Experiments with Ultra-Cold Neutrons and cold neutrons

CHIPP Plenary Meeting, Oct. 15th, 2007

Klaus Kirch
Paul Scherrer Institut

PAUL-SCHERRER-INSTITUT

Ultra Cold Neutron Source

v_{UCN} ~ 6m/s

4 x 10^9 UCN/800s

ρ ~ 2000 cm^{-3}

ρ_{exp}> 1000 cm^{-3}

Ultra Cold Neutron Source

FUNSPIN

v_{CN} ~ 600 m/s

$3x10^8$ $cm^{-2}s^{-1}$

~10^{10} s^{-1}

P_A ~ 95%

P_{av} ~ 90%

NIMA539(2005)622

Neutrons in fundamental physics

- Time reversal violation (TRV), CP-violation
  - Electric Dipole Moment (EDM)
- Mirror parity, Dark matter
  - neutron – mirror neutron (n-n‘) oscillations
- Weak interaction, TRV, V_{ud}, Big-Bang-Nucleosynthesis
  - neutron lifetime, neutron decay correlations
  - Baryon number violation
  - $n-\bar{n}$ oscillations
- Strong interaction
  - neutron – deuteron scattering length
- Gravitation, QM, charge conservation, …

Physics with polarized cold neutrons

- Two nuclear/particle physics experiments are presently making use of the FUNSPIN beam
  - Search for time reversal violating effects in the decay of free neutrons, R-96-04
  - The spin dependent neutron scattering length of the deuteron, R-03-01

R-96-04: Search for time reversal violation

G. Ban[d], A. Bialek[c], K. Bodek[a], A. Czarnecki[g*], P. Gorel[db], K. Kirch[b], St. Kistryn[a], A. Kozela[c], M. Kuzniak[ab], O. Naviliat-Cuncic[d], J. Pabisz[a], N. Severijns[e], E. Stephan[f], J. Zejma[a]

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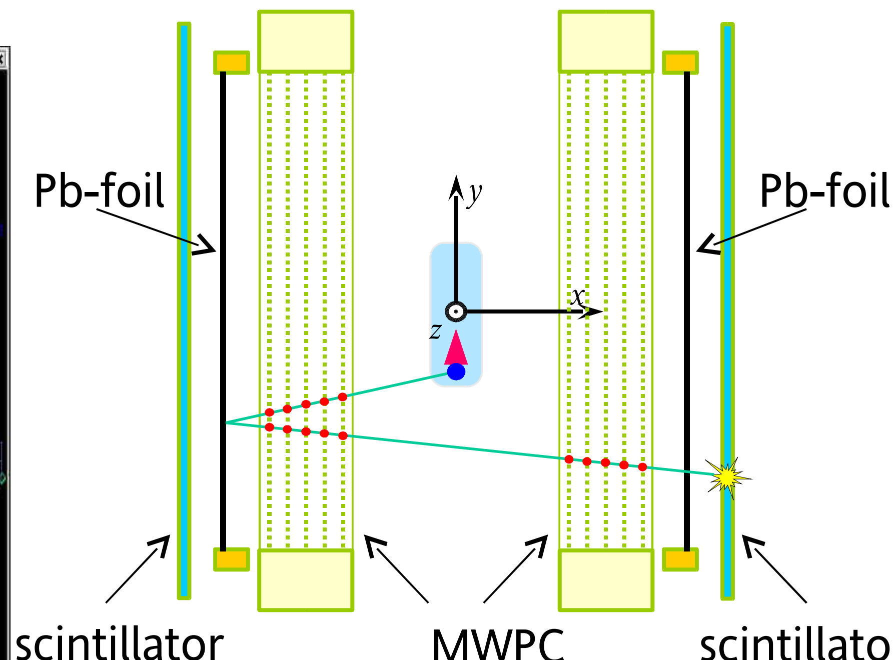
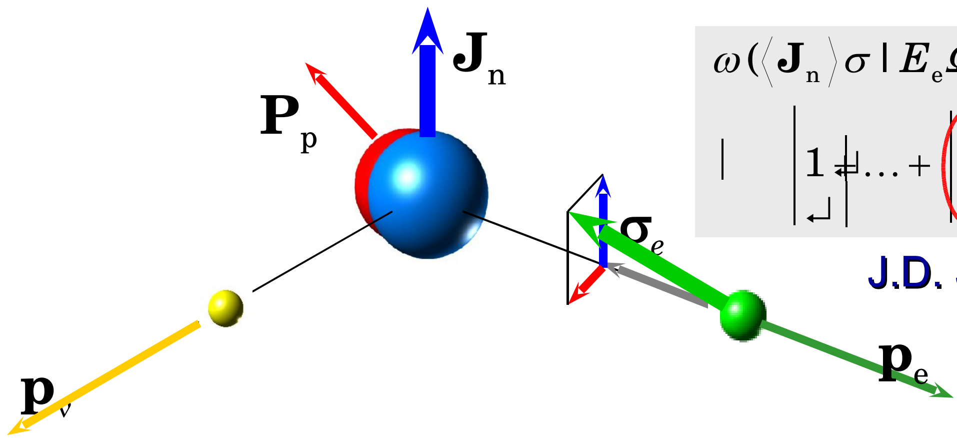
b) Paul Scherrer Institute, Villigen, Switzerland
c) Institute of Nuclear Physics, Cracow, Poland
d) Laboratoire de Physique Corpusculaire, Caen, France
e) Catholic University, Leuven, Belgium
f) Institute of Physics, University of Silesia, Katowice, Poland
g) University of Alberta, Edmonton, Canada
*) Theory support

