Ultracold neutron sources and neutron electric dipole moment experiments

Klaus Kirch
ETH Zürich – Paul Scherrer Institut
A very warm Thank You to the organizers!
Outline

- How to measure the neutron EDM?
- What are UCN and how to produce them?
- UCN sources and nEDM efforts worldwide
- A few more words on our approach at PSI
- Some other things with relation to FPUA
Outline

- How to measure the neutron EDM?
- What are UCN and how to produce them?
- UCN sources and nEDM efforts worldwide
- A few more words on our approach at PSI
- Some other things with relation to FPUA

I assume the motivation to be clear after today’s talk!
Nature has probably violated CP when generating the Baryon asymmetry!?

New theories provide the CP-violation to describe Nature

Experiments must access with high sensitivity CP-violating observables

Sakharov 1967: B-violation
C & CP-violation
non-equilibrium

\[ \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10} \]

SM expectation:
\[ \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18} \]
EDM and symmetries

$$H = -\left( d \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{E} + \mu \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{B} \right)$$

A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

Purcell and Ramsey, PR78(1950)807; Lee and Yang; Landau
How to measure the neutron (or other) electric dipole moment?

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

\[ \sigma(d_n) = \frac{\hbar}{2\alpha ET \sqrt{N}} \]
Ultra-cold neutrons

similar to ideal gas with temperatures of milli-Kelvin
(very dilute and not in thermal equilibrium with walls)
move with velocities of few m/s
have kinetic energies of order 100 neV

strong

Fermi potential $V_F$

$magnetic$

$V_m = -\mu B$

$60 \text{ neV} \ T^{-1}$

$V_g = m_n g h$

$100 \text{ neV} \ m^{-1}$

$E_n < 300 \text{ neV}$

$5 \text{ T field} \rightarrow 300 \text{ neV}$

$3 \text{ m up} \rightarrow 300 \text{ neV}$
UCN can be stored

Some typical values of relevance to experiments:

- $v_{\text{UCN}} \sim 5 \text{ m/s}$ (often: slow is better)
- $t_{\text{obs}} \sim 10^2$-$10^3 \text{ s}$
- $\rho \sim 10 \text{ cm}^{-3}$
- Volumes 5-100 l or more (e.g. our nEDM $\sim 20$ l)

Almost all experiments need more UCN

- in absolute number (counting statistics!)
- therefore, for a given volume, in density
How to get the free, slow neutrons?

- **Release** neutrons from nuclei
  - fission, e.g.: $^{235}\text{U} + n \rightarrow ^{236}\text{U}^* \rightarrow \text{Kr} + \text{Ba} + (2-3)n$
  - spallation, e.g.: $p (E_{\text{kin}} \sim 600\text{MeV}) + \text{Pb} \rightarrow 8n + \text{XYZ}$
  - [other processes not used for slow neutron physics]

- **Moderate** in elastic collisions
  - Thermal moderator ((heavy) water, graphite, …)
  - Cold moderator (hydrogen, deuterium, polyethylene, …)
  - $\rightarrow$ UCN can be extracted from Maxwellian tail

- **Convert** cold neutrons to UCN

- **Extract** UCN to vacuum (or use them in SF-He)

- **Guide** UCN to experiment
Neutron production: moderation & thermal equilibrium

Maxwell-Boltzmann

$$\rho(v) dv = \frac{2\Phi_0}{\alpha} \frac{v^2}{\alpha^2} \exp\left(-\frac{v^2}{\alpha^2}\right) \frac{dv}{\alpha}$$

$$\rho(UCN) = \frac{2\Phi_0}{3\alpha} \left(\frac{E_c}{k_B T}\right)^{3/2}$$

$$\rho(UCN) = 70 \times 10^{-13} \Phi_0 [\text{cm}^{-2}\text{s}^{-1}] \text{ cm}^{-3}$$

$$10^{-13} \Phi_0 [\text{cm}^{-2}\text{s}^{-1}] \text{ cm}^{-3}$$

$$\alpha = (2k_B T/m)^{1/2}$$

30 K

300 K
Neutron production: moderation & thermal equilibrium

Maxwell-Boltzmann

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$$10^{-13} \Phi_0 \, [\text{cm}^{-2}\text{s}^{-1}] \, \text{cm}^{-3}$$

$$\alpha = (2k_B T/\text{m})^{1/2}$$

30 K

300 K
The Steyerl turbine

Steyerl turbine (2nd generation)
at PF2 / ILL
10 years later

Steyerl turbine
at FRM-I (Munich)

