td>(6, 1, -4/3)</td>
<td>-2/3</td>
<td>0 $Xu^a u^b$</td>
<td>[S]</td>
</tr>
<tr>
<td>X_9</td>
<td>(3, 2, 7/6)</td>
<td>1/3</td>
<td>-1 $XQ^a e^b, XL^a \bar{u}^b$</td>
<td>[-, -]</td>
</tr>
</tbody>
</table>

TABLE II. Minimal interactions that break B and/or L from scalars $X_i$ that do not permit $|\Delta B| = 1$ interactions at tree level, indicated schematically, with the Hermitian conjugate implied. Interactions labelled M1-M9 appear in models 1-9 of Ref. [4]. Interactions A-G possess $|\Delta L| = 2$, $|\Delta B| = 0$. M19, M20, and M21 follow from M8, M17, and M18 under $X_7 \rightarrow X_6$, respectively, but they do not involve first-generation fermions only.

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<tr>
<td>M1 $X_5 X_5 X_7$</td>
<td>A $X_1 X_8 X_7^\dagger$</td>
<td>M10 $X_7 X_8 X_8 X_1$</td>
</tr>
<tr>
<td>M2 $X_4 X_4 X_7$</td>
<td>B $X_3 X_4 X_7^\dagger$</td>
<td>M11 $X_5 X_5 X_4 X_3$</td>
</tr>
<tr>
<td>M3 $X_7 X_7 X_8$</td>
<td>C $X_3 X_8 X_4^\dagger$</td>
<td>M12 $X_5 X_5 X_8 X_1$</td>
</tr>
<tr>
<td>M4 $X_6 X_6 X_8$</td>
<td>D $X_5 X_2 X_7^\dagger$</td>
<td>M13 $X_4 X_4 X_5 X_2$</td>
</tr>
<tr>
<td>M5 $X_5 X_5 X_5 X_2$</td>
<td>E $X_8 X_2 X_5^\dagger$</td>
<td>M14 $X_4 X_4 X_5 X_3$</td>
</tr>
<tr>
<td>M6 $X_4 X_4 X_4 X_2$</td>
<td>F $X_2 X_2 X_1^\dagger$</td>
<td>M15 $X_4 X_4 X_8 X_1$</td>
</tr>
<tr>
<td>M7 $X_4 X_4 X_4 X_3$</td>
<td>G $X_3 X_3 X_1^\dagger$</td>
<td>M16 $X_4 X_7 X_8 X_3$</td>
</tr>
<tr>
<td>M8 $X_7 X_7 X_7 X_1^\dagger$</td>
<td></td>
<td>M17 $X_5 X_7 X_7 X_1^\dagger$</td>
</tr>
<tr>
<td>M9 $X_6 X_6 X_6 X_1^\dagger$</td>
<td></td>
<td>M18 $X_4 X_7 X_7 X_3^\dagger$</td>
</tr>
</tbody>
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[SG & Xinshuai Yan, arXiv: 1808.05288]
Patterns of $|\Delta B|=2$ Violation

**Discovery implications for $0\nu\beta\beta$ decay**

TABLE IV. Possible patterns of $|\Delta B|=2$ discovery and their interpretation in minimal scalar-fermion models. Note that only $n-\bar{n}$ oscillations and $e^-n \to e^-\bar{n}$ break B-L symmetry and that the pertinent conversion processes can be probed through electron-deuteron scattering. The latter are distinguished by the electric charge of the final-state lepton accompanying nucleon-antinucleon annihilation. Note that the $0\nu\beta\beta$ query refers specifically to the existence of $\pi^-\pi^- \to e^-e^-$ from new, short-distance physics. Note that we can possibly establish model D and $|\Delta L|=2$ violation, but that model does not give rise to $\pi^-\pi^- \to e^-e^-$. In contrast we cannot establish $X_8$ alone and thus cannot establish model C.

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<th>Model</th>
<th>$n\bar{n}$?</th>
<th>$e^-n \to e^-\bar{n}$?</th>
<th>$e^-p \to \bar{\nu}_X\bar{n}$?</th>
<th>$e^-p \to e^+\bar{p}$?</th>
<th>$0\nu\beta\beta$?</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y [A]</td>
</tr>
<tr>
<td>M2</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y [B]</td>
</tr>
<tr>
<td>M1</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>? [D]</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>? [C?]</td>
</tr>
</tbody>
</table>

Note high-intensity, low energy PVES experiments (P2, e.g.) can be used to broader purpose
Summary

• The long-standing $g_A$ problem in LQCD appears to have been finally solved!

• The possibility of light, dark physics in neutron decay has generated intense interest — with no end as yet!