NIMA473(2001)326
NIMA565(2006)711



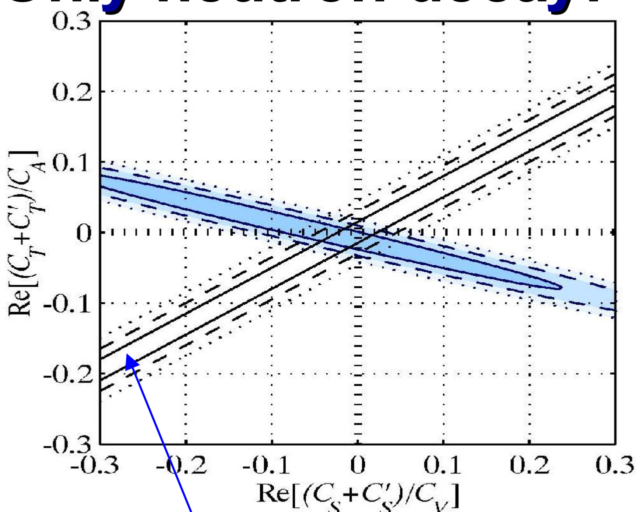
Transverse e⁻ polarization: R & N



$$\omega(\langle \mathbf{J}_n \rangle \sigma \mid E_e \Omega_e)\, dE_e d\Omega_e \propto \left[1 + \ldots + R \frac{\mathbf{p}_e \times \sigma}{E_e} + N \sigma \cdot \langle \mathbf{J}_n \rangle + G \frac{\mathbf{p}_e \cdot \sigma}{E_e} + \ldots \right] dE_e d\Omega_e$$

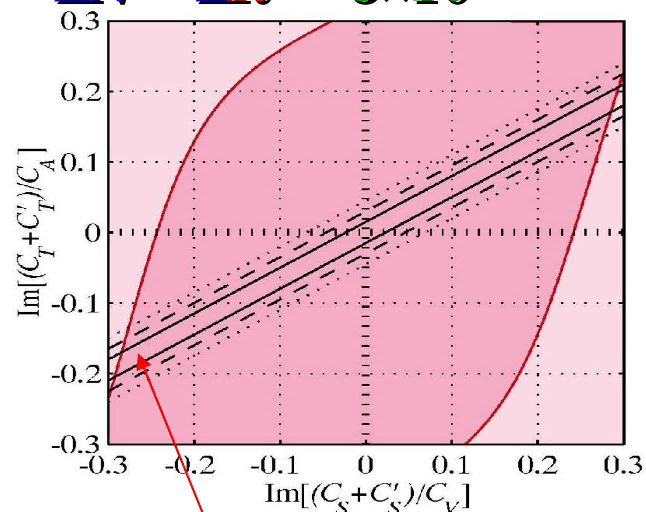
J.D. Jackson et al., Phys. Rev. 106, 517 (1957)

Only neutron decay:



***N*-correlation**

$\Delta N = \Delta R \approx 5\times10^{-3}$



***R*-correlation**

- Data acquired and analyzed to 1.5% level
- Final data taking for $5\text{x}10^{-3}$ precision presently ongoing at FUNSPIN
- A new experiment could reach $5\text{x}10^{-4}$ but would need strong motivation from theory

Graphs: courtesy K. Bodek

R-03-01: the nd-experiment

a high-accuracy measurement of the spin-dependent neutron-deuteron scattering length $b_{i,d}$

contact: florian.piegsa @ psi.ch

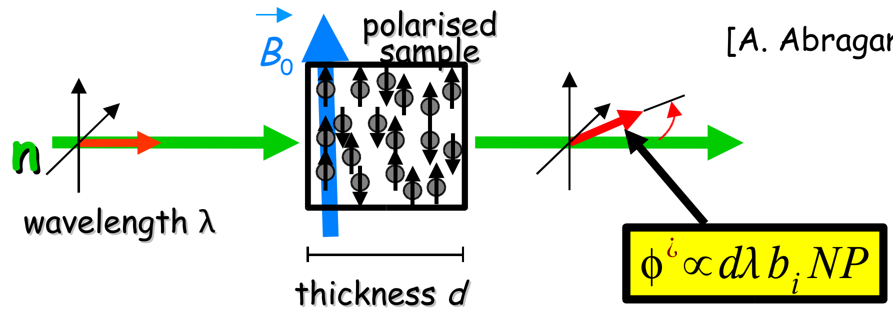
NIMA526(2004)91

Motivation: Effective field theories (EFT's) need the nd doublet scattering length $b_{2,d}$, which is known with only 6% accuracy (experim. input parameter – 3 nucleons).

It is accessable via a linear combination of $b_{i,d}$ and $b_{c,d}$.

Method: Measure the pseudomagnetic precession of neutron spins, which is proportional to $b_{i,d}$, in a polarised solid deuterated plastic target.