Courtesy: P. Geltenbort, ILL
UCN production at ILL PF-2

Maxwellian distribution
2000 UCN/cm³

extracted UCN
40 UCN/cm³

~10 UCN/cm³ in experiments

A. Steyerl et al.,
Superthermal UCN production

- Golub and Pendlebury, PL62A(1977)337: superfluid He
- Golub and Böning, ZPB51(1983)95
- Yu, Malik, Golub, ZPB62(1986)137

\[ \rho_{UCN} = \Phi_{CN} R \tau_{UCN} \]

He: small R, long \( \tau \)
D\(_2\): large R, small \( \tau \)

Cooling machine = phonon pump

Detailed balance: upscattering cross section = \( \exp(-\Delta E/kT) \times \) downscattering
CN energy dependent UCN production

F. Atchison et al., PRL99(2007)262502

C.A. Baker et al., PLA308(2003)67
\[ \rho_{UCN} = \Phi_{CN} \cdot R \cdot \tau_{UCN} \]

<table>
<thead>
<tr>
<th></th>
<th>(R)</th>
<th>(\tau_{UCN})</th>
</tr>
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<tbody>
<tr>
<td>(D_2)</td>
<td>(10^{-8})</td>
<td>(0.03\ldots0.1)</td>
</tr>
<tr>
<td>(He)</td>
<td>(1\ldots3 \times 10^{-9})</td>
<td>(10\ldots1000)</td>
</tr>
</tbody>
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...inside He-II one can produce about 2 orders of magnitude higher UCN density from the same cold neutron flux than inside solid \(D_2\).

Courtesy: Y. Masuda

C.L. Morris et al., PRL89(2002)272501

for crude estimates ...
for crude estimates ...

\[ \rho_{\text{UCN}} = \Phi_{\text{CN}} \, R \, \tau_{\text{UCN}} \]

<table>
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<th>( R ) ([\text{cm}^{-1}] )</th>
<th>( \tau_{\text{UCN}} ) [s]</th>
</tr>
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... inside He-II one can produce about 2 orders of magnitude higher UCN density from the same cold neutron flux than inside solid \( \text{D}_2 \)

... extracting UCN from the converter dilutes the UCN density but also increases the effective UCN lifetime for a solid \( \text{D}_2 \) source

Y.Pokotilovski, Nucl. Instr. and Meth.
UCN sources

[some belong to specific experiments]

- **Operating:**
  - ILL PF-2 (turbine)
  - LANL (sD2)
  - PSI (sD2)
  - TRIGA Mainz (sD2)
  - RCNP (SF-He)
  - ILL SUN (SF-He)
  - [ILL: GRANIT, cryoEDM]
  - [NIST: lifetime]

- **R&D and construction**
  - ILL SuperSUN
  - TRIUMF/RCNP
  - PNPI WWR-M
  - NCSU PULSTAR
  - FRM-2
  - SNS-EDM

- **Possible projects**
  - J-PARC
  - PIK
  - ESS
Neutron EDM projects

(Essentially all of them aiming at 1-2 orders of magnitude improvement)

- Operating:
  - PNPI, ILL@ILL (result 2013/14, upgrading)
  - nEDM@PSI (2017 upgrade to n2EDM)

- R&D and construction
  - cryoEDM@ILL
  - @RCNP/TRIUMF
  - @FRM-2
  - @SNS
  - @PNPI
  - @LANL

- Possible future projects
  - @J-PARC
  - @PIK
  - @ESS
LANL UCN Source

- UCN production via single phonon scattering (superthermal process)
- UCN loss due to:
  - upscattering from phonons
  - upscattering from para-D2
  - absorption on D & H
- The only operating UCN source in US
- Best UCN source for correlation measurements
  - Combination of current and density
  - Low and stable background

Courtesy: A. Saunders, T. Ito

Rich science program at LANL UCN source

• UCNA experiment (PI: A. Saunders & A. Young)
  – Precision measurement of the angular correlation between the neutron spin and electron momentum
• UCNB experiment (PI: M. Makela)
  – Measurement of the angular correlation between the neutron spin and neutrino momentum
• UCNτ (PI: A. Saunders, S. Seestrom, S. Clayton)
  – Neutron lifetime measurement based on magneto-gravitational trap
• Actinide science (PI: M. Makela)
  – Study of interaction between neutrons and actinides
• Detector R&D for the Nab experiment at SNS
• Neutron storage R&D for the SNS nEDM experiment
LANL nEDM effort

