Towards a neutron EDM experiment at the PSI ultra-cold neutron source

K. Kirch
Paul Scherrer Institut

- General considerations
- Our approach
- Present status
- Open questions

Baryon asymmetry

Observed:
\( \frac{n_B}{n_\gamma} = 6 \times 10^{-10} \)

SM expectation:
\( \frac{n_B}{n_\gamma} \sim 10^{-18} \)
The EDM limits to date

$dn \leq 6.3 \cdot 10^{-26} \text{ e}\cdot\text{cm}$

RAL-Sussex-ILL PRL82(1999)904

Electro-weak standard model expectation: $\sim 10^{-32} \text{ e}\cdot\text{cm}$
How to measure the EDM?

\[ h\nu_{\uparrow\uparrow} = 2 (\mu_B + d_n E) \]
\[ h\nu_{\uparrow\downarrow} = 2 (\mu_B - d_n E) \]
\[ h\Delta\nu = 4 d_n E \]

Typical values for the Sussex-RAL-ILL EDM:
- \( \alpha = 0.75 \)
- \( T = 130 \text{ s} \)
- \( E = 10 \text{ kV/cm} \)
- \( N_0 = 18000 / \text{cycle} \)
- \( \delta d_n = 2.5 \times 10^{-24} \text{e\cdotcm/} \text{cycle} \)
- \( \delta d_n = 10^{-26} \text{e\cdotcm/year} \)
- \( \Delta B < 800 \text{ fT} \)

PRL82(1999)904

Ramsey Resonance Curve
Major experimental questions

- How to get (many) UCN into the box?
- How to make sure, B behaves well?
- How to maximize $E, \alpha, T$?
- How to fight systematics ($B, v \times E, \ldots$)?

Different approaches …
Our approach

• Produce high UCN density separate from EDM
• EDM in vacuum and at room-temperature
• Double- or multi-chamber setup
• Cs laser optically pumped magnetometer (LsOPM) array
• Internal field stabilization
• Resonance frequency stabilization
• Digital frequency generation with possibility of phase shifts
• UCN velocity sensitive detection scheme
• Improve many details (coatings, polarization, DAQ, MC, ...)
• Hands-on work with old Sussex-RAL experiment
• Setup improved experiment at PSI in 2008
• Aim first at $1 \times 10^{-27}$ e·cm
The neutron EDM collaboration

Laboratoire de Physique Corpusculaire, Caen, France

K. Bodek, St. Kistryn, M. Kuzniak, J. Zejma
Institute of Physics, Jagiellonian University, Cracow, Poland

A. Ivlev, N. Khomytov, D. Mzhavia, B.M. Sabirov
Joint Institute of Nuclear Research, Dubna, Russia

S. Gröger, P. Knowles, M. Rebetez, A. Weis
Department de Physique, Université de Fribourg, Fribourg, Switzerland

C. Plonka
Institut Laue-Langevin, Grenoble, France

G. Quéméner, D. Rebreyend, U.C. Tsan
Laboratoire de Physique Subatomique et de Cosmologie, Grenoble, France

T. Brys, M. Daum, P. Fierlinger, R. Henneck, S. Heule, M. Kasprzak, K. Kirch, A. Pichlmaier
Paul Scherrer Institute, Villigen, Switzerland

EDM FLAVOUR 05
UCN source at PSI

Deliver 600 MeV protons with 2mA, i.e. **1.2 MW** !, at 1% duty cycle to UCN target station
The PSI UCN source

- Diamond-Like Carbon coated ~2 m³ trap
- UCN shutter
- 1.2m
- ~3 m³ D₂O
- 2 mA, 600 MeV proton beam 1% duty cycle
- \( \rho \sim 3000 \text{ cm}^{-3} \)
- \( \rho_{\text{exp}} > 1000 \text{ cm}^{-3} \)
- PRC 71, 054601 (2005)
- PLB 625, 19 (2005)
- PRL 94, 212502 (2005)
- PRL 95, 182502 (2005)
- & multiple NIM A
- http://ucn.web.psi.ch

