High-precision studies in fundamental physics with slow neutrons

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Topics

- The impossible particle and its properties
- Search for an electric dipole moment of the neutron
- Short-range gravity
- Test of Einstein’s $E = mc^2$
The neutron before Chadwick
“Such an atom would possess striking properties. Its outer field would vanish [...] and therefore it should easily penetrate matter. The existence of such an atom is presumably difficult to observe with a spectrograph, and ...“

“Such an atom would possess striking properties. Its outer field would vanish [...] and therefore it should easily penetrate matter. The existence of such an atom is presumably difficult to observe with a spectrograph, and it could not be stored in a closed vessel.”

How to store it nevertheless?

Mirror reflection under any angle of incidence

→ **UCN can be trapped in “neutron bottles”**

Trapping potential #1:

**neutron optical potential** $V + iW$

Physical origin:

- neutron scattering by nuclei
- interference of incident and scattered waves
- refractive index:

$$n = \frac{k'}{k} = \sqrt{1 - \frac{V}{E}}$$

$$V = \frac{2\pi\hbar^2}{m} Na$$

Typical values for $V$:

Be: 252 neV,  Al: 54 neV,  Ti: -49 neV
Trapping potential #2: neutron gravity \( mgz \) for \( \Delta z = 1 \text{ m} \): \( \Delta E = 100 \text{ neV} \)

as good for trapping (if bottle is tall enough):
Trapping potential #2:

\textbf{neutron gravity} \ mgz \ 

for $\Delta z = 1 \ m$: $\Delta E = 100 \ \text{neV}$
Trapping potential #3:

**magnetic interaction** \( \pm \mu B \)

for \( \Delta B = 1 \text{T} \): \( \Delta E = \pm 60 \text{ neV} \)

Adiabatic spin transport if

\[
\frac{1}{|B|} \cdot \left| \frac{dB}{dt} \right| \ll \frac{\mu \cdot B}{\hbar} = \omega_L
\]

\( \rightarrow \) mT fields sufficient in typical situations

Magnetic gradient fields suppress losses due to wall collisions
Neutron properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin(P)</td>
<td>(s^P)</td>
<td>(\frac{1}{2}^+)</td>
</tr>
<tr>
<td>Mass (relative to (^{12})C mass standard)</td>
<td>(m_n)</td>
<td>1.008 664 915 8(6) (\text{u})</td>
</tr>
<tr>
<td>Mass (absolute units)</td>
<td></td>
<td>939.565 33(4) (\text{MeV c}^{-2})</td>
</tr>
<tr>
<td>Neutron - proton mass difference</td>
<td>(m_n - m_p)</td>
<td>0.001 388 448 9(6) (\text{u})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.293 331 8(5) (\text{MeV c}^{-2})</td>
</tr>
<tr>
<td>Charge</td>
<td>(q_n)</td>
<td>((-0.4 \pm 1.1) \times 10^{-21} \text{e})</td>
</tr>
<tr>
<td>Mean-square charge radius</td>
<td>(\langle r_n^2 \rangle)</td>
<td>-0.116 1(22) (\text{fm}^2)</td>
</tr>
<tr>
<td>Electric polarisability</td>
<td>(\alpha_n)</td>
<td>((9.8^{+1.9}_{-2.3}) \times 10^{-4} \text{fm}^3)</td>
</tr>
<tr>
<td>Magnetic moment</td>
<td>(\mu_n)</td>
<td>(-1.913 042 7(5) \mu_N)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-6.030 773 8(15) \times 10^{-8} \text{eV T}^{-1})</td>
</tr>
<tr>
<td>Electric dipole moment</td>
<td>(d_n)</td>
<td>(&lt; 2.9 \times 10^{-26} \text{e cm (90% c.l.)})</td>
</tr>
<tr>
<td>Mean (n\bar{n})-oscillation time of free neutron</td>
<td>(\tau_{n\bar{n}})</td>
<td>(&gt; 8.6 \times 10^7 \text{s (90% c.l.)})</td>
</tr>
<tr>
<td>... of bound neutron</td>
<td></td>
<td>(&gt; 1.2 \times 10^8 \text{s (90% c.l.)})</td>
</tr>
<tr>
<td>Parameters of (\beta)-decay, (n \rightarrow p + e^- + \bar{\nu}_e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Q)-value</td>
<td>(Q)</td>
<td>0.782 332 9(5) (\text{MeV c}^{-2})</td>
</tr>
<tr>
<td>Mean life time</td>
<td>(\tau_n)</td>
<td>885.7(8) (\text{s})</td>
</tr>
<tr>
<td>Ratio of weak coupling constants (g_A/g_V)</td>
<td>(\lambda)</td>
<td>-1.2670 (30)</td>
</tr>
<tr>
<td>Coefficients of angular correlations:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>neutron spin - electron momentum: (P_n \cdot p_e)</td>
<td>(A)</td>
<td>-0.1162 (13)</td>
</tr>
<tr>
<td>momenta of antineutrino and electron: (p_\nu \cdot p_e)</td>
<td>(\alpha)</td>
<td>-0.102 (5)</td>
</tr>
<tr>
<td>neutron spin - antineutrino momentum</td>
<td>(B)</td>
<td>0.983 (4)</td>
</tr>
<tr>
<td>triple correlation (P_n \cdot (p_e \times p_\nu))</td>
<td>(D)</td>
<td>(-0.6 (10) \times 10^{-3})</td>
</tr>
<tr>
<td>Phase angle between (V) and (A) weak currents</td>
<td>(\phi_{VA})</td>
<td>-180.08 (10)^0</td>
</tr>
</tbody>
</table>


