Pedestrian neutrons

tool and object for
fundamental physics

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Pisa, 24 July 2019
Topics

• The impossible particle and how to catch it
• Search for an electric dipole moment of the neutron
• Short-range gravity
• Production of pedestrian neutrons at ILL
• Neutron lifetime
• How to produce more ultracold neutrons?
... and Godfather created the neutron
... and Godfather created the neutron
... and Godfather created the neutron

“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 ...“
... and Godfather created the neutron

“Such an atom would posses 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?

Trapping potential #1:

**neutron optical potential** \( V + iW \)

Physical origin:

Interference of incident plane wave with spherically scattered waves in forward direction

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

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

Mirror reflection under any angle of incidence

→ “UltraCold Neutrons” can be trapped in “neutron bottles”
**UCN properties of selected materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>(N) ([10^{22} \text{ cm}^{-3}])</th>
<th>(V) ([\text{neV}])</th>
<th>(\sigma_{\text{loss}}) [barn] at 1.8 Å</th>
<th>(W/V\times10^{-5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{58}\text{Ni})</td>
<td>9.0</td>
<td>335</td>
<td>4.4</td>
<td>8.6</td>
</tr>
<tr>
<td>BeO</td>
<td>7.25</td>
<td>261</td>
<td>0.66</td>
<td>1.35</td>
</tr>
<tr>
<td>Be</td>
<td>12.3</td>
<td>252</td>
<td>0.14</td>
<td>0.5</td>
</tr>
<tr>
<td>Al</td>
<td>6.02</td>
<td>54</td>
<td>0.28</td>
<td>2.25</td>
</tr>
<tr>
<td>Ti</td>
<td>5.6</td>
<td>-48</td>
<td>5.8</td>
<td></td>
</tr>
</tbody>
</table>
Low-energy neutron scattering:

only s-waves: \( f(\Omega) \rightarrow \) scattering length, i.e., a (complex) number

\[
\begin{align*}
\text{a} > R_0 & \\
\text{a} < R_0 & \\
\text{a} < 0 &
\end{align*}
\]
Trapping potential #2:

**neutron gravity**  \( mgz \)  

for \( \Delta z = 1 \text{ m} \): \( \Delta E = 100 \text{ neV} \)
Trapping potential #2:

**neutron gravity**  \( mgz \)  

for \( \Delta z = 1 \) m: \( \Delta E = 100 \) neV

as good for trapping
(if bottle is tall enough): 

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

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

for \( \Delta B = 1 \) T: \( \Delta E = \pm 60 \) 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 (studied with cold and ultracold neutrons):

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin parity</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>$1.0086649158(6)$ u</td>
</tr>
<tr>
<td>Mass (absolute units)</td>
<td></td>
<td>$939.56533(4)$ MeV $c^{-2}$</td>
</tr>
<tr>
<td>Neutron - proton mass difference</td>
<td>$m_n - m_p$</td>
<td>$0.0013884489(6)$ u</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.2933318(5)$ MeV $c^{-2}$</td>
</tr>
<tr>
<td>Charge</td>
<td>$q_n$</td>
<td>$(-0.4 \pm 1.1) \times 10^{-21}$ e</td>
</tr>
<tr>
<td>Mean-square charge radius</td>
<td>$\langle s_n^2 \rangle$</td>
<td>$-0.1161(22)$ fm$^2$</td>
</tr>
<tr>
<td>Electric polarisability</td>
<td>$\alpha_n$</td>
<td>$(9.8^{+1.9}_{-2.5}) \times 10^{-4}$ fm$^3$</td>
</tr>
<tr>
<td>Magnetic moment</td>
<td>$\mu_n$</td>
<td>$-1.9130427(5)$ $\mu_N$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$=-6.0307738(15) \times 10^{-8}$ eV T$^{-1}$</td>
</tr>
<tr>
<td>Electric dipole moment</td>
<td>$d_n$</td>
<td>$&lt; 2.9 \times 10^{-26}$ e cm (90% c.l.)</td>
</tr>
<tr>
<td>Mean n$\pi$-oscillation time of free neutron</td>
<td>$\tau_{n\pi}$</td>
<td>$&gt; 8.6 \times 10^7$ s (90% c.l.)</td>
</tr>
<tr>
<td>... of bound neutron</td>
<td></td>
<td>$&gt; 1.2 \times 10^8$ 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>$0.7823329(5)$ MeV $c^{-2}$</td>
</tr>
<tr>
<td>Mean life time</td>
<td>$\tau_n$</td>
<td>$885.7(8)$ 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: $P_\pi \cdot p_e$</td>
<td>$A$</td>
<td>$-0.1162(13)$</td>
</tr>
<tr>
<td>momenta of antineutrino and electron: $p_\nu \cdot p_\pi$</td>
<td>$a$</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 $P_\pi \cdot (p_e \times p_\nu)$</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>$-180.08(10)^\circ$</td>
</tr>
</tbody>
</table>
nEDM
neutron lifetime
nuclear few-body interactions
n-oscillations
n-gravity
Heavy elements
A world of matter
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-36} seconds
10^{-43} seconds
10^{-37} degrees
10^{-33} degrees
10^{16} degrees
10^{10} degrees
6000 degrees
18 degrees
3 degrees K
radiation
positron (anti-electron)
proton
neutron
mean
hydrogen
deuterium
helium
lithium
quark
anti-quark
electron

