Fundamental Symmetries and Spin Physics beyond SM

Wide Range of probes and techniques

17 talks (6 theorists and 11 experimentalists)

- PV electron scattering (2 expt.),
- Exotic spin-dependent forces (1 expt., 1 theory)
- n electric dipole moments (3 expt., 1 theory)
- p, D EDM (2 expt., 1 theory)
- nuclear EDM (1 theory)
- charmed baryon EDM (1 theory/expt.)
- Atomic EDM (3 expt., 2 theory)
- Dark matter/axions (2 expt., 2 theory)

Dipangkar Dutta (MSU), Andreas Wirzba (FZ Jülich)
Parity violating electron scattering

long history of improving precision and discovery

Upcoming Measurements

- quark axial-vector coupling
- Neutron skin (test EOS)

Ciprian Gal (UVa)
Sebastian Baunack (Mainz)
Exotic Spin Dependent Forces

1. Initialization
2. Superposition
3. Accumulate phase
4. Interferometer
5. Readout

Convert weakly magnetic signal (such as nuclear dipolar $\mu_n$) to phase $\Phi$ which can be detected by quantum interferometer.

Exotic spin-interactions between electrons

NV based diamond nanoscale magnetometer

Xing Rong (USTC, China)
EDM searches have tremendous discovery potential

Experimental constraint

BSM discovery territory

estimated CKM contribution

System

estimated $\theta_{QCD}$ contribution

Klaus Kirch (PSI)

Energy reach of EDM searches

Matt Dietrich (ANL)
The neutron EDM itself...

Expect from SM: $d_n < 10^{-30}$ ecm

Experimentally: $< 3.0 \times 10^{-26}$ ecm

Pendlebury et al., PRD92(2015)092003

Analysis of blinded data in progress
### Neutron EDM projects

<table>
<thead>
<tr>
<th></th>
<th>RAL SUSSEX ILL (Grenoble, FR)</th>
<th>PSI (Villigen, CH)</th>
<th>TUM ILL (Grenoble, Munich)</th>
<th>LANCSE EDM (Los Alamos, US)</th>
<th>SNS EDM (Oakridge, US)</th>
<th>PNPI ILL (Grenoble, FR ⇒ Gatchina, RU)</th>
<th>TRIUMF (Vancouver, CA)</th>
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<tbody>
<tr>
<td><strong>temperature</strong></td>
<td>RT</td>
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<td>RT 0.7 K</td>
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<td>none</td>
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<td>$^3$He</td>
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<td>Xe+Hg</td>
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<td><strong>source</strong></td>
<td>reactor, turbine</td>
<td>spall., sD$_2$</td>
<td>reactor, cold beam, $^4$He</td>
<td>D$_2$</td>
<td>spall, internal $^4$He</td>
<td>reactor, turbine, $^4$He</td>
<td>spall., $^4$He</td>
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<td></td>
<td></td>
<td></td>
<td>3</td>
<td>10</td>
<td>125</td>
<td>4</td>
<td>10$^4$</td>
</tr>
<tr>
<td><strong>[UCN/cc]</strong></td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>1000</td>
<td>~50</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td><strong>goal [e-cm]</strong></td>
<td>$3 \times 10^{-26}$</td>
<td>$1 \times 10^{-26}$</td>
<td>$1 \times 10^{-27}$</td>
<td>$2 \times 10^{-27}$</td>
<td>$&lt; 10^{-27}$</td>
<td>$2 \times 10^{-28}$</td>
<td>$5 \times 10^{-26}$</td>
</tr>
<tr>
<td><strong>status</strong></td>
<td>done</td>
<td>new</td>
<td>Setup at ILL started: 'PanEDM'</td>
<td>Successful source upgrade</td>
<td>Critical Component Demonstration</td>
<td>FIRST UCN OBSERVED from prototype source (2017)</td>
<td></td>
</tr>
</tbody>
</table>

+ Crystal EDM (Nagoya)
+ Beam EDM (Bern)

Phase II is projected to achieve $1.5 \times 10^{-29}$ e-cm

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Peter Fierlinger (TUM)
New Kid on the Block (TRIUMF UCN source)

TUCAN Collaboration

Preliminary # of UCNs from prototype source for 60s of beam on target

New source design
10^7 UCN/s expected

Beatrice Franke (TRIUMF)
Radium EDM

Transverse Cooling
HV Electrodes
Magnetic Shielding & Magnet Coils
Standing wave holding “ODT”
10 W 1550 nm

For EDM:
\[ \text{Ra-225} \]
\[ I = \frac{1}{2}, J = 0 \]
\[ \tau_{1/2} = 15 \text{ days} \]