• The energy scale of B-L violation speaks to different explanations as to why the neutrino is light (A “TeV scale” mechanism could also generate B-L violation in the quark sector)

• We have noted neutron-antineutron conversion, i.e., neutron-antineutron transitions as mediated by an external current (as via scattering)

• Experiments with intense low-energy electron beams, e.g., can also be used to search for B-L violation & help solve the $\nu$ mass puzzle
Backup Slides
Dark Photon Constraints

Assuming $A'$ does not decay to the hidden sector

Figure 4: Obtained upper limits at 90% CL on the mixing parameter $\varepsilon^2$ versus the DP mass $m_{A'}$, compared to the published exclusion limits from meson decay, beam dump and $e^+e^-$ collider experiments [16–22]. Also shown is the band where the inconsistency of theoretical and experimental values of muon ($g-2$) reduces to less than 2 standard deviations, as well as the region excluded by the electron ($g-2$) measurement [2, 23, 24].

In the NA48/2 data sample, the suppression of the DP product in the $K^\pm$ decay with respect to its production in the $\pi^0$ decay is partly compensated by the favourable $K^\pm/\pi^0$ production ratio, lower background (mainly from $K^\pm\to\pi^\pm\ell^+\ell^-$ for $\ell^\pm=\mu$) and high acceptance [25, 26].

For the $A'\to e^+e^-$ decay, the expected sensitivity of the NA48/2 data sample to $\varepsilon^2$ is maximum in the mass interval $140 \text{ MeV}/c^2 < m_{A'} < 2m_\mu$, where the $K^\pm\to\pi^\pm A'$ decay is not kinematically suppressed, the $\pi_0$ background is absent, and $B(A'\to e^+e^-) \approx 1$ assuming that the DP decays only into SM fermions. In this mass interval, the expected NA48/2 upper limits have been computed to be in the range $\varepsilon^2 = (0.8 - 1.1) \times 10^{-5}$ at 90% CL, in agreement with earlier generic estimates [2, 24]. This sensitivity is not competitive with the existing exclusion limits.

Conclusions

As early for the photon ($DP$) production in the $\pi^0\to\gamma A'$ decay followed by the prompt $A'\to e^+e^-$ decay has been performed using the data sample collected by the NA48/2 experiment in 2003–2004. No DP signal is observed, providing new and more stringent upper limits on the mixing parameter $\varepsilon^2$ in the mass range $9–70 \text{ MeV}/c^2$. In combination with the theoretical searches, this result rules out the DP as an explanation for the muon ($g-2$) measurement under the assumption that the DP couples to quarks and decays predominantly to SM fermions.

The NA48/2 sensitivity to the dark photon production in the $K^\pm\to\pi^\pm A'$ decay has also been evaluated.

[NA 48/2, Raggi (2015)]
Figure 4-4. A compilation of WIMP-nucleon spin-independent cross section limits (solid curves), hints for WIMP signals (shaded closed contours) and projections (dot and dot-dashed curves) for U.S.-led direct detection experiments that are expected to operate over the next decade. Also shown is a band indicating the cross sections where WIMP experiments will be sensitive to backgrounds from solar, atmospheric, and di
use supernovae neutrinos.

The flux of these neutrinos is much lower, and exposures with sensitivities to WIMP-nucleon cross sections of $\sim 10^{-48}$ cm$^2$ are required to be sensitive to this neutrino component. Depending on the particular WIMP mass under consideration, these neutrino backgrounds can have a recoil spectrum that is very similar to an authentic WIMP signal. Given the Poisson fluctuations from the neutrino signal and their relatively large total flux uncertainties, this creates a challenge to improving the sensitivity of WIMP searches much beyond such cross sections [39]. Figure 4-4 shows not only the current landscape, but also the projected sensitivities of proposed experiments superimposed on the neutrino background, where coherent neutrino scattering will begin to limit WIMP sensitivity. This will eventually require either background subtraction or techniques such as directional or annual modulation to press beyond this background in the absence of a positive WIMP sighting.
Observations of the CMB power spectrum constrain the ratio of tensor (gravitational wave) to scalar (density fluctuations) power $r$

$r < 0.07$ at 95% C.L.  
[Adi et al., PRL 116 (2016) 031302]  
(BICEP2 + Keck + Planck)]

This quantity has not been detected making ultralight (axion-like) dark matter ($m_a \sim 10^{-22}$ eV) "fuzzy (quantum wave) dark matter" possible....

[Hu, Barkana, Gruzinov, PRL 85 (2000) 1158;  
Schive, Chiu, Broadhurst, Nat. Phys. 10 (2014) 496...;  
Graham & Rajendran, PRD 84 (2011) 055013, for direct detection prospects ]
A new pseudoscalar boson (not connected to QCD) can explain the "dark matter"!

But this is ruled out if "r" is found to be too big!

