HIGH PRECISION EXPERIMENTS
WITH COLD AND ULTRA-COLD NEUTRONS

Hartmut Abele
PSI, 10 September 2013

Hartmut Abele, Vienna University of Technology
Participating Institutions 2010 - 2013:

- IST Braunschweig
- Univ. Heidelberg
- ILL
- Univ. Jena
- Univ. Mainz
- Exzellenzcluster 'Universe' München
- Techn. Univ. München
- PTB Berlin
- Vienna University of Technology

Priority Areas

- CP-symmetry violation and particle physics in the early universe.
- The structure and nature of weak interaction and possible extensions of the Standard Model.
- Tests of gravitation with quantum objects
- Charge quantization and the electric neutrality of the neutron.

New Infrastructure (UCN-Source, cold Neutrons)
- * Coordinators (S. Paul, H.A.)
Priority Programme 1491

Research Area A: *CP-symmetry violation and particle physics in the early universe*
- Neutron EDM $\Delta E = 10^{-23}$ eV

Research Area B: *The structure and nature of weak interaction and possible extensions of the Standard Model*
- Neutron $\beta$-decay $V – A$ Theory

Research Area C: *Relation between gravitation and quantum theory*
- Neutron bound gravitational quantum states

Research Area D: *Charge quantization and the electric neutrality of the neutron*
- Neutron charge

Research Area E: *New measuring techniques*
- Particle detection
- Magnetometry
- Neutron optics
Neutron Alphabet deciphers the SM

SM Parameters
- Strength: $G_F$
- Quark mixing: $V_{ud}$
- Ratio: $\lambda = g_A/g_V$

$$\tau^{-1} = V_{ud}^2 G_F^2 (1 + 3\lambda^2) \frac{f^R m_e^5 c^4}{2\pi^3 \hbar^7}$$

$$d\Gamma \propto N(E_e) \left\{ 1 + a \frac{p_e \cdot \bar{p}_\nu}{E_e E_\nu} + b \frac{\Gamma m_e}{E_e} + \langle \vec{J} \rangle \cdot \left[ A \frac{\vec{p}_e}{E_e} + B \frac{\bar{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \bar{p}_\nu}{E_e E_\nu} \right] + \sigma \cdot \left[ N \langle \vec{J} \rangle + G \frac{\vec{p}_e}{E_e} + Q' \hat{\rho}_e \hat{\rho}_e \cdot \langle \vec{J} \rangle + R \langle \vec{J} \rangle \times \frac{\vec{p}_e}{E_e} \right] \right\} d\Omega_e d\Omega_\nu dE_e,$$
Recent Results: PERKEO Collaboration

**Electron Asymmetry A:**

\[ A = -0.11972^{(+52)}_{-65} \]

PERKEO II combined:

\[ \lambda_{\Pi} = -1.2748^{(+13)}_{-14} \]

\[ A_{\Pi} = -0.11926^{(+47)}_{-53} \]

Mund et al.,
PRL 110, 172502 (2013)

**Neutrino Asymmetry B:**

\[ B = 0.9802(50) \]

Schumann et al.,
PRL 99, 191803 (2007)

**Proton Asymmetry C:**

first precision measurement

\[ C = x_C(A + B) \]

\[ C = -0.2377(36) \]

Schumann et al.,
PRL 100, 151801 (2008)
a bit history:

λ from neutron β-decay

-1.1900(200), PDG (1960)
-1.2500(200), PDG (1975)
-1.2610(40), PDG (1990)
-1.2594(38), Gatchina (1997)
-1.2660(40), M, ILL (1997)
-1.2740(30), PERKEO II (1997)
-1.2686(47), Gatchina, ILL (2001)
-1.2739(19), PERKEO II (2002)
-1.27590(+409)(−445), UCNA (2011)
-1.2756(30), UCNA (2013)
-1.2748(+13−14) PERKEO II (2013)