[A. Abragam et al., PRL **31** (1973) 776]



This will be the first direct measurement of $b_{i,d}$ and would improve its present accuracy.

present data: [W. Dilg et al., Phys. Letters B 36 (1971) 208]

B. van den Brandt, H. Glättli, P. Hautle, J. Kohlbrecher, J.A. Konter, F.M. Piegsa & O. Zimmer

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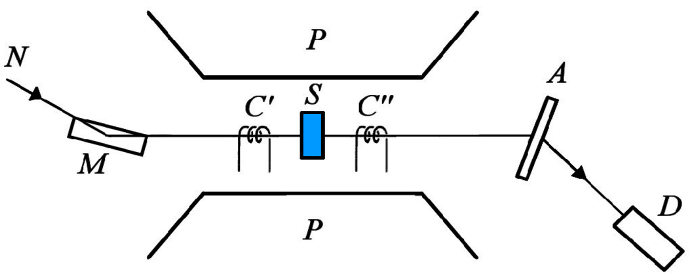
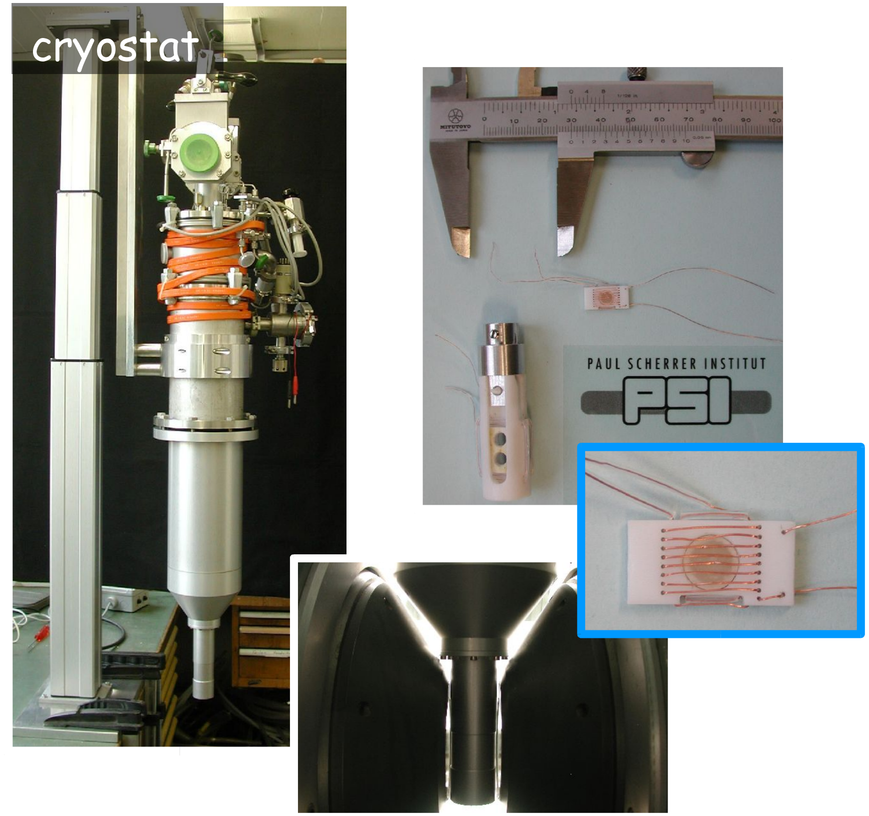
Used Technique:

Ramsey's atomic beam method
adapted to cold neutrons:

N:	polarised cold neutron beam (FUNSPIN – SINQ @ PSI)
M:	wavelength monochromator
C',C'':	$\pi/2$ rf-spin flipper
S:	polarised sample
P:	pole pieces of 2.5 Tesla magnet
A:	spin analyser
D:	detector





- specially designed dilution cryostat (T~100mK)
- sample in target cell filled with L^4He thermally anchored to the mixing chamber
- Nuclear Polarisation by dynamic nuclear polarisation method (DNP)

B. van den Brandt, H. Glättli, P. Hautle,
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Common features:
- extremely challenging
- need(ed) a considerable amount of R&D
- first time measurements
- very hard to do elsewhere.