• New R&D effort towards a goal of building a room temperature nEDM experiment with a sensitivity goal of $\delta d_n \sim 3 \times 10^{-27}$ e-cm.
  – This effort currently funded by LANL internal funds (PI: Takeyasu Ito)

• The current activities include:
  – UCN source upgrade
    • New source insert with more optimized source geometry
    • Increased proton beam current with more optimized pulsed beam delivery
    • Improved UCN transport
  – Prototyping of an nEDM apparatus

• Short term goal (3 years)
  – Demonstration of stored UCN in a prototype nEDM apparatus with a sufficient number of UCN for an nEDM experiment with a sensitivity of $\delta d_n \sim 3 \times 10^{-27}$ e-cm
PULSTAR SD$_2$ UCN Source

E.Korobkina, A.Cook, R.Golub, P.R.Huffman, A.Hawari, G.L.Medlin, G.Palmquist, A.R.Young, B.Wehring

**DESIGN**

- Multi-stage moderation allows high UCN yield per MW reactor power
- Uniquely positioned in thermal column to minimize heating, efficient transport of thermal neutrons

**STATUS**

- Thermal flux benchmarked by measurement, $5 \times 10^{11}$ n/cm$^2$·s in UCN converter volume
- Construction finished on source assembly, gas handling system, helium liquefier
- System to spin convert D$_2$ to $<2\%$ para-content and analyze with Raman scattering
- Cryogenic tests passed safety approval, characterization underway
- Target useful UCN density 30 UCN/cc
- Factor of 2 from reactor power upgrade in next 3 years
- First experiment, nEDM systematic study apparatus

Courtesy: A. Young

UCN User Facility at TRIGA Mainz

Courtesy: W. Heil

two operation modes:
steady state (UCN C)
100 kW\(_{th}\), \(10^{12}\) n/cm\(^2\)s

pulse mode (UCN D)
250 MW\(_{th}\) (30 ms), \(2\cdot10^{15}\) n/cm\(^2\)s

2 $  1.75 $  1.5 $

- 250 MW\(_{max}\) (30 ms) (FWHM) \(10^{15}\) n/cm\(^2\)
- 160 MW\(_{max}\) (40 ms) (FWHM)
- 70 MW\(_{max}\) (65 ms) (FWHM)

50 W

0 ms  800 ms
Experimental setup used to measure the UCN source performance

UCN storage volume:
- stainless steel (10 L)

- NiMo coated glass tubes

- biological shield

- reactor core

- sD$_2$ converter (8 mol)

- $\Delta h = 116$ cm

- ~4 m

Courtesy: W. Heil
Results

UCN densities in storage volume of 10 L

Measured UCN/VCN counts/0.1s in the flow mode versus time after a reactor pulse.

Conf-I: Nocado tubes
Conf-II: NiMo coated glass tubes
Latest result on UCN production

(supermirror converter vessel with Be-coating)

(\tau_{\text{buildup}} \approx 1 \text{ min})

\sim 493000 \text{ accumulated UCN from 4 liters He-II}

\sim 120/\text{cm}^3

Courtesy: O. Zimmer

left to right:
Martin Simson
Florian Martin
OZ
Felix Rosenau
Sergey Ivanov
Project **SuperSUN** (3 m magnetic 12-pole UCN reflector)

- In-situ UCN polarizer
- Enhancement of UCN spectrum possible
- Weak dependence of $\rho_{\text{UCN}}$ on wall quality (values in source for $E < 296$ neV):

\[
\begin{align*}
    f &= \frac{W}{V} \\
    n_\infty (\text{cm}^{-3}, \text{for } B_R = 2.5 \text{ T}) &= 1820 \quad 1400 \quad 1200 \quad 1040 \\
    n_\infty (\text{cm}^{-3}, \text{without magnet}) &= 820 \quad 390 \quad 230 \quad 130
\end{align*}
\]

numbers for monochromatic beam H172b (5 times more in direct beam)
nEDM at RCNP/TRIUMF $10^{-27} \sim 10^{-28} \text{ e cm}$