Close to publication:

aCORN @ NIST
aSPECT @ Mz, ILL
PERKEO III @ UHD, ILL, TUW

New Instruments

Nab, PERC
Sensitive theories beyond the Standard Model
Left Right Symmetry
Supersymmetry
Tensor or scalar interactions
GUT
Key Instrument: PERC

A clean, bright and versatile source of neutron decay products
Univ. Heidelberg & TU Wien, Mainz, ILL, FRM2, TU Munich

- **High Flux**: $\Phi = 2 \times 10^{10} \text{ cm}^{-2}\text{s}^{-1}$
  $\rightarrow$ Decay rate of 1 MHz / metre

- **Polarizer**: $99.7 \pm 0.1 \%$
- **Spin Flipper**: $100.05 \pm 0.1 \%$
- **Analyzer**: $100 \% ^3\text{He-cells}$

Talk by B. Maerkisch: PERKEO & PERC

Ideal experiment for ESS, Poster, Camille Theroine

Poster by G. Konrad: PERC-Detector System

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**Diagram:**

- **Polarizer**
- **Chopper**
- **Spin flipper**
- **v-selector**
- **Decay Volume, 8m**
- **Beam stop**
- **Analyzing area**
- **n-guide + solenoid: field $B_0$**
- **polarized, monochromatic n-pulse**
- **n + γ-beam stop**
- **solenoid, field $B_1$**
- **p+ + e-**
- **window-frame**
- **beam**
PERC – a clean bright and versatile source of neutron decay products

Source of electrons and protons from neutron decay
Magnetic field
- Decay volume: 8 m, 0.5 - 1.5 T
- Filter: 3 – 6 T
Non-depolarising guide

Preliminary Magnet Design

L = 11.3m

Precision experiments in particle and astrophysics with cold and ultracold neutrons

Heidelberg
Wien
FRM II, München
Grenoble
München

Bastian Märkisch

 prioritize programme 1491
PERC beam site Mephisto at FRM II

- “Empty” new hall
- Neutron guide: length 40 m, $R = 3000$ m, $m = 2.5$
- Expected intensity equal to PF1B at ILL
- Only very few neighbours: low background
- Easy ground level access
<table>
<thead>
<tr>
<th>SOURCE OF ERROR</th>
<th>COMMENT</th>
<th>SIZE OF CORRECT.</th>
<th>SIZE OF ERROR:</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-uniform n-beam</td>
<td>for $\Delta \Phi/\Phi = 10%$ over 1 cm width</td>
<td>$2.5 \times 10^{-4}$</td>
<td>$5 \times 10^{-5}$</td>
</tr>
<tr>
<td>other edge effects on e/p-window</td>
<td>for worst case at max. energy</td>
<td>$4 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>magn. mirror effect, contin's n-beam</td>
<td></td>
<td>$1.4 \times 10^{-2}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>magn. mirror effect, pulsed n-beam</td>
<td>for $\Delta B/B = 10%$ over 8 m length</td>
<td>$5 \times 10^{-5}$</td>
<td>$&lt;10^{-5}$</td>
</tr>
<tr>
<td>non-adiabatic e/p-transport</td>
<td></td>
<td>$5 \times 10^{-5}$</td>
<td>$5 \times 10^{-5}$</td>
</tr>
<tr>
<td>background from n-guide</td>
<td>}is separately measurable</td>
<td>$2 \times 10^{-3}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>background from n-beam stop</td>
<td></td>
<td>$2 \times 10^{-4}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>backscattering off e/p-window</td>
<td></td>
<td>$2 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>backscattering off e/p-beam dump</td>
<td></td>
<td>$5 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>backscatt. off plastic scintillator</td>
<td>}for worst case</td>
<td>$2 \times 10^{-3}$</td>
<td>$4 \times 10^{-4}$</td>
</tr>
<tr>
<td>~ same with active e/p-beam dump</td>
<td>}for worst case</td>
<td>--</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>neutron polarisation</td>
<td>Status 2010</td>
<td>$3 \times 10^{-3}$</td>
<td>$1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

**Neutron Polarimetry on the $10^{-4}$ level**

**Talk Christine Klauser**

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What about the lifetime?