PSI - Cracow - ILL – Vienna - Efremov
UCN source status: on track

civil construction under way, hardware either ready, under construction or in detailed design: UCN scheduled for 2008

Oct 05
Magnetometry approach

• improve magnetic field measurement & control
• complement co-magnetometry approach (or even give up on it)
• use many highly sensitive sensors for scalar and gradient information
• use active feed-back stabilization of the magnetic field and gradients
• generate oscillatory field using (weighted) information of Cs magnetometers
• use double or multiple neutron chambers
Self-oscillating laser-pumped Cs magnetometer

- non-magnetic sensor head
- Larmor frequency: 3.5 kHz @ 1 μT

1 magnetometer (OPM) needs 25 μW
1 laser delivers >10 mW

1 laser = many sensors

JRNIST 110, 179 (2005)
JOSA B 22, 77 (2005)

http://www.unifr.ch/physics/frap/
Field fluctuations inside magnetic shield

limited by current source

long term drift

intrinsic sensitivity
Active field stabilization

Simple field stabilization coils give $10^3$ improvement at 100 s. Gradient correction of the same order can be expected.

Cramér-Rao limit: $\sim \tau^{-3/2}$
Magnetic field measurements in the Sussex/RAL/ILL EDM setup
Simultaneously running Cs magnetometer and Hg co-magnetometer:

preliminary results:
~ 1 order of magnitude more stable Hg reading with active field stabilization using Cs magnetometer

field stability ASD ≤ 200 fT over 100s time scales measured with Cs magnetometers

B~1μT
~3.5 kHz
~8 Hz
Other ongoing EDM research

- Development of superior UCN materials:
  - high critical velocity (or very low)
  - low UCN loss
  - low UCN depolarization
  - high specific resistivity
  - non-magnetic (or fully magnetized)
- High rate, high stability UCN detection
- State of the art DAQ
- Efficient UCN polarization and analysis
- Improved calculational tools
- Analysis of systematics
The EDM limitations to date:

A) Statistics

(UCN density, storage time, electric field strength, polarization and depolarization, ....)

\[ d_n \leq 6.3 \times 10^{-26} \text{ e cm} \]

RAL-Sussex-ILL PRL82(1999)904

\[ \rho_{\text{UCN}} = 145 \pm 7 \text{ cm}^{-3} \]

A. Saunders et al. PLB593(2004)55

UCN source development in CH, USA, F, Germany, Japan

A.P. Serebrov et al., JETP Lett. 59(1994)757
The EDM limitations to date:

B) Systematics

- magnetic field homogeneity
- magnetic field gradients
- magnetic field drifts
- motional magnetic fields
- electric field uniformity
- electric field II magnetic field
- electric field reproducibility
- leakage currents
- depolarization
Thank you!
Competition

- At least 3 new EDM projects worldwide within the next 5 years (and maybe more (both 3 and 5))
  - all aim at sensitivities below $10^{-27} \text{e}\cdot\text{cm}$
  - all use at least two differential HV chambers
  - 2 will use superfluid Helium below 0.5K, 1 will be operated in vacuum
  - 2 will rely on "external" magnetometry, 1 will have a co-magnetometer
  - 2 will measure the neutron precession frequency using the Ramsey method of separated oscillatory fields, 1 will measure the difference frequency of neutrons and $^3\text{He}$
  - 2 will detect the UCN in external detectors, 1 has the detection combined with the magnetometry
  - 2 detection schemes do not depend on UCN velocity, 1 aims for velocity dependence
  - 1 will have zero E-field chambers, one doesn’t, one didn’t decide
Diamond Like Carbon Coating

- Developed reliable DLC characterization
- Large area DLC coatings with high critical velocity, low loss and depolarization
- Prototype for UCN source storage tank with DLC coating under construction
- Pulsed Laser Deposition (PLD) of DLC presently being optimized
- PLD for UCN guide tubes under construction
- Research into high resistivity DLC coatings
Detector development

Various options, e.g.
thin GS10 Li glass scintillator,
4 m/s critical velocity,
25% resolution, fast, radiation hard,
easily shaped and segmented
Adapted Geant4 for UCN

