A New Search for a Neutron Electric Dipole Moment

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for
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Outline

- ✓ Introduction and Motivation
- ✓ Past Neutron EDM Searches
- ✓ Proposed Experiment
- ✓ Progress and Schedule

Introduction

- Hamiltonian for neutron ground state in external electric **E** and magnetic **B** fields

$$H = -2\,(\boldsymbol{\mu}_n \cdot \mathbf{B} + d_n \cdot \mathbf{E})$$

  - P (**E** –> –**E**) and T (**B** –> –**B**; **J** –> –**J**) operations not symmetries of the Hamiltonian
  - T violation –> CP violation by CPT theorem

- CP violation seen in neutral kaon and B-meson systems –> in agreement with SM

- Searches for CP violation in light quark and lepton systems yielded null results

Why Search for $d_n \neq 0$?

- CP violation in the Standard Model (SM)
  - complex phase δ in CKM matrix
  - θ-term in QCD Lagrangian

- SM CKM predictions for EDMs are suppressed

	Prediction [e-cm]	Present Limit [e-cm]
e	~ 10^{-38}	~ 10^{-27}
μ	~ 10^{-36}	~ 10^{-18}
n	~ 10^{-31}	~ 10^{-26}

[see Erler and Ramsey-Musolf, hep-ph/0404291]

- Discovery of EDM with value above SM CKM prediction ?
  - CP violation in QCD sector
  - new physics beyond the SM
  - additional source of CP violation needed to explain BAU

- Proposed extensions to the SM yield EDMs above SM CKM prediction
  - e.g., supersymmetry, multi-Higgs models, left-right symmetry
  - e.g., n EDM ~ (10^{-28} – 10^{-26}) e-cm

Several orders of magnitude increase in neutron sensitivity has potential for major discovery !

Past Neutron EDM Searches

Three Classes of Experiments Spanning Five Decades

Neutron Scattering Experiments

Look for enhancement of neutron-electron interaction due to possible $d_n \neq 0$