UCN density: 2600 /cm$^3$

E < 90 neV

$^{129}\text{Xe}$ co-magnetometer

Courtesy: Y. Masuda
Present Status

2013.11.10
We produced 35L He-II at a temperature of 0.6 K.

2013.11.12
We observed UCN production and UCN polarization in the new UCN source.

2014.5
We will start Ramsey resonance in an electric field.
We are constructing EDM apparatus at RCNP.
We will start EDM measurement in 2015.
Magnetic shielding and fields
- prototyping at Univ. Winnipeg

SC polarizer

He-II cryostat
- 0.8 K
- pumping on $^3$He

Cold moderator cryostat
- heavy water and deuterium

EDM cell and HV
- at TRIUMF
- at UBC

Comagnetometer

$^3$He-$^4$He heat exchanger

UCN detector
- at UWpg

Steering quads
- available at TRIUMF

Spallation target
- beam power: 20 kW (during 1 min beam on target) and 5 kW (average)
- tungsten
- water cooled
- manufacturing process is currently qualified in Japan
2014:
• septum
• dipole
• replacement of shielding towards cyclotron

2015:
• kicker
• decommissioning of existing beamline M13
• quads
• source shielding

2015/16:
• target
• moderators
• He-II cryostat
• UCN guides
• UCN polarizer
• finish shielding

2015 Non-Shutdown & 2016 Shutdown:
• target
• moderators
• He-II cryostat
• UCN guides
• UCN polarizer
• finish shielding

March 15, 2014

Courtesy: R. Picker, J. Martin
MCNP neutron flux calculation results and heat generation in thermal column of WWR-M reactor at 15 MW

\[ \rho_{\text{ucn}} = 10^4 \text{ cm}^{-3} \quad (\tau = 10 \text{ s}) \]

\[ \Phi = 4.5 \cdot 10^{12} \text{ n/(cm}^2\text{s)} \]

\[ \Phi(\lambda = 9 \text{ A}) = 3 \cdot 10^{10} \text{ n/(cm}^2\text{sA)} \]

\[ Q_{\text{He}} = 6 \text{ W} \]

\[ Q_{\text{Al}} = 13 \text{ W} \]

\[ Q_{\text{LD}_2} = 100 \text{ W} \]

\[ Q_{\text{C}} = 700 \text{ W} \]

\[ Q_{\text{Pb}} = 15 \text{ kW} \]

\[ \Phi = 10^{14} \text{ n/(cm}^2\text{s)} \]

\[ Q = 15 \text{ MW} \]
UCN density

maximal density inside closed source

density in experimental trap with volume 35 l

density in experimental trap with volume 350 l

“Our task for 2014 is test of full-scale technological system with model of UCN source”
New measurements of neutron electric dipole moment @ILL


Konstantinov Petersburg Nuclear Physics Institute of National Research Centre “Kurchatov Institute”
188300 Gatchina, Russia

⁺Institut Max von Laue-Paul Langevin BP 156, 38042 Grenoble Cedex 9, France

*Ioffe Physical Technical Institute of the RAS, 194021 St.Petersburg, Russia

Submitted 10 December 2013

\[ |d_n| < 5.5 \cdot 10^{-26} \text{ e} \cdot \text{cm (90\% confidence level)} \]
Neutron EDM @ SNS

1. Arizona State University
2. Brown University
3. Boston University
4. University of California, Berkeley
5. California Institute of Technology
6. Duke University
7. Harvard University
8. Indiana University
9. University of Illinois, Urbana-Champaign
10. University of Kentucky

11. Los Alamos National Laboratory
12. Massachusetts Institute of Technology
13. Mississippi State University
14. North Carolina State University
15. Oak Ridge National Laboratory
16. Simon Fraser University
17. University of Tennessee
18. Valparaiso University
19. University of Virginia
20. Yale University

Courtesy: B. Filippone
Key Features of SNS experiment

• Production of Ultra-Cold Neutrons (UCN) in superfluid LHe
• Polarized $^3$He co-magnetometer
  – Also functions as neutron spin precession monitor via spin-dependent $n$-$^3$He capture cross section
    • Detected via wavelength-shifted scintillation light in LHe
  – Ability to vary influence of external B-fields via “dressed spins”
    • Extra RF field allows control of $n$ & $^3$He relative precession frequency
    – Can study dependence on B-field, B-gradients & $^3$He density
• Highly uniform E and B fields
• Superconducting Magnetic Shield
• Two cells with opposite E-field
• Control of central temperature
  – Can vary $^3$He diffusion which changes geometric phase effect on $^3$He