The Big Bang

- nEDM
- neutron lifetime
- n-neutron oscillations
- nEDM
- n-gravity
- nuclear few-body interactions
- Heavy elements
- A world of matter

10^{-10} seconds
10^{-14} seconds
10^{-18} seconds
10^{-22} degrees
10^{-27} degrees
10^{-32} degrees
10\,000\ degrees
3\,000\ degrees
18 degrees
3 degrees K
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
Search for an electric dipole moment of the neutron
Violation of fundamental symmetries

- A non-zero particle EDM violates $T$ (time reversal symmetry) and parity $P$
- If we assume $CPT$ conservation, also $CP$ is violated, which is needed to explain the matter/antimatter asymmetry in the Universe

$$H = -\mu B \cdot \frac{S}{S} - dE \cdot \frac{S}{S}$$

Purcell and Ramsey, PR 78 (1950) 807
• CP violation within the Standard Model (SM) is too weak to explain the matter/antimatter asymmetry in the Universe

• nEDM tiny in the SM ($10^{-31}$ ecm), but large in many beyond-SM theories

• nEDM sensitive probe to search new fundamental forces

Pendlebury and Hinds, NIM A 440 (2000) 471
Ultra-cold neutrons (UCN) trapped at 300 K in vacuum

How is it measured?

RAL/SUSSEX/ILL experiment:

- Four-layer μ-metal shield
- Quartz insulating cylinder
- Storage cell
- Hg u.v. lamp
- Vacuum wall
- RF coil to flip spins
- Magnet
- UCN polarizing foil
- UCN detector
- Approx scale 1 m

High voltage lead
Magnetic field coil
Upper electrode
PMT for Hg light
Mercury prepolarizing cell
Hg u.v. lamp
UCN guide changeover
Ultracold neutrons (UCN)
Ramsey’s method

Particle beam or trapped particles
(...spin echo)

Polarized particles

External clock

$\omega_1 \sim \omega_L$

$E_{dB}$

$\sigma_{dn} = \frac{\hbar}{2\alpha ET \sqrt{N}}$

EDM changes frequency:

$\hbar \omega_L \sim \mu_n B \pm d_n E$
$^{199}$Hg co-magnetometer for correction of magnetic field drifts

**Neutron Resonant Frequency (Hz)**

Run duration (hours)

**Ratio of Precession Frequencies**

**Ramsey Resonance Curve**

**Mercury Spin Precession**

**Digitised Voltage (bits)**
Best result so far (RAL / Sussex / ILL)

\[ |d_n| < 2.9 \times 10^{-26} \text{ e cm} \ (90\% \text{ CL}) \]

C.A. Baker et al., *PRL* 63 (2006) 131801

- $10^{-22}$ eV spin-dependent interaction
- one spin precession per half year
Next steps?

- World-wide effort: projects at PSI, SNS, TRIUMF, TUM, PNPI, ILL
- Accuracy goal: below $10^{-27}$ ecm
- needs new UCN sources, excellent magnetic shielding...
Short-range gravity

Small extra-dimensions:
Explanation why gravity is such a weak force?