N.B. $\varphi^* = f_a \theta^*$ [m eV]

Kobayashi et al., PRD 96 (2017) 123514
Electric & Magnetic Dipole Moments

Taken relativistically for fermion $f$ with charge $-e$

$$\mathcal{H} = e \bar{\psi}_f \gamma^\mu \psi_f A_\mu + a_f \frac{1}{4} \bar{\psi}_f \sigma^{\mu\nu} \psi_f F_{\mu\nu} + d_f \frac{i}{2} \bar{\psi}_f \sigma^{\mu\nu} \gamma_5 \psi_f F_{\mu\nu}$$

 photon field  \hspace{1cm} A_\mu \hspace{1cm} F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu

$$\mu_f = g_f \frac{e}{2m_f} \hspace{1cm} g_f = 2 + 2a_f$$

$a_f$ is an anomalous magnetic moment

For an elementary fermion $a_f$ and $d_f$ can only be generated through loop corrections (N.B. $D>4$)
EDMs & Sensitivity to New Physics

The electric and (anomalous) magnetic moments change chirality:

\[ \bar{\psi} \sigma^{\mu\nu} \psi = (\bar{\psi}_L \sigma^{\mu\nu} \psi_R + \bar{\psi}_R \sigma^{\mu\nu} \psi_L) \]

\[ \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi = (\bar{\psi}_L \sigma^{\mu\nu} \gamma_5 \psi_R + \bar{\psi}_R \sigma^{\mu\nu} \gamma_5 \psi_L) \]

By dimensional analysis we infer the scaling:

\[ d_f \sim e \frac{\alpha}{4\pi} \frac{m_f}{\Lambda^2} \sin \phi_{CP} \]

\[ d_{d_{\text{quark}}} \sim 10^{-3} e \frac{m_d(\text{MeV})}{\Lambda(\text{TeV})^2} \sim 10^{-25} \frac{1}{\Lambda(\text{TeV})^2} \text{e-cm} \]

Note ILL limit on neutron EDM:

\[ d_n < 3 \times 10^{-26} \text{ e-cm} @ 90\% \text{CL} \quad \text{[Pendlebury et al., 2015]} \]

EDM experiments have (at least) TeV scale sensitivity.
EDMs in the SM

The contribution from the CKM matrix first appears in three-loop order!

The EDM is flavor diagonal, so that...

- at one-loop order no “Im V…” piece survives
- at two-loop order the “Im V…” piece vanishes
- at three-loop order the gluon-mediated terms dominate

\[ |d_d| \sim 10^{-34} \text{ e-cm} \]

[Khriplovich, 1986]

Inaccessibly small!

Strong interaction effects can enhance but only by \(10^2\) or \(3\) in neutron

[Gavela et al., 1982; Khriplovich & Zhitnitsky, 1982; Mannel & Uraltsev, 2012; ... Seng, 2015]
Lepton EDMs in the SM

The contribution from the CKM matrix first appears in four-loop order!

cf. $d_{\text{e eff}}$ from CPV e-N
[Pospelov & Ritz, 2013]

$$d_{\text{e}} \sim 10^{-44} \text{ e-cm}$$  [Khriplovich & Pospelov, 1991]

Majorana neutrinos can enhance a lepton EDM
[Ng & Ng, 1996]

but not nearly enough to make it “visible”

For “fine tuned” parameters

$$d_{\text{e}} \lesssim 10^{-33} \text{ e-cm}$$  [Archambault, Czarnecki, & Pospelov, 2004]

Look to CPV in $\nu$ oscillations to probe leptogenesis!
Permanent EDMs in Complex Systems

A fundamental EDM points along the particle’s spin, breaking both T and P

\[ \mathcal{H} = -d\vec{E} \cdot \frac{\vec{S}}{S} - \mu \vec{B} \cdot \frac{\vec{S}}{S} \]

Applied electric fields can be enormously enhanced in atoms and molecules [Purcell and Ramsey, 1950]

Searches in different systems:
paramagnetic & diamagnetic & the neutron

ACME (ThO) [Baron et al., 2014]  
YbF [Hudson et al., 2011]  
[Fr] Tl [Regan et al., 2002]  
Hg [Graner et al., 2016]  
Xe [Rosenberry & Chupp, 2001]  
Ra [Bishof et al., 2016]  

with many more (& more methods) under development! [Pospelov & Ritz, 2005; Engel, Ramsey-Musolf, & van Kolck, 2013; Jung, 2013; Chupp et al., 2017]
Theoretical Framework

Fixing the Fermi constant

\[ G_F^{(0)} / \sqrt{2} = g^2 / 8M_W^2 \] is fixed from muon decay

\[ \mathcal{L}_{\mu \rightarrow e \bar{\nu}_e \nu_\mu} = -4 G_F^{(0)} (1 + \delta_\mu + \epsilon_\mu) \bar{e}_L \gamma_\mu \nu_{eL} \cdot \bar{\nu}_{\mu L} \gamma^\mu \mu_L + \text{h.c.} \]

Thus testing CKM unitarity probes weak universality!