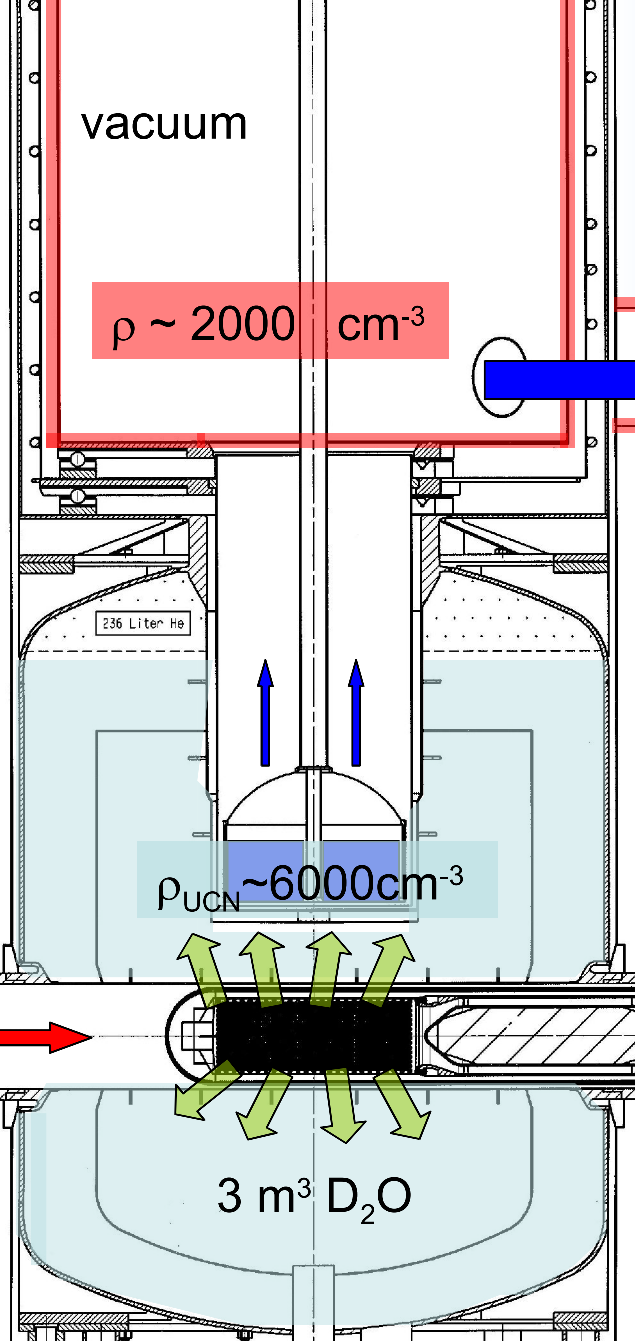
Physics with ultracold neutrons

- Need stronger UCN source
  - Requires source R&D and fundamental understanding of the underlying physics
- With stronger sources can perform various experiments - two flagships:
  - Measurement of the neutron lifetime
  - Search for the neutron electric dipole moment

The PSI UCN source

Ultra Cold Neutron Source

$2\ m^3$ volume storage trap



UCN guide

$\rho_{exp} > 1000\ cm^{-3}$

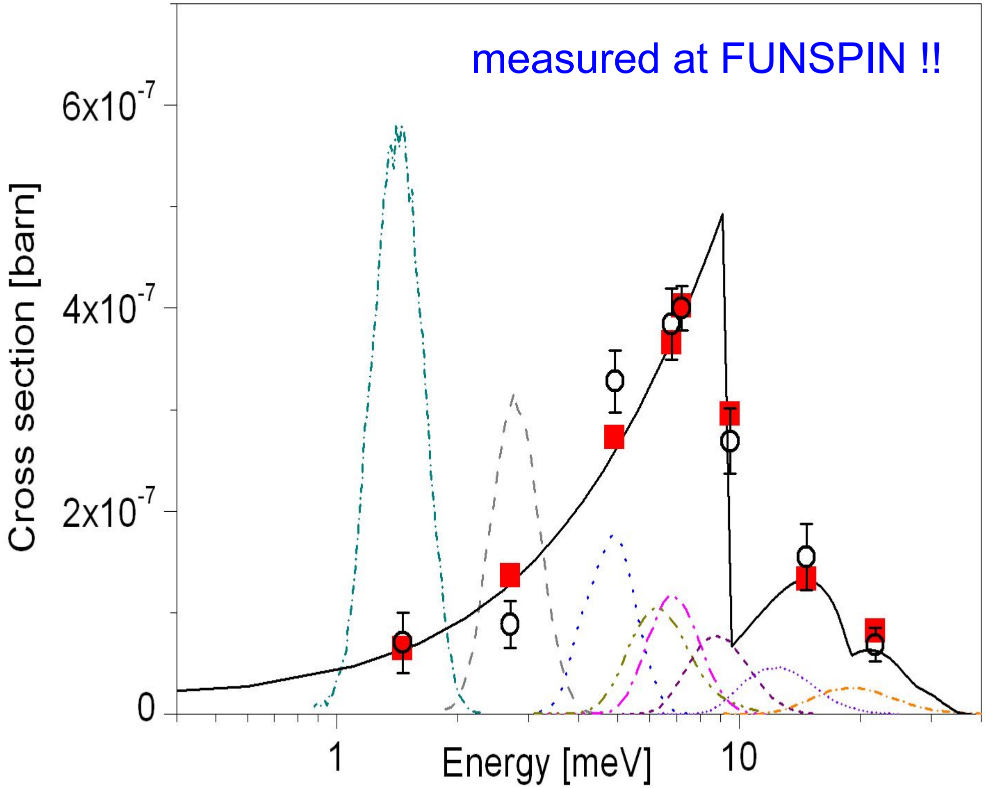
compare with typical $10\ cm^{-3}$ at ILL

30 liters solid D_2

2 mA,600 MeV proton beam 1% duty cycle

- high power (1.2 MW)
- low duty cycle (1%)
- scheduled for 2008/09
- multi-user capability

Source physics:
UCN production in solid D_2



Downscattering of cold neutrons via generation of phonons in solid Deuterium explained with a simple Debye-model and multi-phonon excitations.