Courtesy: B. Filippone
Status and Plans

- Completed focused R&D program: 2012 - 2013
  - E-field demonstration, B-field demonstration, $^3$He transport studies, Systematic studies test apparatus development, Storage cell studies, SQUID studies
- Received Approval (Dec. 2013) to begin construction of key internal components:
- Begin operation of experiment: 2019-2020
Progress & achievements:

- Superthermal source produces UCN at expected rate; stable @0.5 K, excellent He purity.
- Polarisation 65% in source
- Source storage time 165 s, with known areas for improvement.
- Transport to/from Ramsey cells achieved, but with relatively low efficiency.
- $E=10 \text{ kV/cm}$, with clear path to 3x increase.
- Dynamic shielding understood. Lab demonstration shows we can increase it beyond $1E6$.
- Successful & reliable operation of solid-state detectors.
- SQUID system can monitor field changes at 10 pT level (currently limited by magnetic noise).
- ILL delivering new high-intensity beamline.

Capabilities, limitations & future resource needs of this apparatus are now much clearer. In light of this...
Following a review, and in light of the current budgetary situation, STFC (the UK particle-physics funding agency) has decided that the project is **too expensive and ambitious** for it to carry the costs alone.

The collaboration has been asked to undertake a **managed withdrawal**, and to move forward instead with a more gradual, less risky approach, either joining a competing experiment or working in conjunction with new collaborators abroad.

Discussions are underway.
TUM FRM-2 nEDM

nEDM setup ready in a few months for UCN
Status of the crystal-diffraction nEDM (01.01.2014)

(PNPI-ILL)

Sensitivity estimation for $\text{Bi}_{12}\text{SiO}_{20} (444)$ plane

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_0$, $10^8\text{V/cm}$</th>
<th>$\tau$, ms</th>
<th>Count rate, $10^4\text{n/s}$</th>
<th>$K_{inp}$</th>
<th>$\sigma_d$, e·cm per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$-quartz (110) in-flight</td>
<td>2.0</td>
<td>0.6 (L=50cm)</td>
<td></td>
<td></td>
<td>(2-3)$10^{-25}$</td>
</tr>
<tr>
<td>$\text{Bi}<em>{12}\text{SiO}</em>{20}$ (444) storage</td>
<td>4.65</td>
<td>8 (L=15 cm)</td>
<td></td>
<td></td>
<td>(2-3)$10^{-26}$</td>
</tr>
</tbody>
</table>

Crystal field measurement

$E \approx \pm 10^8 \text{V/cm}$
A new idea for a nEDM beam experiment at ESS

Sensitivity up to $\sim 5 \times 10^{-27}$ ecm / day
High Intensity Proton accelerator & UCN Source at the Paul Scherrer Institut

590 MeV Proton Cyclotron
2.2 .. 2.4 mA Beam Current
("performance improving consolidation")

Excellent performance of HIPA and regular beam delivery to UCN during many weeks in 2012, 2013

UCN-Source
- 1st test: 12/2010
- Safety approval: 06/2011
- UCN start 08/2011
- Improvements in cryo-system during winter shutdown 11/12
- Reliable performance 2012
- UCN to nEDM 2012; 2013
  -> intensity 90 times over 2010
  -> ctd. improvements
The PSI UCN source

- Pulsed 1.3 MW p-beam: 600 MeV, 2.2 mA, 1% duty cycle
- Spallation target (Pb/Zr): (~8 neutrons/proton)
- Heavy water moderator → thermal neutrons: 3.6 m³ D₂O
- Cold UCN-converter: ~30 dm³ solid D₂ at 5 K
- UCN guides towards experimental areas: 8.6m(S) / 6.9m(W)
- DLC coated UCN storage vessel: height 2.5 m, ~2 m³
The PSI UCN source
Continuous improvement under way: Proton pulses and charge on target

Referring to yesterday’s discussion of Higgs/proton or DM candidate per trigger: 1 typical pulse ~ few seconds, 5E16 protons on target, 1E8 UCN
Continuous improvement under way: UCN per proton pulse