$\tau = 888.0 \pm 2.3 \text{ s} \quad \text{NIST}$

$\tau = 878.5 \pm 0.8 \text{ s} \quad \text{PNPI}$

$\tau = 879.8 \pm 0.75 \text{ s}$

$$\tau^{-1} = V_{ud}^2 G_F^2 (1 + 3 \lambda^2) \frac{f R m_e^5 c^4}{2 \pi^3 \hbar^7}$$

$\tau = 880.2 \pm 1.5 \text{ s from PERKEO} \quad \text{and} \quad 0^+ \rightarrow 0^+$
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Demonstration of Quantum States in the Gravity Potential of the Earth
Nesvizhevsky et al.
Nature 2002

qBounce, 2009
a 2-level system can be considered as a Spin $\frac{1}{2}$ - System

\[ |3 > 3.32 \text{ peV} \]
\[ |1 > 1.4 \text{ peV} \]

$q$Bounce: Vibrating mirror

Show Case I: Rabi-type Spectroscopy of Gravity

NMR Spectroscopy Technique to explore magnetic moments

3 Regions:
I: 1st State selector/ Polarizer
II: Coupling
   - RF field
   - Vibr. mirror
III: 2nd State Selector / Analyzer

Gravity Resonance Spectroscopy Technique to explore gravity
Rabi Spectroscopy

NMResonance Spectroscopy Technique to explore magnetic moments

Fig. 4. Resonance curve of the Li\textsuperscript{7} nucleus observed in LiCl.

Fig. 5. Resonance curve of the F\textsuperscript{19} nucleus observed in NaF.
Transmission

![Graph showing frequency spectrums with labels 1↔3 and 1↔4, indicated at 2.1 mm/s.]

G. Cronenberg, PhD
Preparation: velocity selection

UCNs at PF2
Accept $5.7 < v_x < 9.5$ m/s
Gravity and Quantum Mechanics

Schrödinger equation:

\[
\left( -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial z^2} + mgz \right) \varphi_n(z) = E_n \varphi_n(z)
\]

boundary conditions:

\[ \varphi_n(0) = 0 \]

with 2nd mirror at height \( \varphi_n(l) = 0 \)

Solutions: Airy-functions: Ai & Bi

<table>
<thead>
<tr>
<th>( E_n )</th>
<th>( E_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.41peV</td>
<td>1.41peV</td>
</tr>
<tr>
<td>2.46peV</td>
<td>2.56peV</td>
</tr>
<tr>
<td>3.32peV</td>
<td>4.2 peV</td>
</tr>
</tbody>
</table>

~ 1 µm Surface roughness
\[ n + ^{10}B \rightarrow ^{7}Li^* + \alpha \]

**Region 1: State Selector**

- UCN
- rough mirror
- neutron mirror

\begin{align*}
\text{Energy} [\text{peV}] & : \\
\text{Height} [\mu\text{m}] & : \\
\text{Length} [\text{cm}] & : \sim 8 \text{ cm}
\end{align*}
Region II

UCN → |1⟩ → |4⟩

\( \omega_{pq} \)

neutron mirror

scatterer

II

scatterer

II

counter
Region 2: the vibration table

- Oscillation with 4 Piezo actuators
- Internal capacitive sensors for position/tip/tilt

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z range</td>
<td>140 μm</td>
</tr>
<tr>
<td>Z range closed loop</td>
<td>100 μm</td>
</tr>
<tr>
<td>Z resolution closed loop</td>
<td>0.8 nm</td>
</tr>
<tr>
<td>Tip/tilt range</td>
<td>±0.5 mrad</td>
</tr>
<tr>
<td>Tip/tilt resolution closed loop</td>
<td>0.05 μrad</td>
</tr>
<tr>
<td>Tested frequency range</td>
<td>0-850 Hz</td>
</tr>
<tr>
<td>Maximal tested amplitude</td>
<td>4.8 mm/s</td>
</tr>
</tbody>
</table>
The key technology: Controlling the vibrations

T. Lins, Diplomarbeit, January 2011
Region III

scatterer

$|1\rangle \rightarrow |4\rangle$

neutron mirror

$\omega_{pq}$

neutron mirror

scatterer

$|1\rangle$?