M. Kasprzak (PSI,SMI), PhD thesis
submitted to PRL
and
PRL95(2005)182502
PRL94(2005)212502
PRC71(2005)054601
NIMA533(2004)491
PRB68(2003)094114

PSI with participants from
JUC, JINR, ILL, LANL, TUM, NCSU, IUB

UCN: Neutron lifetime

R-07-01.0_bv38

Letter of Intent

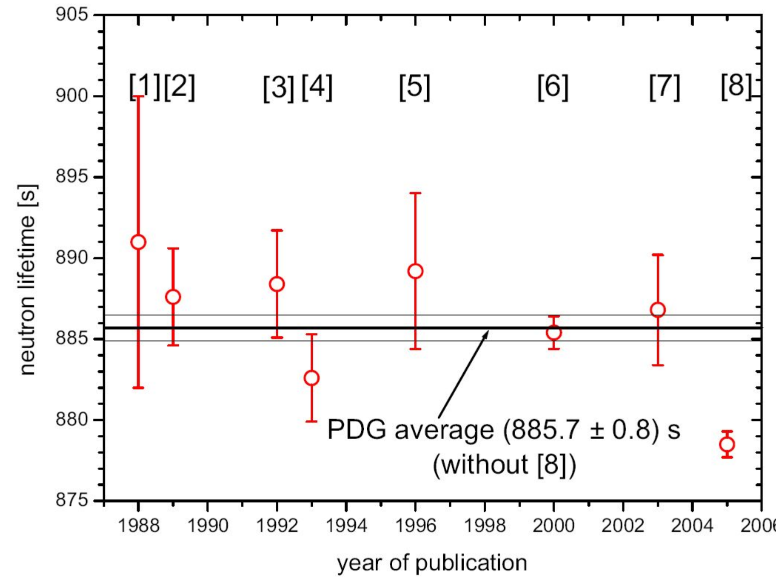
A Precision Measurement of the Neutron Lifetime in a Trap with Superconducting Magnets

I. Altarev, A. Frei, E. Gutsmiedl, F.J. Hartmann, A.R. Müller, S. Paul, R. Picker, R. Stoepler

Physik-Department, Technische Universität München, 85748 Garching, Germany

Summary

The interesting quantities in the β decay of the free neutron are i) the lifetime τ_n and ii) the correlation of spin and direction of flight of the decay products with those of the neutron. They allow testing the unitarity of the Cabibbo-Kobayashi-Maskawa matrix. In addition, τ_n determines the helium abundance immediately after the Big Bang and hence is very important for cosmology. The result of the latest measurement of τ_n differs from the average of the Particle Data group by 6σ! In order to measure τ_n, we plan to store ultra-cold neutrons in a trap confined by walls with superconducting magnets. Thus we avoid losses during the reflections at material walls that led to systematic errors in past experiments that were hard to control. The large volume of our trap (750 dm³) results in a large number of stored neutrons. We intend to measure the time distribution of the protons from neutron decay as well as the number of surviving neutrons. We expect an experimental error of 0.1s.



(878.5±0.8)s
Serebrov et al.
PLB605(2005)72

The neutron lifetime impacts weak interaction physics and Big Bang nucleosynthesis

CHIPP Plenary 2006:

EDM projects aiming at 10^{-28} e cm

- Sussex et al. @ILL: 2007 …
- LANL et al. @SNS: 2011 …

} Superfluid ^{4}He, SC-shields, SQUIDS, (^{3}He, multi-chamber)

- PNPI et al. @ILL: ?
- TUM et al. @FRM-II: ?

RAL-Sussex-ILL
$d_n < 2.9 \times 10^{-26}$ e cm
PRL97(2006)131801

- nEDM@PSI (presently @ILL): 2008 …
  Room temperature, vacuum, B-field stabilization, multiple magnetometry

IPC CAEN — Joint Institute for Nuclear Research — FRAP Fribourg Atomic Physics — ILL — LPSC Grenoble — PAUL SCHERRER INSTITUT PSI

The nEDM@PSI collaboration grew stronger in 2007

nEDM Strategy

- Phase I:
  - Operate and improve OILL@ILL (-2008)
  - Move of OILL in 2008
  - Design of n2EDM, related R&D
- Phase II:
  - Operate OILL@PSI (2009-2010)
  - Sensitivity goal: 5×10^{-27} ecm
  - Setup of n2EDM, continued R&D
- Phase III:
  - Operate n2EDM@PSI (2011-2015)
  - Sensitivity goal: 5×10^{-28} ecm

Optimize in-vacuum, room-temperature technique

EDM summary

- nEDM is the UCN experiment with (probably) the largest impact
- Model parameter space restricted by experiment (strong and SUSY CP problems): Any improvement of experimental sensitivity translates into new limits or discovery
- Strong worldwide competition: good position
- Possibility to obtain other results on the way