The Big Bang
Search for an electric dipole moment of the neutron
Statements well before Lee and Yang 1956 paper:

Dirac, Rev. Mod. Phys. 21 (1949) 329:
I donot believe there is any need for physical laws to be invariant under reflections in space and time, although the exact laws of nature so far known have this invariance.

Purcell & Ramsey, Phys. Rev. 78 (1950) 807:
The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle ... becomes a purely experimental matter.
EDM violates 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 (Sakharov criteria)

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$
• 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
How is it measured?

Ultra-cold neutrons (UCN) trapped in an evacuated vessel at room temperature

RAL/SUSSEX/ILL experiment:

- 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)
- UCN detector
- UCN polarizing foil
- RF coil to flip spins
- Magnet
- Storage cell
- Quartz insulating cylinder
- Four-layer μ-metal shield
- Vacuum wall

Baker et al., PRL 63 (2006) 131801

~ 0.5 m
Better do in-beam or storage experiment?

Experimental sensitivity:

\[ \sigma(d_n) = \frac{h}{4\pi\alpha ET\sqrt{N}} \]

- **Better in-beam experiment?**
  - \( T \text{ small} \ (\cong 10 \text{ ms}) \)
  - \( N \text{ large} \ (\text{a few} \ 10^8 \text{ s}^{-1}) \)
  - \( v \cong \text{a few} 100 \text{ ms}^{-1} \)
  - \( \Rightarrow \text{large} \ \vec{v} \times \vec{E} \text{ effect} \)

- **Better storage experiment?**
  - \( T \text{ large} \ (\cong 150 \text{ s}) \)
  - \( N \text{ small} \ (\cong 10^4 \text{ per filling}) \)
  - \( v \leq 5 \text{ ms}^{-1} \)
  - \( \Rightarrow \text{small} \ \vec{v} \times \vec{E} \text{ effect} \)
Ramsey’s method

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

EDM changes frequency:
\[ \hbar \omega_L \sim \mu_n B \pm d_n E \]
$^{199}\text{Hg}$ co-magnetometer for correction of magnetic field drifts

Courtesy
M. v. d. Grinten
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
Follow-up experiment: Cryo-EDM
(Rutherford – Sussex – Kure – Oxford – ILL)

Accuracy goal: $10^{-27}$ ecm
Double-chamber EDM experiment (PNPI-ILL)

Intermediate result:

$|d_n| < 5.5 \times 10^{-26} \text{ e cm} \ (90\% \text{ CL})$

A. Serebrov et al., JETP Lett. 99 (2014) 4

Several current projects preparing for big improvements:
PSI, Los Alamos, SNS, PNPI, TRIUMF, TUM
Short-range gravity

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

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

$$F = -G \frac{m_1 m_2}{r^2} \rightarrow -G^* \frac{m_1 m_2}{r^{2+n}}$$
First observations (2002)

Proposal: Luschikov and Frank, JETP Lett 28 (1978) 559

Nesvizhevsky et al., Nature 415 (2002) 299
Rabi-type spectroscopy of gravity

By the qBounce collaboration (H. Abele, T. Jenke...)