<table>
<thead>
<tr>
<th>Year</th>
<th>Normkicks</th>
<th>Count (Mill)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec.22 2010</td>
<td>-</td>
<td>0.03</td>
</tr>
<tr>
<td>Nov11-2011</td>
<td>- 2.0</td>
<td></td>
</tr>
<tr>
<td>Sep21-2012</td>
<td>- 2.6</td>
<td></td>
</tr>
<tr>
<td>June 27 - 2013</td>
<td>- 3.4</td>
<td></td>
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</table>

UCN Counts /s

Time (s)
Continuous improvement under way

2s Normkicks

<table>
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<th>Date</th>
<th>Value</th>
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UCN Counts /s

Time (s)

UCN Counts after storage

Storage time (s)

25 liter vessel
Installing nEDM at PSI in 2009

Coming from ILL
Sussex-RAL-ILL collaboration
PRL 97 (2006) 131801
14 Institutions
Seven countries
45 Members
10 PhD students

The nEDM collaboration
Features of nEDM@PSI

- Hg-199 co-magnetometer
  - improved S/N by factor >4
  - laser read-out proven, being implemented

- CsM array
  - 16 scalar sensors in operation (6 HV)
  - vector CsM proven

- B-field
  - homogeneity (T2~1000s)
  - reproducibility (~50pT), after degaussing (~200pT)

- Simultaneous spin analysis
- Known systematics well under control down to ~2 x 10^{-27} ecm
nEDM sensitivity

\[ \sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}} \]

<table>
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<tr>
<th></th>
<th>RAL/Sussex/ILL*</th>
<th>PSI 2013</th>
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<tbody>
<tr>
<td></td>
<td>best</td>
<td>avg</td>
</tr>
<tr>
<td>E-field</td>
<td>8.8</td>
<td>8.3</td>
</tr>
<tr>
<td>Neutrons</td>
<td>14 000</td>
<td>14 000</td>
</tr>
<tr>
<td>T_{free}</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>T_{duty}</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.6</td>
<td>0.453</td>
</tr>
<tr>
<td>( \sigma/d ) (10^{-25} e.cm)</td>
<td>2.3</td>
<td>3.0</td>
</tr>
</tbody>
</table>

2013 data taking:
3266 cycles
25 days \( \rightarrow \text{aim at 100 days in 2014} \)
2013 accumulated sensitivity 6\times10^{-26} e.cm

*Best nedm limit: 2.9\times10^{-26} ecm (90\% CL), Baker et al., PRL97(2006)
Preliminary conclusion

- Presently ~3 UCN sources worldwide in a user mode (state of the art is still below 100 cm$^{-3}$ in reasonable volumes; potential improvements up to 1000 cm$^{-3}$)

- Around 5-10 more projects and ideas for improved sources, some of which aim at the order of 10’000 cm$^{-3}$

- 2 nEDM experiments are taking data, 5 or more may come online in the next 5 years

- These are complex installations and difficult experiments – experience tells us that they need time.

- Some efforts may join forces in the future.
Upcoming technical workshop

Challenges of the world-wide experimental search for the electric dipole moment of the neutron

2-6 November 2014 Centro Stefano Franscini
Europe/Zurich timezone

November 2-6, 2014 in Ascona, Switzerland

The international workshop, nEDM2014, on techniques, methods and instrumentation for searches of a neutron electric dipole moment will be held in Ascona, Switzerland, from Sunday, November 2nd to Thursday, November 6th, 2014. It is organized by the Paul Scherrer Institut (PSI), the ETH of Zurich, the Institut Laue Langevin (ILL), Grenoble and the Rutherford Appleton Laboratory (RAL), Oxford at the Centro Stefano Franscini on Monte Verità.

Searches for a permanent electric dipole moment (EDM) of the neutron are among the highest priority experiments of low energy particle physics. A finite EDM violates time reversal symmetry (while a magnetic dipole does not) and goes beyond the Standard Model of Particle Physics. The workshop focuses on vital issues of the experimental approaches and brings together the leading experts in the field and students from all efforts world-wide.

The workshop will consist of invited and contributed talks and poster sessions.

nEDM2014 is the second workshop, held in the spirit of the 2012 meeting at the Oak Ridge National Laboratory, Tennessee, United States of America.