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Ultra Cold Neutron Source

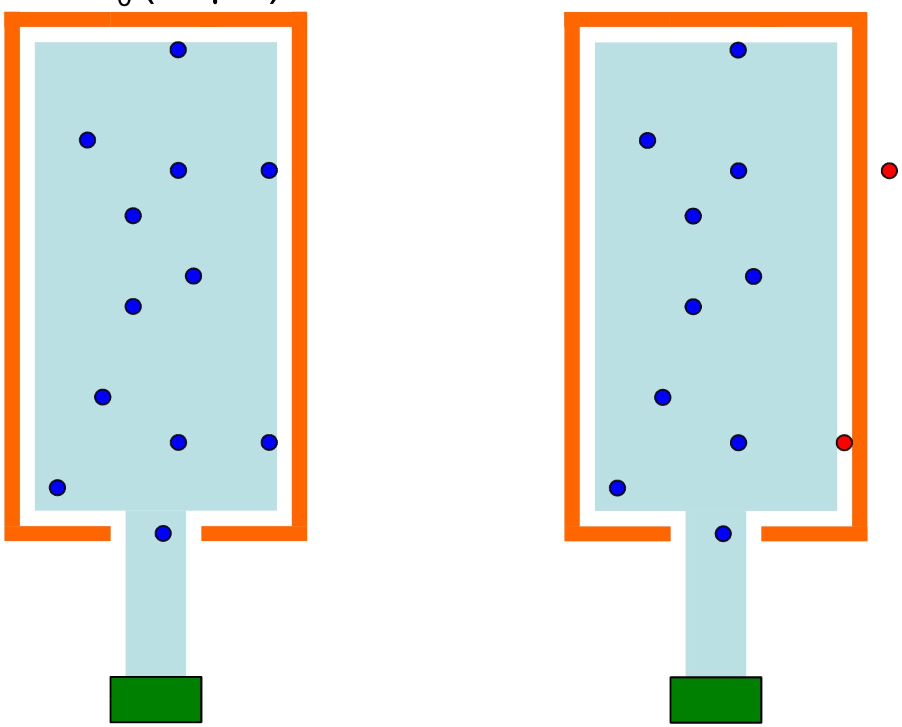
EDM detour: Mirror matter

- Idea: Add mirror particles in order to restore parity symmetry (Lee&Yang, Kobzarev&Okun&Pomeranchuk, Blinnikov&Khlopov, Foot, Berezhiani, …)
  - Same masses
  - Same space
  - Share gravitational interaction and explain Dark Matter
  - Mixing of neutral particles possible, e.g. H – H', $\gamma - \gamma'$, $\nu - \nu'$, and n – n'
- Fast n – n' oscillations could explain cosmic rays of highest energy Berezhiani & Bento, PRL96(2006)081801
- No direct experimental limit on n – n'
- Indirect limit from neutron – antineutron search of order 1s

e	e'
ν	ν'
p	p'
n	n'
$\bar{e}$	$\bar{e}'$
$\bar{\nu}$	$\bar{\nu}'$
$\bar{p}$	$\bar{p}'$
$\bar{n}$	$\bar{n}'$
W, Z	W', Z'
γ	γ'

How to measure transitions neutron – mirror neutron ?

$B=B_0$ (>5μT) B=0 (<50nT)