**NMR Spectroscopy Technique to explore magnetic moments**

- Region I: 1st State selector / Polarizer
- Region II: Coupling
  - RF field
- Region III: 2nd State Selector / Analyzer

**Gravity Resonance Spectroscopy Technique to explore gravity**

- Region I: 1st State selector / Polarizer
- Region II: Coupling
  - Vibr. mirror
- Region III: 2nd State Selector / Analyzer
Latest results


$f_{13} = 464.1 \pm 1.2 \text{ Hz}$

$f_{14} = 648.8 \pm 1.6 \text{ Hz}$

$V(z) = \frac{GMm}{r} \left( 1 + \alpha e^{-z/\lambda} \right)$
Ramsey spectrometer for gravity states


Advantages:
• Long flight path $\rightarrow$ smaller uncertainty $\Delta E$
• static central mirror for free state evolution
Team of happy experimentalists
Quantum bouncing ball

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

\[ \psi_n(z) \sim Ai \left[ \frac{z}{z_0} - \frac{E_n}{E_0} \right]; c_n = \int_0^\infty \Psi(z, 0) \psi(z) dz \]
Airy - Quantum States 1 & 2

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

Jenke et al.
NIM 2013, PRL 2014

\[ E = mgh \]

\[ \sim 10 \text{ cm} \]

\[ \text{counts} \]

\[ \text{Height [\mu m]} \]

\[ \text{Horizontal position [mm]} \]

\[ 200 \mu m \]
Snapshots of $|\psi|^2$ with 1.5 $\mu$m resolution

Preliminary results from Ph.D. thesis of Martin Thalhammer, TU Vienna and ILL
Preparation, $L = 0 \text{ mm}$

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

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

preliminary
2\textsuperscript{nd} turning point $L = 41 \text{ mm}$
again falling, $L = 51$ mm
still falling, $L = 54$ mm
“lowest” point, $L = 61$ mm
only 20 µm step, $L = 51$ mm
From where do we get our neutrons?

Reactor sources:
- Institut Laue-Langevin
  - 58 MW
- Forschungsreaktor FRM II
  - 20 MW

Spallation sources:
- PSI Villigen
- SNS Oak Ridge
Neutron production at research reactors

FRM II
(Munich)

Thermal neutrons:
\[ E_{\text{kin}} \sim 25 \text{ meV} \]
\[ v \sim 2200 \text{ m/s} \]
\[ \lambda \sim 1.8 \text{ Å} \]
\[ T \sim 300 \text{ K} \]
Nuclear fission in fuel element

ILL (Grenoble)
Moderation in heavy-water reflector and cold source (liq. D$_2$)

Cold neutrons:

- $E_{\text{kin}} \sim 5$ meV
- $v \sim 1000$ m/s
- $\lambda \sim 4$ Å
- $T \sim 60$ K
(Ultra)cold neutron production at ILL

Ultracold neutrons:
- $E_{\text{kin}} < 3 \times 10^{-7} \text{ eV}$
- $v < 7 \text{ m/s}$
- $\lambda > 600 \text{ Å}$
- "$T$" $\sim 2 \text{ mK}$
((Ultra)cold) neutron production at ILL

Ultracold neutrons:
\[ E_{\text{kin}} < 3 \times 10^{-7} \text{ eV} \]
\[ v < 7 \text{ m/s} \]
\[ \lambda > 600 \text{ Å} \]

“\( T \)” \( \sim \) 2 mK

25 K (cold neutrons)
300 K (thermal neutrons)
2000 K (hot neutrons)

Neutron turbine
A. Steyerl
TUM/ILL 1985
((Ultra)cold) neutron production at ILL

Neutron turbine
A. Steyerl
TUM/ILL 1985

~ 20 cm$^{-3}$

vertical guide

cold source

reactor core
Instruments on “level D” at ILL

Neutron turbine  qBounce  Big GraviTrap
Big bang nucleosynthesis and the neutron lifetime

$10^{-6}$ s (100 MeV) quarks & gluons form nucleons

$n + e^+ \leftrightarrow p + \nu, \quad n + \nu \leftrightarrow p + e, \quad n \rightarrow p + e + \nu$

\[
\frac{[n]}{[p]} = \exp \left( - \frac{\Delta mc^2}{kT} \right)
\]