Also each extracted \( V_{i,j} \) can contain BSM effects

N.B. explicit studies in the MSSM...

[Kurylov & Ramsey-Musolf, 2002; Bauman, Erler, Ramsey-Musolf, 2012]
A neutron-antineutron oscillation is a spontaneous process & thus the spin does not ever flip. However, $n(+) \rightarrow \bar{n}(-)$ occurs directly because the interaction with the current flips the spin. This is concomitant with $n(p_1, s_1) + n(p_2, s_2) \rightarrow \gamma^*(k)$, for which only $L = 1$ and $S = 1$ is allowed via angular momentum conservation and Fermi statistics. [Berezhiani and Vainshtein, 2015]

Here $e + n \rightarrow \bar{n} + e$, e.g., so that the experimental concept for “$n\bar{n}$ conversion” would be completely different.
Neutron-Antineutron Conversion

**Different mechanisms are possible**

* $n - \bar{n}$ conversion and oscillation could share the same “TeV” scale BSM sources

  Then the quark-level conversion operators can be derived noting the quarks carry electric charge

* $n - \bar{n}$ conversion and oscillation could come from different BSM sources

  Then the neutron-level conversion operators could also be different

Note studies of scattering matrix elements of Majorana dark matter [Kumar & Marfatia, PRD, 2013]
Effective Lagrangian

Neutron interactions with B-L violation & electromagnetism

\[ \mathcal{L}_{\text{eff}} \supset -\frac{1}{2} \mu_n \bar{n} \sigma^{\mu\nu} n F_{\mu\nu} - \frac{\delta}{2} n^T C n - \frac{\eta}{2} n^T C \gamma^\mu \gamma^5 n j_\mu + \text{h.c.} \]

magnetic moment

\[ n \rightarrow \bar{n} \]

“spontaneous” oscillation

[SG & Xinshuai Yan, arXiv: 1710.09292, PRD 18]

Since the quarks carry electric charge, a BSM model that generates neutron-antineutron oscillations can also generate conversion (here \( e^- n \rightarrow e^- \bar{n} \))
Theoretical Framework
On non “V-A” currents

\[ \mathcal{L}^{\text{eff}} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \left[ \left( 1 + \delta_\beta \right) \bar{e} \gamma_\mu (1 - \gamma_5) \nu e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d \right. \]

\[ + \quad \epsilon_L \bar{e} \gamma_\mu (1 - \gamma_5) \nu \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d + \tilde{\epsilon}_L \bar{e} \gamma_\mu (1 + \gamma_5) \nu \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d \]

\[ + \quad \epsilon_R \bar{e} \gamma_\mu (1 - \gamma_5) \nu \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d + \tilde{\epsilon}_R \bar{e} \gamma_\mu (1 + \gamma_5) \nu \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d \]

\[ + \quad \epsilon_S \bar{e}(1 - \gamma_5) \nu \cdot \bar{u} d + \tilde{\epsilon}_S \bar{e}(1 + \gamma_5) \nu \cdot \bar{u} d \]

\[ - \quad \epsilon_P \bar{e}(1 - \gamma_5) \nu \cdot \bar{u} \gamma d - \tilde{\epsilon}_P \bar{e}(1 + \gamma_5) \nu \cdot \bar{u} \gamma d \]

\[ + \quad \epsilon_T \bar{e} \sigma_{\mu \nu} (1 - \gamma_5) \nu \cdot \bar{u} \sigma^{\mu \nu} (1 - \gamma_5) d + \tilde{\epsilon}_T \bar{e} \sigma_{\mu \nu} (1 + \gamma_5) \nu \cdot \bar{u} \sigma^{\mu \nu} (1 + \gamma_5) d \]

\[ + \quad \text{h.c.} . \]

\[ \epsilon_L + \epsilon_R \quad \text{CKM unitarity} \]

\[ \epsilon_L - \epsilon_R, \quad \epsilon_P, \quad \tilde{\epsilon}_P \quad R_\pi \]

\[ \epsilon_S \quad b, \quad B \quad [a, \quad A] \]

\[ \epsilon_T \quad b, \quad B \quad [a, \quad A], \quad \pi \rightarrow e \nu \gamma \]

\[ \tilde{\epsilon}_P \quad R_\pi \]

\[ R_\pi \equiv \frac{\Gamma(\pi \rightarrow e \nu[\gamma])}{\Gamma(\pi \rightarrow \mu \nu[\gamma])}. \]

\[ \epsilon_S, \quad \epsilon_T \quad \text{enter in linear order!} \]

“most visible”