Pokotilovski, PLB639(2006)214

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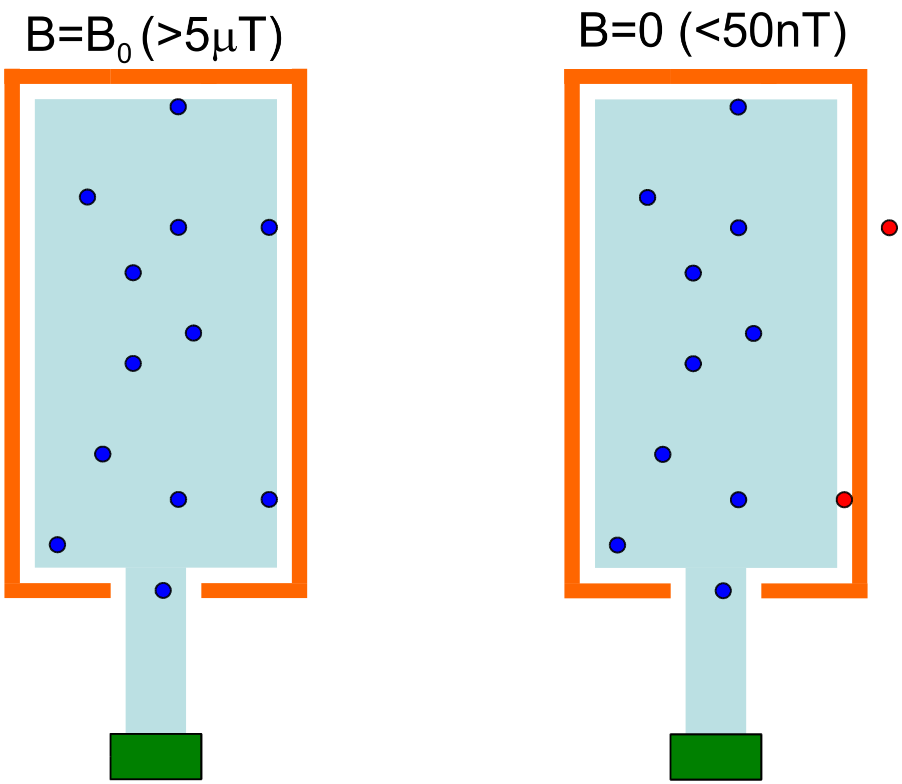
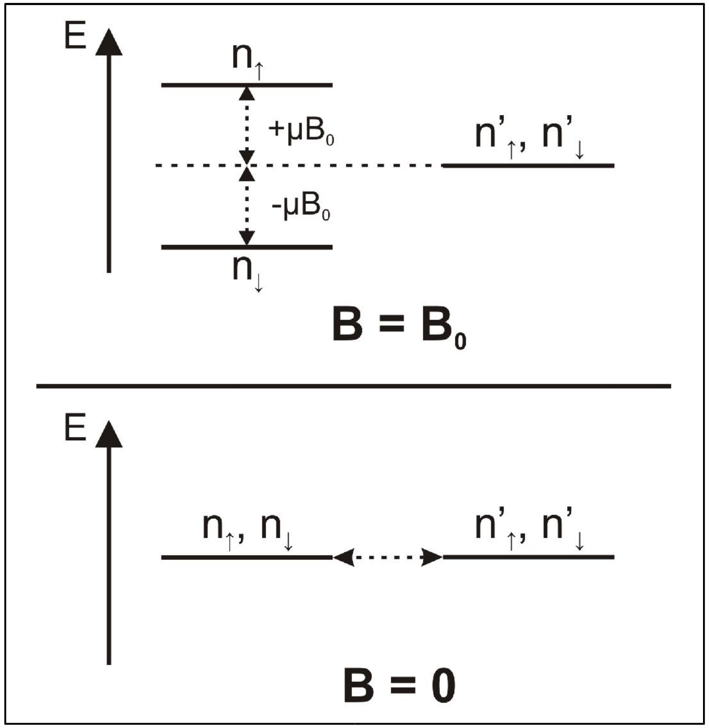
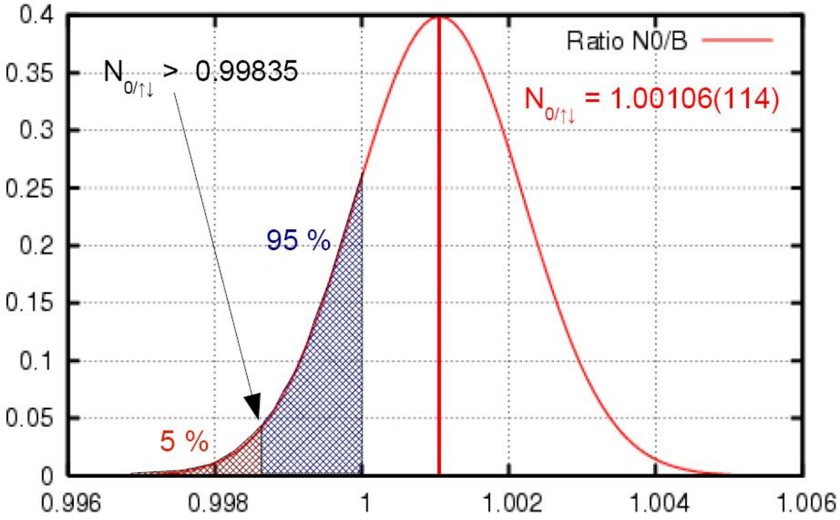
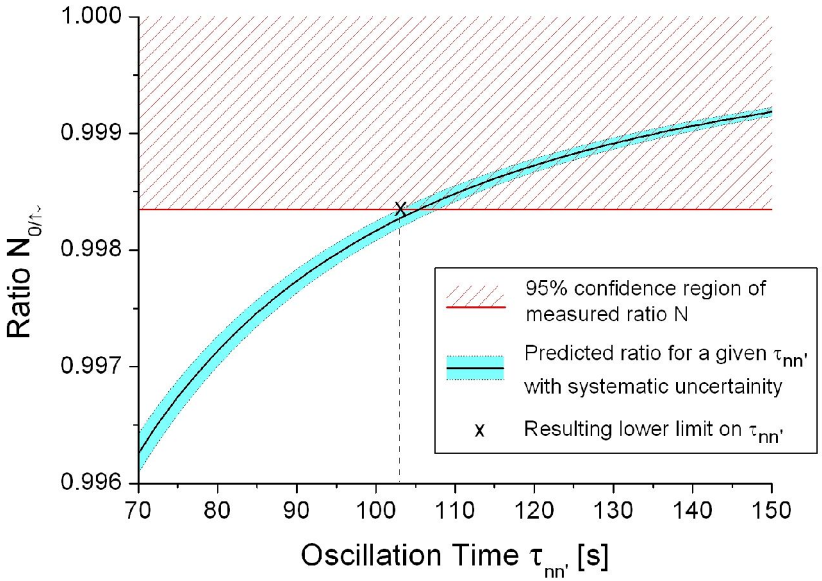




Pokotilovski, PLB639(2006)214

n – n‘ limit





The limit on the oscillation time is deduced from the UCN count ratio of measurements with magnetic field on and off:

$\tau_{nn'}$ > 103 s (95% C.L.)

G. Ban *et al.,* arXiv:0705.2336 (May 16th, 2007) accepted for publication in Phys. Rev. Lett.

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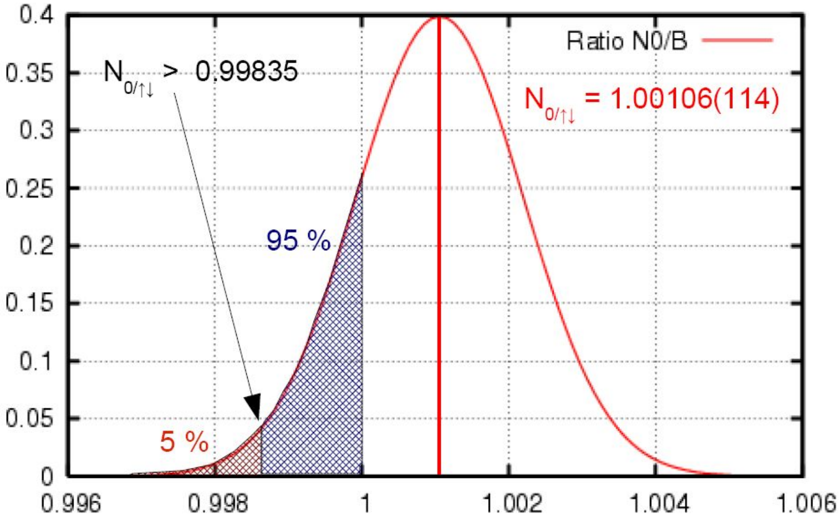