1 s (1 MeV) neutrinos decouple $\Rightarrow$ neutrons decay

$n \rightarrow p + e + \nu, \quad p + n \leftrightarrow d + \gamma$

3 min (0.1 MeV) deuterons become stable

$p(n,\gamma)d, \quad d(d,n)^3He, \quad d(d,p)^3H, \quad ^3He(n,\gamma)^4He \ldots$

after 30 min primordial abundances of light elements:

$^1H \quad 75\%$

$^4He \quad 25\%$

$^2H \quad 30ppm$

$^3He \quad 13ppm$

$^7Li \quad 4 \times 10^{-10}$

A. Coc, NIM A 611 (2009) 224
Cyburt et al. Rev. Mod. Phys 88 (2016) 015004-1
Steven Weinberg, “The first three minutes"
Impact for nuclear and particle physics

\[ \lambda = \frac{g_A}{g_V} \] (from $\beta$ asymmetry)


uncertainty due to radiative corrections:

\[ \delta |V_{ud}|^2 = 3.8 \times 10^{-4} \rightarrow \text{request } \delta \tau_n < 0.3 \text{ s} \]
How can we measure the neutron lifetime?

• **In-beam experiments:**
  • measure radioactivity of a neutron beam:
    \[
    \frac{dN}{dt} = - \frac{N}{\tau_n} = - \frac{\rho V}{\tau_n}
    \]
  • needs absolute knowledge of \( \frac{dN}{dt}, \rho, V \) and detection efficiency

• **UCN trapping experiments:**
  • measure decrease of neutron number directly:
    \[
    N(t) = N(0) \exp \left( -\frac{t}{\tau} \right)
    \]
  • no absolute determinations, but:
    \[
    \tau^{-1} = \tau_n^{-1} + \tau_{\text{loss}}^{-1}
    \]
The NIST in-beam neutron lifetime experiment

\[ \tau_n = (887.7 \pm 1.2_{\text{stat}} \pm 1.9_{\text{sys}}) \text{s} \]


Trap of variable length, electrode distances used for blinding
Loss per wall collision for trapped UCN gas:

\[ \bar{\mu}(E) = 2f \left[ \frac{V}{E} \arcsin \left( \sqrt{\frac{E}{V}} \right) - \sqrt{\frac{V}{E}} - 1 \right] \]

\[ f = \frac{W}{V} \]

Not sufficiently under control for reliable calculation

→ need experimental strategy
The liquid-wall trap of Walter Mampe

- Liquid surfaces (fomblin oil)
- Modulation of losses via well-defined variation of the ratio surface/volume
- Extrapolation: volume $\rightarrow \infty$
- Result:

$$\tau_n = 887.6 \pm 3 \text{ s} \quad \text{W. Mampe et al., Phys. Rev. Lett. 63 (1989) 593}$$

- Result of follow-up experiment MAMBO II:

$$880.7 \pm 1.8 \text{ s} \quad \text{A. Pichlmaier et al. Phys. Lett. B 693 (2010) 221}$$
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- Result of follow-up experiment MAMBO II:

$$880.7 \pm 1.8 \text{ s}$$

Experiment with detection of upscattered neutrons

- Liquid surfaces (fomblin oil)
- Result (+ revision):
  
  \[ \tau_n = 885.4 \pm 0.9_{\text{stat}} \pm 0.4_{\text{syst}} \text{ s} \]
  

  \[ 881.6 \pm 0.8_{\text{stat}} \pm 1.9_{\text{syst}} \text{ s} \]
  
  Arzumanov et al. JETP Lett. 95 (2012) 224
Neutron lifetime experiment GraviTrap with low-$T$ „fomblin“ oil coated walls

A. Serebrov et al., PLB 605 (2005) 72

\[ \tau_{\text{storage}}^{-1} = \tau_n^{-1} + \tau_{\text{loss}}^{-1} \]

\[ \tau_{\text{storage}} = 878.5(8) \text{ s} \]

Frequency of wall collisions (/s)
Successor experiment Big GraviTrap
(during installation in 2014 at ILL)
Job (installation) done...