For Testing:
\[ \text{Ra-226} \]
\[ I = 0, J = 0 \]
\[ \tau_{1/2} = 1600 \text{ yrs} \]

\[ ^{228}\text{Ra MOT} \]
200,000 atoms
40 \( \mu \)K

\[ \psi = |\alpha\rangle \]
\[ |\beta\rangle \]

A large quadrupole and octupole deformation results in an enhanced Schiff moment
- Auerbach, Flambaum & Spevak (1996)

\[ \chi^2/25 = 1.4 \]

\[ d_{\text{Ra-225}} = (4 \pm 6_{\text{stat}} \pm 0.2_{\text{syst}}) \times 10^{-24} \text{ e-cm} \]
\[ d_{\text{Ra-225}} < 1.4 \times 10^{-23} \text{ e-cm} \text{ 95\% C.L.} \]

J. R. Guest et al., PRL 98 093001 (2007)

M. Bishof et al. PRC 94, 025501 (2016)
BSM searches with hyper-polarized gases: 
(\(^3\)He/\(^{129}\)Xe spin clocks) 

W. Heil (Mainz) 
Stefan Zimmer (Heidelberg)

- **Search for neutron spin coupling to a Lorentz and CPT-violating background field**
  \[
  V(r) / \hbar = \langle \tilde{b} \rangle \hat{\mathbf{e}} \cdot \hat{\sigma} / \hbar \quad \tilde{b}_\perp^n < 8.4 \times 10^{-34} \text{ GeV (68\% C.L.)}
  \]

- **Short range spin-dependent interaction (axion search):**
  \[
  V(r) = \frac{g_s g_p}{8\pi} \frac{(\hbar)^2}{m_n} (\sigma_n \cdot \hat{r}) \left[ \frac{1}{r\lambda} + \frac{1}{r^2} \right] e^{-r/\lambda}
  \]
  \(g_n^A g_p^A\) in the range \(10^{-3} \text{ m} < \lambda < 10^1 \text{ m}\)

ARIADNE: probing QCD axion parameter space

\[^{129}\text{Xe} \text{ electric dipole moment (MIXed-collaboration): \)
\[|d_{xe}| < 1.2 \times 10^{-27} \text{ emc (95\% CL)}\]
EDM of Charmed Baryons using bent crystals @ LHCb

How to put polarized $\Lambda_c^+$ inside the crystal
- Fixed-target + bent crystal in LHCb beam pipe
- Incident beam: 7 TeV protons extracted from LHC beam halo using bent crystals $\approx 100$ m upstream of the target
- Feasibility proven by UA9 collaboration
- Initial transversal polarization $s_0 \approx 50\%$

How to measure the spin precession
- Angular distribution of the decay $\Lambda_c^+ \rightarrow pK^−\pi^+$
  $$dN/d\Omega \propto 1 + \alpha s \cdot k$$

With few weeks of data taking ($\approx 10^{15}$ protons on target) the EDM sensitivity would reach $\sigma_\delta \approx 10^{-17}$ ecm

The $\Lambda_c^+$ magnetic moment can be measured, for the first time, with $\sigma_{g-2} \approx 4 \times 10^{-3}$

Joan Ruiz Vidal (Valencia)
**2H EDM @ COSY**

Next steps:

- Improve beam position monitors & Siberian snake.
- First EDM measurement with deuterons (Nov./Dec. 2018)

Frank Rathmann (FZ Jülich)
What can theory (lattice) say about the nEDM?

**Contribution of quark EDM to neutron EDM**

\[
g_T^d = 0.784(28); \quad g_T^u = -0.204(11); \quad g_T^s = -0.0027(16)
\]

**2015 results:** \( g_T^d = 0.774(66); \quad g_T^u = -0.233(28); \quad g_T^s = -0.008(9) \)

Relation between charges \( g_T^q \), couplings \( d_T^q \), and the neutron EDM \( d_n \)

\[
d_n = d_T^u g_T^u + d_T^d g_T^d + d_T^s g_T^s + \ldots
\]

**Constraint on \( d_n \) in Split SUSY**

This is the only result so far on nEDM from lattice QCD

**QCD \( \theta \)-term**

- Actively being calculated and progress at \( M_\pi > 330 \text{ MeV} \); need better variance reduction to get precision at \( M_\pi = 135 \text{ MeV} \)
- **Quark EDM**
  - Calculated: \( g_T^d = 0.784(28); \quad g_T^u = -0.204(11); \quad g_T^s = -0.0027(16) \)
- **Quark Chromo EDM**
  - Exploratory studies show signal in connected contribution; next step: disconnected diagrams & renormalization/mixing
- **Weinberg Three-gluon Operator**
  - Exploratory studies just started
- **Four-quark Operators**
  - Not yet explored

\( d_{n, \text{lattice}} \approx \frac{3}{5} d_{n, \text{quark model}} \)
Hadronic CP violation: from QCD to hadron level