Magnetic Resonance: In-Flight Neutrons

Use thermal/cold neutrons from reactor

Magnetic Resonance: Ultra-Cold Neutrons

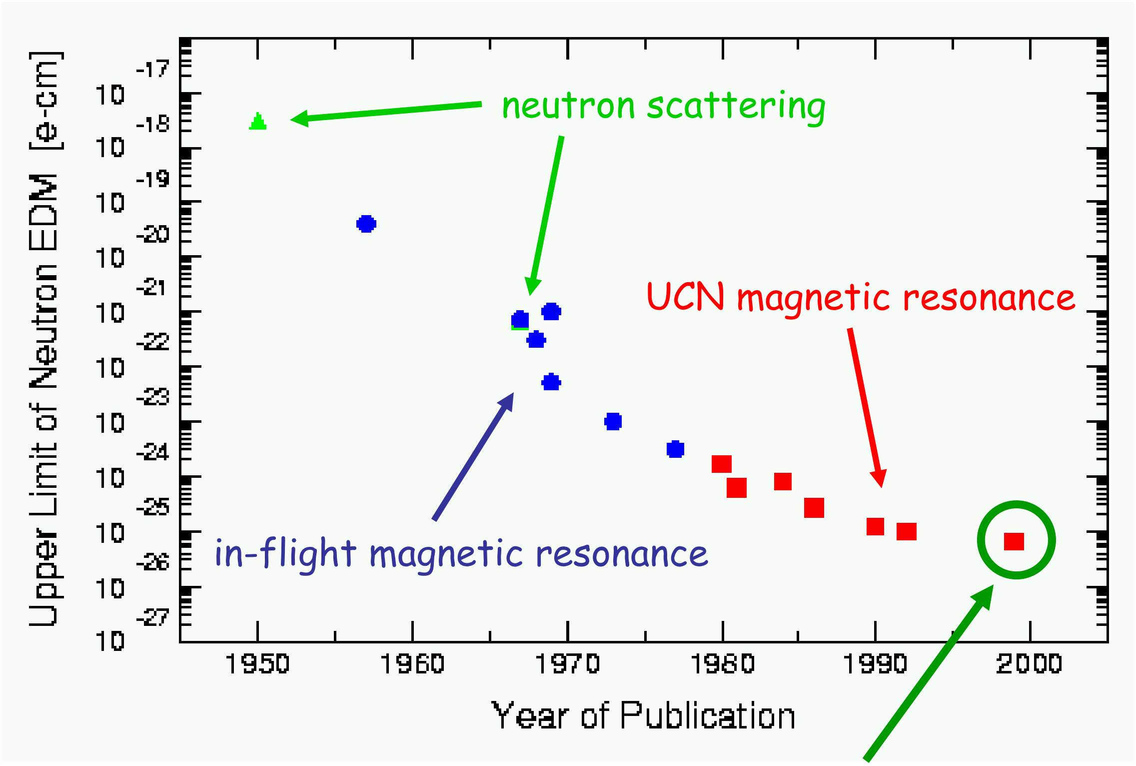
"Bottled" neutrons with energies E < V

$h\nu = -2\,(\boldsymbol{\mu}_n\cdot\mathbf{B} \pm \mathbf{d}_n\cdot\mathbf{E})$

E, **B** parallel and anti-parallel

$d_n = h\Delta\nu \,/\, 4|\mathbf{E}|$

Past Neutron EDM Searches



Best limit to date from ILL reactor (1999): $d_n \leq 6.3 \times 10^{-26}$ e-cm (1999)

- Incorporated for the first time a "co-magnetometer" of polarized ^{199}Hg atoms -> reduced systematic error associated with **B** field

Proposed experiment has potential for 2 orders-of-magnitude improvement and greatest reach of all next-generation EDM experiments

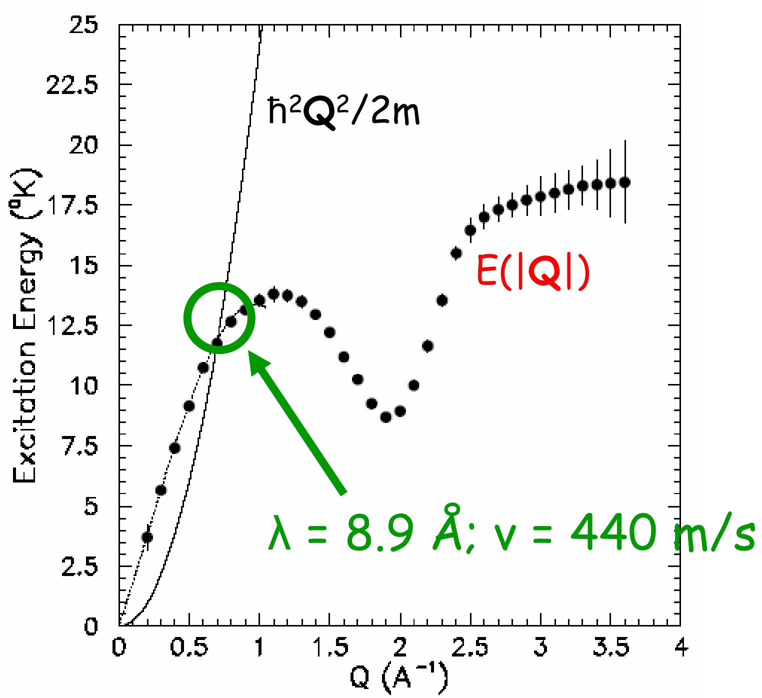
Proposed Experiment

- Overall strategy
  - Locally produce UCN inside a closed neutron trap via the downscattering of cold neutrons in superfluid ^{4}He at 300 mK (recoil phonon)
  - Introduce dilute (~10^{-10}) admixture of polarized ^{3}He atoms as co-magnetometer
    - ^{3}He EDM negligibly small due to Schiff shielding
  - Extract d_n from comparison of ^{3}He and neutron precession frequency when **E**, **B** parallel and anti-parallel