Modification of gravity
with $n$ additional dimensions at distances $r < R$:

$$F = -G \frac{m_1 m_2}{r^2} \rightarrow -g \frac{m_1 m_2}{r^2} \frac{L^n}{r^n}$$

New spectroscopic tool:
First observations (2002)

V. Nesvizhevsky et al., Nature 415 (2002) 299
Rabi-type spectroscopy of gravity
qBounce collaboration (H. Abele, T. Jenke...)

3 Regions:
I: 1st State selector/ Polarizer
II: Coupling
   – RF field
III: 2nd State Selector / Analyzer

3 Regions:
I: 1st State selector/ Polarizer
II: Coupling
   – Vibr. mirror
III: 2nd State Selector / Analyzer
Most recent results on Gravity Resonance Spectroscopy

Transitions 1-3 and 1-4 observed
1-3: (46±5)% Intensity drop
1-4: (61±7)%

60 measurements

Preliminary,

\[ \nu_{13} = 463.74^{+1.05}_{-1.10} \text{ Hz} \]
\[ \nu_{14} = 648.24^{+1.46}_{-1.53} \text{ Hz} \]
Advantages:

- Long flight path $\rightarrow$ smaller uncertainty $\Delta E$
- Static central mirror for free state evolution
Airy - Quantum States 1 & 2

\[ n + ^{10}B \rightarrow ^{7}Li^* + \alpha \]

UCN

rough mirror

neutron mirror

\[ E = mgh \]

Jenke et al.
NIM 2013, PRL 2014

Counts

200 \( \mu m \)

\(-10\) \( \text{Height [\mu m]} \) to 50

\( \sim 10 \text{ cm} \)
Snapshots of $|\psi|^2$ with 1.5 $\mu$m resolution

\[
\Psi(z, t) = \sum_{n=0}^{\infty} c_n e^{-iE_n t/h} \psi_n(z)
\]

\[
\psi_n(z) \sim A i \left[ \frac{z}{z_0} - \frac{E_n}{E_0} \right] ; \quad c_n = \int_{0}^{\infty} \Psi(z, 0) \psi(z) dz
\]
Preparation $L = 0$

\[ |\psi_1(z, t_1)|^2 = \sum_n |C_n(t_1)|^2 \cdot |\psi_n(z)|^2 \]

\[ |c_1|^2 = 45\% \]
\[ |c_2|^2 = 36\% \]
\[ |c_3|^2 = 18\% \]

preliminary

Courtesy: M. Thalhammer
2nd bounce, 2nd turning point, $L = 41$ mm

41 mm

Courtesy: M. Thalhammer
Move downwards, $L = 51 \text{ mm}$
L = 54 mm

54 mm
L = 51 mm @ 20 μm
\[ E = mc^2 \]

How can we test it?

- need process, where mass is converted in energy
- thermal-neutron capture reaction:

\[ ^L X + ^1 n \rightarrow ^{L+1} X + \sum_i \gamma_i \]

- thermal energies: \(~10^{-2} \text{ eV}\)
- excess energy: several \(10^6 \text{ eV}\)

Total energy uncertainty: \(< 10^{-8} \)
\[ [m(n) + m(LX) - m(L+1X)]c^2 = \sum_i E(\gamma_i) \]

In terms of mass units \( A \) relative to an atomic mass scale \( u = 10^{-3}/N_A \) kg:

\[ A(n) + A(LX) - A(L+1X) = 10^3 \frac{N_A h}{c} \sum_i \frac{1}{\lambda_i(L+1X)} \]

\( \Delta A(L+1X) \)

\[ \Delta A(L+1X) - \Delta A(K+1Y) = 10^3 \frac{N_A h}{c} \left[ \sum_i \frac{1}{\lambda_i(L+1X)} - \sum_j \frac{1}{\lambda_j(K+1Y)} \right] \]

Penning trap measurements (4 masses)

\[ \omega = \frac{qB}{m} \]

magnetron motion \( (\omega_1) \)
modified cyclotron motion \( (\omega_2) \)
axial motion \( (\omega_3) \)

Gamma-ray wavelength measurements (2 nuclides after neutron capture)

Double crystal monochromator

GAMS
Which isotopes?