Nuclear level inputs
- Nucleon EDM
- CP-odd NN potential

CPV hadron EFT
- Nucleon EDM
- P, CP-odd π-N interaction
- P, CP-odd contact N-N interaction

GeV scale CPV QCD
- θ-term
- quark EDM
- quark chromo-EDM
- Weinberg operator
- P, CP-odd 4-quark interaction

TeV scale CPV QCD
- θ-term
- quark EDM
- quark chromo-EDM
- Weinberg operator
- P, CP-odd 4-quark interaction
+ Processes with W, Z, H

QCD calculations

RGE

EFT

To nuclear level calculation

Nodoka Yamanaka (IPN Orsay)
**EDM of light nuclei and counting rule**

EDM of light nuclei can be measured using storage rings

- No Schiff’s screening
- Very high sensitivity to new physics expected

- **Isovector** coupling obeys a **counting rule**
  \[ d_{A}^{(\text{pol})} \sim d^{(2/3H)} + n \times 0.005 \, G^{(1)}_{\pi} \, e \, fm \]
  EDM of cluster with open shell
  - \( \alpha\)-N polarization (times \# \( \alpha\)-N combinations)
  - Explained by the **cluster structure**
  - NY, T. Yamada, Y. Funaki, in preparation

- Isoscalar and isotensor appears from single valence nucleon and \(^3\)H cluster (vanish for \( \alpha\)-N polarization)

Example of \(^{11}\)B EDM:
\[ d_{11B} = 0.02 \, G^{(1)}_{\pi} \, e \, fm \]
Spin in curved space-time and gravity induced false EDM effects

Kolya Nikolaev (Landau ITP)

The Earth as a laboratory: storage rings rests on the terrestrial surface.

No real need in full machinery of General Relativity: weak field approximation is OK: it suffices to know the free fall acceleration \( g \), the Earth rotation is a fairly trivial effect.

Two principal effects:

- The spin-orbit interaction in the Earth gravitational field (the de Sitter precession, aka the geodetic effect (1916))

- Focusing EM fields are imperative to impose the closed particle orbit in a storage ring compensating for the particle weight: first derivation by Silenko & Teryaev (2005) for magnetic case

- The both effects have similar structure and both produce false EDM signal in frozen spin pure electric ring

- No explicit separation of the two in otherwise fundamental Orlov et al. (2012)
False EDM from gravity induced imperfection

- Absolute evil in an all electric EDM ring - false EDM signal

- Obukhov et al. (2016))

\[ \vec{\Omega}_{gE} = \frac{1 - G(2\gamma^2 - 1)}{\gamma c^2} [\vec{v} \times \vec{g}] \]

- Upon the frozen spin constraint \( \nu^2 = \frac{1}{1+G} \)

\[ \vec{\Omega}_{gE} = \frac{g\sqrt{G}}{c} \hat{e}_r \]

- First derived by Orlov et al. (2012) by brute force solution of GR equations without explicit separation of the spin-orbit and focusing effects.


- Orlov et al (2012): gravity under full control, false effects can be cancelled out with counterrotating beams

Standard Candle to study systematics
Axions & ALPs, scalar-pseudoscalar interactions, pseudo-magnetic fields

Manifestations of Dark Bosons

**Motivation**
Overwhelming astrophysical evidence for existence of dark matter (~5 times more dark matter than ordinary matter).

\[ \rho_{DM} \approx 0.4 \text{ GeV/cm}^3 \]
\[ \nu_{DM} \sim 300 \text{ km/s} \]
Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, Abel et al., PRX 7, 041034 (2017)]

3 orders of magnitude improvement!

Yevgeny Stadnik (JGU Mainz)

nEDM

Oscillation frequency (Hz)

10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9}

10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15} 10^{-18} 10^{-21} 10^{-24}

Supernova energy loss

Big bang nucleosynthesis

CASPER (projected)

QCD axion

short-time base

long-time base

Galaxies

↓ Super-Planckian ↓

axion decay constant

Storage Ring

see

Frank Rathmann’s plenary talk

[Abel et al., PRX, 2017]
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 $O(1)$ 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!
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

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

[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]

Susan Gardner (U Kentucky)
Mechanisms of 0ν ββ 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
Heavy-Baryon EDMs

Feasibility of a dedicated experiment (S2) explored in EPJ C77 (2017) 828
Final Words

Session 6/F: Fundamental Symmetries and Spin-Dependent BSM

Lots of current activity, many new upcoming results expected (see Spin2020)

huge discovery potential

exciting times ahead

Thank you
to the organizers (especially Paolo & Andrea),
to all the speakers (+ apologies for butchering their talks) of session 6/F,
and - last but not least - to all the participants

Dipangkar Dutta (MSU), Andreas Wirzba (FZ Jülich)