Work on trap preparation

First result (measurements to be continued with colder trap):

Serebrov et al., PRC 97, 055503 (2018):

$$\tau_n = (881.5 \pm 0.7 \pm 0.6)\ \text{s}$$
UCN $\tau$ ("fill and kill")

done at Los Alamos

magneto-gravitational trapping
asymmetric trap $\rightarrow$ chaotic trajectories
Morris et al., arXiv:1610.04560:
\[ \tau_n = (878.8 \pm 2.6 \pm 0.6) \text{ s} \]

\[ \tau_n = (877.7 \pm 0.7 + 0.3/-0.1) \text{ s} \]

+ triple blind analysis
– no monitoring of depolarised UCNs

Statement in first arXiv version:
“…is the first measurement of \( \tau_n \) that does not require corrections larger than the quoted uncertainties” but:
The neutron storage ring NESTOR

Principle: balance of centrifugal and Stern-Gerlach forces
In a magnetic sextupole ring

Fig. 2 Field lines and magnetic induction $B$ of a linear sextupole (a) and of a sextupole torus (b).
NESTOR: the real device
Results 1980

\[ N_n \]

\[ \tau = 918 \, \text{s} \]

\[ \tau = 907 \pm 70 \, \text{s} \]
Fig. 12. Neutron lifetime in the storage ring. The diagram contains all data normalized to $N = 1000$.

...no corrections larger than the quoted uncertainties

$\tau_n = (876.7 \pm 10) \text{ s}$
$\tau_n = (876.7 \pm 10) \text{ s}$

Fig. 12. Neutron lifetime in the storage ring. The diagram contains all data normalized to $N = 1000$.

...no corrections larger than the quoted uncertainties
Current situation


Beam method average* (blue zone):
888.0 ± 2.1 seconds

Bottle method average (green zone):
879.6 ± 0.6 seconds

Uncertainty

Disagreement
HOPE – Halbach OctuPole neutron lifetime Experiment

PhD works Loris Babin, Felix Rosenau, Fabien Lafont, Kent Leung

- magneto-gravitational trap
- $V_{\text{eff}} \approx 2 l$
- trap depth 47 neV
- counting the dead & survivors
- depolarisation monitoring
- employs a new UCN source
Halbach octupole radial trap

- \( B(r) = B_R (r/R)^3 \)
- 32 magnet slices
- \( B_R = 1.35 \) T (NdFeB)

12 8-pole modules + hands & forces = magnetic trap
Exp. established statistical sensitivity at SUN-2 prototype UCN source: 0.7 s /50 days
How to produce more ultracold neutrons?

UCN sources based on neutron conversion:

固体重氢 sD$_2$: 超流氦-4:

- **温度**: 5 K, 0.5 K (1.3 K)
- **自旋效应**: 帕拉-D$_2$ 含量 < 1%, 自旋-0
- **UCN 存储寿命**: $\approx 0.15$ s, $\tau_n \approx 880$ s
- **微小结构**: 单晶 - 晶粒, 均匀液体
- **实现**: 在堆中(在堆)
UCN production in superfluid He

R. Golub, J.M. Pendlebury, PL 53A (1975) 133

\[ \rho_{UCN} = P \tau \]

\[ \tau^{-1} = \tau^{-1}_{\text{decay}} + \tau^{-1}_{\text{upscattering}} + \tau^{-1}_{\text{capture}} + \tau^{-1}_{\text{wall losses}} \]

\[ \sigma_{\text{capture}}(^4\text{He}) = 0 \]

\[ T \quad \tau_{\text{max}} [\text{s}] \]

<table>
<thead>
<tr>
<th>( T [\text{K}] )</th>
<th>( \tau_{\text{max}} [\text{s}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>0.8</td>
<td>310</td>
</tr>
<tr>
<td>0.7</td>
<td>510</td>
</tr>
<tr>
<td>0.5</td>
<td>820</td>
</tr>
<tr>
<td>0</td>
<td>880</td>
</tr>
</tbody>
</table>

\( \rightarrow \text{ need } T < 0.5 - 0.6 \text{ K } \)
and low-loss walls

"phonon-roton" dispersion of superfluid \( ^4\text{He} \)

1 meV (12 K)

7 nm\(^{-1}\) (0.9 nm \( \rightarrow \) UCN)

\( \omega \) free neutron dispersion

cold neutron beam

cold neutron
phonon
ultra cold neutron

\( \tau \sim 100 \text{ s} \)

\( \tau \sim 880 \text{ s} \)

\( \tau \sim 310 \text{ s} \)

\( \tau \sim 510 \text{ s} \)

\( \tau \sim 820 \text{ s} \)
UCN accumulation and extraction?