Penning Trap: $A^{(L,L+1)X}$ can be measured with $10^{-11}$ relative uncertainty! Need mass values for two pairs of stable isotopes

- $^{29}\text{Si}$, $\sigma = 0.3$ barn
- $^{33}\text{S}$, $\sigma = 0.55$ barn
- $^{36}\text{Cl}$, $\sigma = 43.7$ barn

Atomic Mass data available
What is needed to determine gamma energies (or wavelengths) with high accuracy?

A $10^{-11}$ relative uncertainty on $A$ requires $\lambda$ measurements with accuracy $10^{-8}$ is necessary but insufficient

High accuracy $\rightarrow$ use gamma spectroscopy based on Laue diffraction

Bragg’s law for photons

$$n \frac{hc}{E_\gamma} = 2d \sin \theta$$

Need absolute measurements of:
- lattice constant $d$
- scattering angle $\theta$

$$\left( \frac{\Delta E_\gamma}{E_\gamma} \right)^2 \sim \left( \frac{\Delta \theta}{\theta} \right)^2 + \left( \frac{\Delta d}{d} \right)^2$$

$\Delta d/d < 10^{-8}$
Flat double-crystal monochromator spectrometer for gamma rays: **GAMS**

\[ \frac{hc}{E_\gamma} = 2d \sin \theta \]

- **Non-dispersive**
  - Measures instrument response
- **Dispersive**
  - Contains additional broadening

**Order:** \((n,n)\) \hspace{1cm} \((n,m)\)

\[ \theta_b \pm \Delta \theta_b \]
Implantation of spectrometer

**Flat Crystals:**
- Resolution: $10^{-6}$
- Eff. Solid Angle: $10^{-11}$
- absolute Energy: $10^{-7}$

Neutron Flux: $5 \times 10^{14}$
Targets: 0.1 – 10g
Target change during reactor cycle
$\Delta d/d$: How perfect are GAMS crystals?

$\Delta d/d < 10^{-8}$, extremely perfect silicon crystals, $d$ known in SI units

Silicon crystal for GAMS6 from WASO4 reference material
- Fabricated by PTB, Braunschweig, Germany
- Characterized by INRIM, Torino, Italy
Angle interferometer with self-calibration

Linear displacement interferometer

\[ \Delta L = 4k \sin \theta \]

Angle interferometer

\[ 2\pi = \sum_{i}^{N} \arcsin \left( \frac{\Delta L_i}{4k} \right) \]

- \( N \Delta L_i \) are measured
- Equation is solved for \( k \)
Result of $E = mc^2$ test using GAMS4

$$E_\gamma - \Delta mc^2 = -(1.2 \pm 4.3) \times 10^{-7}$$


<table>
<thead>
<tr>
<th>$A+1_X$</th>
<th>$\Delta m$ from Penning trap (u)</th>
<th>$\Delta m$ from GAMS4 (u)</th>
<th>Rel. Diff. $\times 10^7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{29}$Si</td>
<td>0.00670861569(47)</td>
<td>0.00670860929(536)</td>
<td>-9.5(8.0)</td>
</tr>
<tr>
<td>$^{33}$S</td>
<td>0.00688901053(50)</td>
<td>0.00688901206(351)</td>
<td>2.2(5.1)</td>
</tr>
<tr>
<td>weighted average relative difference</td>
<td></td>
<td></td>
<td>-1.2(4.3)</td>
</tr>
</tbody>
</table>

Wavelength measurements are limiting
Accuracy reach of GAMS4

Stability of calibration: $2.1 \times 10^{-7}$

Angle measurement and calibration under atmosphere possible not better than on $10^{-7}$ level

J. Krempel, PhD LMU, 2011
New instrument GAMS6
Challenge: redefinition of the kilogram
Routes to a new mass unit definition

\[ h = \frac{4m_{kg} g v}{R_J^{290} R_K^{290} (UI)^{90}} \]

\[ E = mc^2 \]

\[ N_A h v = uc^2 \]

Number of atoms in 1 kg

\[ m_{kg} = 10^3 \times N_A u \]
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Maurits van der Grinten  
*Rutherford Appleton Laboratory*

Peter Fierlinger  
*Technische Universität München*

**Short-range gravity**
Hartmut Abele  
*Atominstitut Wien*

\[ E = mc^2 \]

Michael Jentschel  
*Institut Laue Langevin*