UCN specific features:

- Boundary and bulk material interaction
- Particle tracking with gravity
- Particle tracking through arbitrary (in general: inhomogenous, dynamic) magnetic fields
- Spin tracking through arbitrary magnetic fields

![Graph showing polarization components vs adiabaticity coefficient](image)
EDM FLAVOUR 05
Phase Shifts in the Molecular Beam Method of Separated Oscillating Fields

NORMAN F. RAMSEY AND HENRY B. SILSBEE
Harvard University, Cambridge, Massachusetts
(Received July 20, 1950)

Fig. 1. Theoretical change in transition probability on removing 180° phase shift.

Fig. 3. Theoretical change in transition probability on reversing 90° phase shift.
New Experimental Limit on the Electric Dipole Moment of the Neutron

P. G. Harris,* C. A. Baker, K. Green, P. Iaydjiev,† and S. Ivanov‡
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom

D. J. R. May, J. M. Pendlebury, D. Shiers, K. F. Smith, and M. van der Grinten
University of Sussex, Falmer, Brighton BN1 9QJ, United Kingdom

P. Geltenbort
Institut Laue-Langevin, BP 156, F-38042 Grenoble Cedex 9, France
(Received 17 September 1998)

FIG. 3. Neutron resonant frequency measurements, showing both the raw and the mercury-corrected measurements.

FIG. 4. Results of the neutron EDM measurements, grouped by reactor cycle.

FIG. 2. The Ramsey resonance curve for spin-up neutrons, $N_{1}$. The corresponding pattern for $N_{1}$ is inverted but otherwise identical.
Ramsey resonances with phase shift

I.S. Altarev et al., NPA341(1980)269

Fig. 5. Experimental resonance curves for different phase shifts between variable fields at the spectrometer input and output. $N_1$: neutron intensity with field $H_1$ turned off; $N_2$: neutron intensity with spin flip within the region between the polarizer and analyzer; $N_3$: thermal neutron background; $P$: degree of neutron polarization.


Fig. 5. Resonance curves obtained for the neutron-storage time $T_s = 100$ s.
The Sussex-RAL-ILL EDM experiment

- neutron volume = Hg volume
- low bandwidth (8 Hz)
- integration over the whole volume
- no information about gradients
- no active field stabilization
The PNPI EDM experiment

- high bandwidth → active field stabilization
- information about linear gradient $\partial B / \partial z$

- place of field measurement ≠ neutron volume
- no information about component gradients $\partial B_i / \partial x_j \ (i, j = 1, 2, 3)$
- each sensor needs its own light source
The PNPI experiment

d_n \leq 9.7 \times 10^{-26} \text{ e}\cdot\text{cm}

I.S. Altarev et al.,
Phys.At.Nucl. 59(1996)1152

Main advantages
- Double chamber
- Resonance stabilization

Fig. 5. Resonance curves obtained for the neutron-storage time $T_s = 100$ s.
Some requirements for the B-field

\[ 2 \mu_n \Delta B < 4 \delta d_n E \] for uncorrelated B-field noise per cycle

\[ \Delta B [ \text{fT} ] < 3.3 \times 10^{26} \cdot E [ \text{kV/cm}] \cdot \delta d_n [ \text{e\cdot cm}] \]

typical values
\[ E=10 \text{ kV/cm}, \delta d_n=2.5 \times 10^{-24} \text{ e\cdot cm} \] yield \( \Delta B < 800 \text{ fT} \)

Obviously for an order of magnitude improvement in sensitivity per cycle we need \( \Delta B < 80 \text{ fT} \).
However, things are more subtle …

• stable magnetic field:
  $\Delta B < 80$ fT noise per cycle, see above
• E-field correlated changes are extremely dangerous
• homogenous field:
  $dB/dz < 200$ fT/m, see PRA 70 (2004) 032102
• restrictions on
  – leakage currents,
  – field parallellity E,B
  – $\Delta E$ upon field reversal
• field control for other, also yet unknown effects
• realize $v_{\text{UCN}}$ dependence of many systematics