Superfluid ^{4}He dispersion curve

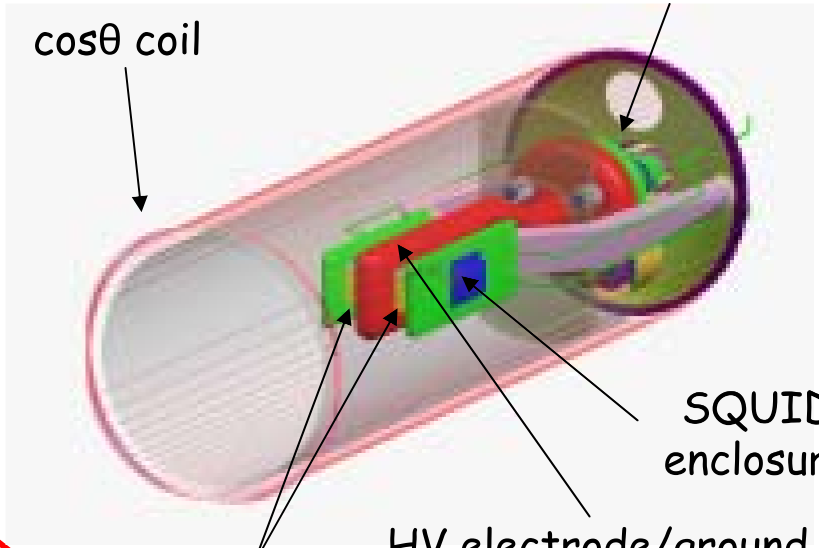
Single recoil phonon: $\mathbf{Q} = \mathbf{k}_i - \mathbf{k}_f$

$$\hbar^2 \mathbf{k}_i^2/2m = \hbar^2 \mathbf{k}_f^2/2m + E(|\mathbf{Q}|)$$



Experimental Schematic

- Neutron trap (UCN cells)
  - three-component fluid of
    - superfluid ^4He (~ $10^{22}/cm^3$)
    - UCN (~ $500/cm^3$)
    - polarized ^3He (~ $10^{12}/cm^3$)
  - Electromagnetic fields
    - high-voltage electrodes (50 kV/cm)
    - uniform cosθ coil field (1 - 10 mGauss)
  - SQUID coils adjacent to UCN cells
    - used to measure ^3He precession frequency



$|B|$ = 1 mGauss, $|E|$ = 0: ν_n = **2.92 Hz**

$|E|$ = 50 kV/cm, $d_n = 4 \times 10^{-27}$ e-cm: $\Delta\nu_n$ = **0.19 × 10^{-6} Hz**

Neutron Precession Frequency

- Measurement of the UCN precession frequency
  - UCN and ^{3}He spins will precess at different frequencies: $\mu_{3He} / \mu_n \sim 1.11$
  - difference between the precession frequencies will be monitored via the spin dependence of the nuclear absorption cross section for the reaction

$$n + {}^3He \rightarrow p + t + 764\ keV$$

Fraction of total neutron absorption by ^{3}He in J=0 state

$\sigma_{J=0} / \sigma_{total} = 1.01 \pm 0.03$

Scintillation light emitted in EUV regime in superfluid ^{4}He; shifted to visible