Factor 50 missing in an experiment at ILL in the 1980’s
→ „one cannot extract UCNs accumulated in superfluid helium“

A.I. Kilvington et al., PL A 125 (1987) 416
Superfluid-He UCN source development (2004+)

window- and gap-less vertical UCN extraction

Cryogenics 46 (2006) 799
Superfluid-He UCN source development (2004+)
Superfluid-He UCN source development (2004+)

2007 (TUM): Implementation at the neutron beam at the research reactor FRM II

f. l. t. r.: Hans Friedrich Wirth, Karsten Baumann, Bea Franke
Superfluid-He UCN source development (2004+)

2007 (TUM): First demonstration of windowless extraction of accumulated UCNs from converter of 1st prototype source at FRM2

Superfluid-He UCN source development (2004+)

2007 (TUM): First demonstration of windowless extraction of accumulated UCNs from converter of 1st prototype source at FRM2

2010 (ILL): Transfer to ILL, upgrade, installation and troubleshooting
Superfluid-He UCN source development (2004+)

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BeO ceramics, Be windows

Leak cured with Stycast 2850 FT, ...30 cooldowns since
Superfluid-He UCN source development (2004+)

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2010 (ILL): 274000 UCNs extracted from 5-l converter of SUN-1 (55/ccm)

PRL 107 (2011) 134801 (PRL highlight)
UCN production in pressurized He-II (@PF1b)

Schmidt-Wellenburg et al., PRC 92 (2015) 024004

0 bar – 20 bar

f. l. t. r.:
Philipp Schmidt-Wellenburg
Amel Rahli, Torsten Soldner,
Kent Leung

\[ \omega \]

1 meV
(12 K)

\[ q \]

7 nm\(^{-1}\)

free neutron dispersion

„phonon-roton“ dispersion of superfluid \(^4\)He
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2010 (ILL): 274000 UCNs extracted from 5-l converter of SUN-1 (55/ccm)

2015 (ILL): 882000 UCNs from 4-l converter of 2\textsuperscript{nd} prototype SUN-2 (220/ccm)

UCN ToF spectra:

- Open converter
  - \(v(\text{max}) = 5.1\) m/s, \(E_\parallel = 144\) neV

- 200 s accumulation
  - \(v(\text{max}) = 3.9\) m/s, \(E_\parallel = 81\) neV
Superfluid-He UCN source development (2004+)

2007 (TUM): First demonstration of windowless extraction of accumulated UCNs from converter of 1st prototype source at FRM2

2010 (ILL): 274000 UCNs extracted from 5-l converter of SUN-1 (55/ccm)

2015 (ILL): 882000 UCNs from 4-l converter of 2nd prototype SUN-2 (220/ccm)

2014+ (ILL): Design and construction of SuperSUN UCN-source user facility
User facility SuperSUN
under construction

Converter volume: 12 liters
Saturated UCN number: $4 \times 10^6$ (stage I, $E < 80$ neV)
$2 \times 10^7$ (stage II, polarised, $E < 230$ neV)

Magnetic 8-pole UCN reflector (stage II)

For calculations of UCN storage see:
Octagonal neutron guide for SuperSUN
Cut through the apparatus:

... can be separated in two independent magnetically shielded rooms
Magnetic shields of PanEDM

Passive SF: > 6 Millions @ 1 mHz
SF of inner shield alone: > 70,000 @ 1 mHz, 1μT excitation

I. Altarev et al., arXiv:1501.07408
I. Altarev et al., arXiv:1501.07861
PanEDM @ SuperSUN @ ILL

<table>
<thead>
<tr>
<th></th>
<th>Stage I</th>
<th>Stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity (1σ) 100 days</strong></td>
<td>$1.9 \times 10^{-27}$ ecm</td>
<td>$4.2 \times 10^{-28}$ ecm</td>
</tr>
<tr>
<td><strong>Limit (90% C.L.) 100 days</strong></td>
<td>$3.0 \times 10^{-27}$ ecm</td>
<td>$7.0 \times 10^{-28}$ ecm</td>
</tr>
</tbody>
</table>
Merci de votre attention!
The neutron and its role in cosmology and particle physics

D. Dubbers and M. G. Schmidt,
Rev. Mod. Phys. 83, 1111 (2011)