Jointly organized by CalTech, ILL, RAL, ETHZ, PSI
Upcoming: Zuoz school 2014
The 22nd PSI summer school on Particle Physics

Lyceum Alpinum, Zuoz

http://www.psi.ch/ltp/zuoz-school
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Some other things you may find of interest related to FPUA:

- Ongoing: MuSUN experiment to measure the muon capture rate on deuterons
  (PI P. Kammel, UWash, C. Petitjean, PSI)

- Ongoing: Spectroscopy of μHe 2S-2P Lambshift
  (PI R. Pohl, MPQ, F. Kottmann, ETHZ)

- Spectroscopy of Positronium 1S-2S at ETHZ
  (PI Paolo Crivelli) → first results in 2014

- Ongoing: Muon/Muonium beam development
  (PI A. Antognini, ETHZ)
  → Midterm: Spectroscopy of Muonium 1S-2S
Ps 1S-2S measurement ongoing @ ETH

- P. Crivelli (ETHZ), S. Friedreich, D. Cooke (ETHZ), A. Antognini (ETHZ), K. Kirch (ETHZ/PSI), J. Alnis (MPQ), T. W. Haensch (MPQ), B. Brown (Marquette University)

ETHZ slow positron beam

Positron source and Ne moderator

Theory: $v_{\text{theory}} = 1233607222.2(6)$ MHz

K. Pachucki and S. G. Karshenboim, PRA. A60, 2792 (1999),

Experiment: $v^a = 1233607216.4(3.2)$ MHz

M. S. Fee et al., Phys. Rev. Lett. 70, 1397 (1993)

Our goal: level of $5 \times 10^{-10}$
- check QED calculations at order $\alpha^7 m$
- best determination of $m_{e^+}/m_e$.

Status:
- resuming data taking after improvement of S/N ratio
- results expected within 2014.
The 590 MeV Ringcyclotron at PSI

2.2 ... 2.4 mA
1.3 ... 1.4 MW
Recent results from particle physics at PSI

**Bound state QED**

The most precise value of the **proton charge radius** via a measurement of the Lambshift in muonic hydrogen

\[ r_p = 0.84087(39) \text{ fm} \]

**Weak interaction**

The most precise measurement of any lifetime: **MuLan**'s \( \mu^+ \) and a 0.6 ppm determination of the **Fermi coupling constant**

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

The most precise measurement (10 ppm) of the \( \mu^- \) lifetime in pure hydrogen yields **MuCap**'s 1% determination of the \( \mu^-p \) capture rate resolving the longstanding issue with the **Pseudoscalar coupling** \( g_p \)

**New physics search**

The best rare decay limit: A new search for \( \mu \rightarrow e\gamma \) yields a branching less than \( 5.7 \times 10^{-13} \)

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[Links to relevant papers and websites]
Thank you!

For your attention, a superb workshop and your great hospitality!

Thanks to colleagues from other experiments for providing information:
Back up
Standard model lepton EDMs

Fourth order electroweak,

F. Hoogeveen:

Expect from SM, approximately:

\[ d_e \leq 10^{-38} \text{ e}\cdot\text{cm} \]
\[ d_\mu \leq 10^{-36} \text{ e}\cdot\text{cm} \]
\[ d_\tau \leq 10^{-35} \text{ e}\cdot\text{cm} \]

Experimentally so far:

\[ d_e < 9 \times 10^{-29} \text{ e}\cdot\text{cm} \]
\[ d_\mu < 2 \times 10^{-19} \text{ e}\cdot\text{cm} \]
\[ d_\tau < 3 \times 10^{-17} \text{ e}\cdot\text{cm} \]

Much greater sensitivity to new, CP-violating physics!

... + new physics?

Fig. 7. The ten diagrams which contribute to the edm of the electron. The W-propagators.

Completely negligible at any experimental sensitivity we can imagine today!
Neutron: Standard Model prediction

Completely negligible at any experimental sensitivity we can imagine today!

Expect from electro-weak SM, approximately:

\[ d_n \leq 10^{-32} \text{ e cm} \]

Experimentally so far:

\[ d_n < 3 \times 10^{-26} \text{ e cm} \]

[Khriplovich & Zhitnitsky '86]
Intensity machines

The graph illustrates the relationship between the average beam intensity ($I_{\text{avg}}$) and the beam energy ($E_{\text{beam}}$) for various intensity machines. The machines are categorized based on their power output, with markers indicating whether they are planned or operating. The axes are labeled with power levels at 1 MW, 100 kW, and 10 MW, as well as energy levels ranging from 0.1 GeV to 100 GeV.