Sinusoidal PMT signal measure of ν_n given $\nu_{^3He}$ from SQUID signals

The EDM Collaboration

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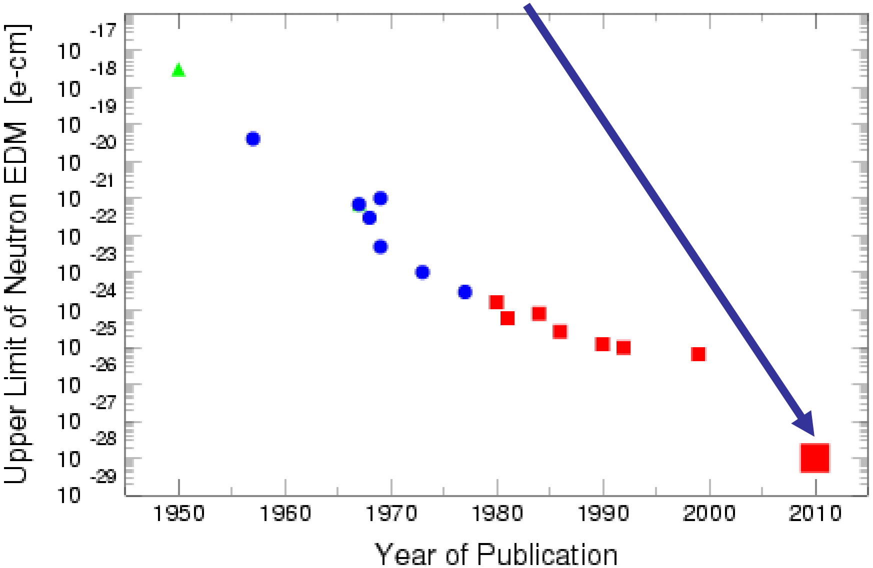
R&D Progress

- Experiment is currently in the R&D phase; technical progress thus far includes
  - Full-scale mockup of the high-voltage multiplier has been constructed and operated successfully at 4K (superfluid tests soon)
  - Work on magnetic fields and magnetic shielding has begun (Caltech)
    - prototype cosθ coil; cryogenic tests of ferromagnetic magnetic shielding
  - Polarized ^3He relaxation times (T_1) measured at 4K and 2.5K
    - longer relaxation times observed at 2.5K (~8.5 hr) than at 4K (~3.9 hr)
  - Particle identification studies underway at a reactor
    - scintillation light from recoiling tritons/protons and β-decay electrons
  - Plans underway to study neutron storage time
    - couple to already-existing UCN beamline at LANL

Schedule and Projected Result

- Anticipated schedule
  - R&D phase to continue through FY2005; full proposal in progress
  - Collaboration eager to start construction phase FY2006
  - Experiment will be mounted at the Spallation Neutron Source at the Oak Ridge National Laboratory (~2010)

- Projected sensitivity
  - ✓ **$\sim 10^{-28}$ e-cm in ~100 days of running**



Sensitivity at this level:

- discover a non-zero value for d_n
- severely constrain proposed SM extensions

If non-zero value is discovered, results from complementary experiments needed:

- CP violation in QCD sector
- new physics beyond the SM

Summary

- Search for neutron EDM is of fundamental importance
  - several orders of magnitude increase in sensitivity has the potential to either discover non-zero value or severely constrain proposed extensions to Standard Model
- New experiment employing novel technique of UCN production in superfluid ^{4}He with ^{3}He as co-magnetometer has potential to increase sensitivity by two orders of magnitude to ~10^{-28} e-cm
- Collaboration has made significant R&D progress on a number of technical issues
  - ready to enter construction phase in FY2006

Other Neutron EDM Searches

From Subcommittee on Fundamental Physics with Neutrons Report to NSAC

Facility	Limit (e-cm)	Date	Technique	Status
ILL (ILL-99)	7.5×10^{-26}	1999	20-ℓ cell Hg magnetometer	Latest publication
ILL	3.4×10^{-26}	2003	20-ℓ cell Hg magnetometer	(ILL-99) Now running
ILL	$8\text{-}20 \times 10^{-27}$	2004-6	20-ℓ cells Hg magnetometer	(ILL-99) Possible continuation
PSI	2×10^{-27}	2006-8	Eight 3-ℓ cells neutron/Cs magnetometer	New proposal under review
ILL	$1\text{-}20 \times 10^{-28}$	2006-9	Superfluid He trap, neutron magnetometer	New proposal under review
LANSCE (1st stage)	$6\text{-}27 \times 10^{-28}$	2008-10	Superfluid He trap, ^{3}He magnetometer	Pre-proposal stage
SNS (2nd stage)	$3\text{-}12 \times 10^{-29}$	2010-12	Superfluid He trap, ^{3}He magnetometer	Pre-proposal stage