UCN

counter
Detector

Boron layer: $n + ^{10}B \rightarrow \alpha + ^{7}Li^* \rightarrow \alpha + ^{7}Li^3 + \gamma$

ArCo$_2$ Counter

Adapted geometry for low background

Improved shielding

$\varepsilon = 86.4 \%$

$R_0 = (0.65 \pm 0.02) \times 10^{-3} \text{ s}^{-1}$

M. Thalhammer, Diplomarbeit 2013

H. Saul, Diplomarbeit 2011

Poster by T. Jenke
Rabi Oscillation

State Revival
Based on 2 natural constants:
- Mass of the neutron $m$
- Planck constant $\hbar$

Plus Acceleration of earth $g$

$|3 > 3.32 \text{ peV}$

$|1 > 1.4 \text{ peV}$

Frequency Reference for Gravitation

$\omega_0 = \left(\frac{9\pi^2 m g^2}{8\hbar}\right)^{1/3}$

$E_n = \hbar \omega_0 \left(n - \frac{1}{4}\right)^{2/3}$

$\omega_{pq} = \frac{E_q - E_p}{\hbar} = \omega_q - \omega_p$

Hartmut Abele, Vienna University of Technology
Discoveries: the dark universe

Spectroscopy of Gravity
- It does not use electromagnetic forces
- It does not use coupling to em Potential

Hyothetical gravity-like forces
- Axions?
- Chameleons?

Axion

$10^{-14}$ eV Scale

constraint on any possible new interaction
Dark Energy – Scalar Fields


2 Parameters $\beta$, $n$

$$V_{\text{eff}}(\phi) = V(\phi) + e^{\beta \phi/M_{\text{Pl}} \rho}.$$
Bounds on coupling $\beta$

- By comparing transition frequency with theoretical expectation:

$$\omega_{ab} - \omega_{ab}^{\text{theo}} = \beta \frac{m}{M} (\langle a|\phi(z)|a\rangle - \langle b|\phi(z)|b\rangle)$$

- as long as $\beta > 10^5$

- Cite as: arXiv:1207.0419v1
Show Case III: Search for gravity-like forces

Resonance Spectroscopy Technique to explore gravity

Rabi-type experiment:

- realization of gravity resonance method possible
- simple setup, no steps
- high(er) transmission
- upper mirror introduces 2nd boundary condition

T. Jenke, SPP1491-Treffen 2012, Frauenchiemsee
Gravity Resonance Spectroscopy 2012

50 days of beam time, 116 measurements

$|1\rangle \leftrightarrow |2\rangle$, $|1\rangle \leftrightarrow |3\rangle$, $|2\rangle \leftrightarrow |3\rangle$ and $|2\rangle \leftrightarrow |4\rangle$

$\sigma$ = 48

- **stat. Significance:** $48\sigma$
- **stat. accuracy:** $\nu_{12} = 258.2 \text{ Hz} \pm 0.8%$
- $\nu_{23} = 280.4 \text{ Hz} \pm 1.0%$
- $\nu_{13} = 539.1 \text{ Hz} \pm 0.5%$
- $\nu_{24} = 679.5 \text{ Hz} \pm 2.2%$