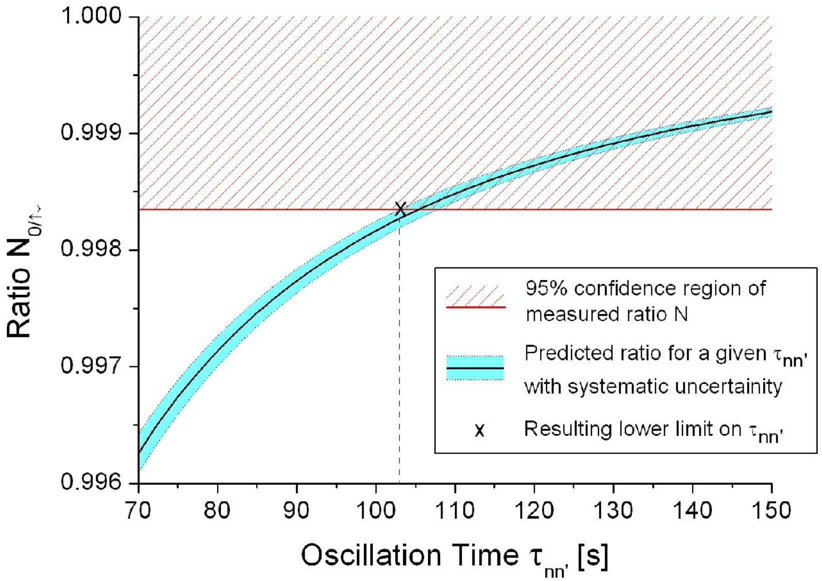

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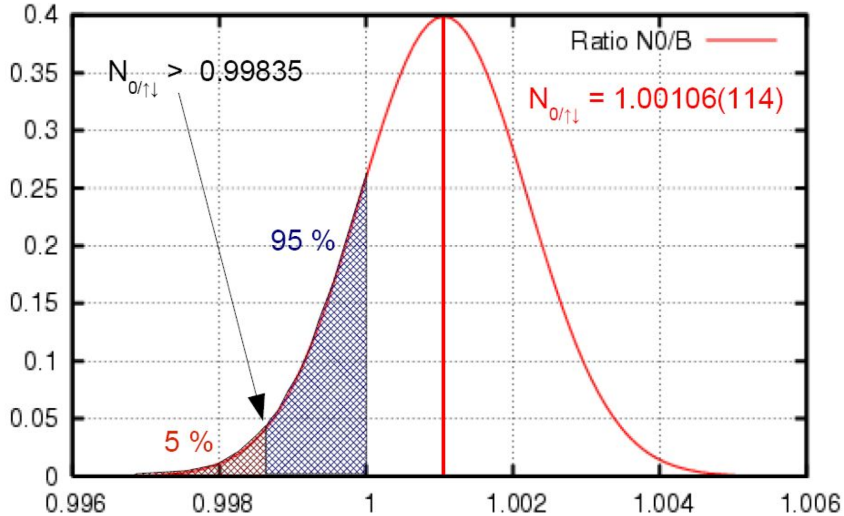

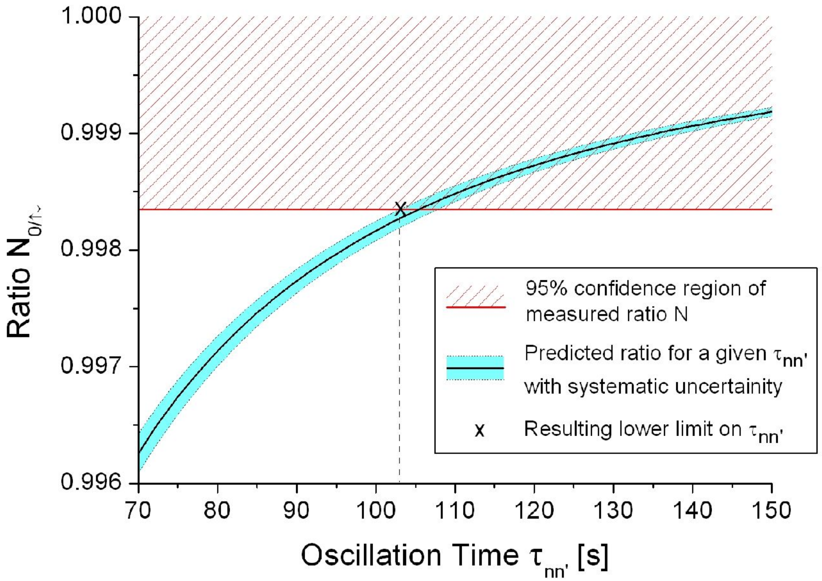

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Andreas Knecht (PSI, UniZH)
Wednesday, Oct. 17th, 2007
9:30 OFLG / 402
“A direct experimental limit on neutron - mirror neutron oscillations”

Conclusions

- Today: unique opportunity for physics with polarized cold neutrons at PSI
  - FUNSPIN is among the best polarized beams worldwide
  - two extra-ordinary experiments on weak and strong interaction physics ongoing at FUNSPIN
- End of 2008: the world‘s most intense UCN source is planned to come online at PSI
  - nEDM will be discovered
    or further limited to the few times 10^{-28} ecm range
  - The precision on τ_n will be improved to 0.1s
  - Other exciting experiments are possible