- **contrast:** 68%

10$^{-14}$ eV Scale
Applications II:  
Strongly coupled chameleons

\[ V_{\text{Chameleon}} = \beta \frac{m}{M_{Pl}} \Lambda \left( \frac{n + 2}{\sqrt{2}} \frac{\Lambda}{d} \left( \frac{d^2}{2} - z^2 \right) \right)^{\frac{2}{n+2}} \]
Applications I: Spin-dependant short-ranged interactions

\[ V_{\text{axion}} = \frac{g_s g_p}{8\pi m_n c} \vec{\sigma} \cdot \vec{n} \left( \frac{1}{\lambda r^2} + \frac{1}{\lambda r} \right) \]

\[ g_s g_p / \hbar c \geq \frac{3 \cdot 10^{-16}}{\sqrt{\text{days}}} \]

\[ (\lambda = 10 \mu m, 68\% \text{ C.L.}) \]

discovery potential [Setup 2010]:

\[ \frac{3 \cdot 10^{-16}}{\sqrt{\text{days}}} \]

T. Jenke, ÖPG 2012
Neutrons test Newton

\[ V(r) = G \frac{m_1 \cdot m_2}{r} (1 + \alpha \cdot e^{-r/\lambda}) \]

**Hypothetical Gravity Like Forces**

**Extra Dimensions:**
The string and \( D_p \)-brane theories predict the existence of extra space-time dimensions

**Infinite-Volume Extra Dimensions:** Randall and Sundrum

**Exchange Forces** from new Bosons: a deviation from the ISL can be induced by the exchange of new (pseudo)scalar and (pseudo)vector bosons

- **Axion**
- **Scalar boson. Cosmological consideration**
- **Bosons from Hidden Supersymmetric Sectors**
- **Gauge fields in the bulk (ADD, PRD 1999)**

\( \rightarrow 0.2 \mu m < \lambda < 0.2 \text{ cm} \)

\( \rightarrow 10^6 < \alpha < 10^9 \)

\( \rightarrow \alpha < 10^6 \)

**Chameleon fields-**
Outlook

• Tests of Newton’s Inverse Square Law of Gravity at micron distances

• Search for an electric charge of the neutron

The Future: Ramsey-Method

Hartmut Abele, Vienna University of Technology
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Since the Standard Model value for $q_n$ requires extreme fine tuning, the smallness of this value may be considered as a hint for GUTs, where $q_n$ is equal to zero.

Storage:

Improve limit by two orders of magnitude

45 kV/mm
Mainz Experiment

- Principle based on Borisovs experiment 1987
- Geometric modifications (see Poster of D. Brose et al.)
- Liquid PFPE as hor. mirror
Comparison with the experiment of Borisov 1987 with $\delta q_n = 9 \cdot 10^{-20} e/\sqrt{d}$:

<table>
<thead>
<tr>
<th>Modification</th>
<th>achieved</th>
<th>aspired</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase of slope</td>
<td>3.5</td>
<td>14</td>
</tr>
<tr>
<td>Enhancement of electric field</td>
<td>X</td>
<td>2</td>
</tr>
<tr>
<td>Extension of the flight path</td>
<td>2.25</td>
<td>X</td>
</tr>
<tr>
<td>Higher UCN flux</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>Reduced flux due to extended flight path</td>
<td>0.5</td>
<td>X</td>
</tr>
<tr>
<td>Overall gain</td>
<td><strong>9.8</strong></td>
<td><strong>157.5</strong></td>
</tr>
</tbody>
</table>

Measured sensitivity: $\delta F = 8 \cdot 10^{-34} N/\sqrt{d}$
Gravity tests with quantum objects

Neutron Beta Decay, PERC collaboration
- J Erhart, E.Jericha, C.Goesselsberger, C.Klauser, G.Konrad, H. Saul X.Wang, Collaboration with HD, MZ, TUM, ILL

Interferometry
- Y. Hasegawa, H. Geppert, M.Zawisky, T.Potocar, D.Erdösi, S.Sponar

Neutron Radiography
- M. Zawisky,

N_TOF/USANS, E. Jericha, G. Badurek,
Gravity Resonance Spectroscopy
- Quantum states in the gravity potential of the earth and coherence superposition

Search for deviations from Newton's gravity law at short distances
- Large extra dimensions
- Dark matter particles
- Dark energy

Tests of weak interaction with neutron beta-decay experiments
- New results published (UCNA, PERKEO)
- Experiment PERC, Nab

Scientific Programme SPP 1491