NEUTRONS FOR SCIENCE

Physics with

Ultracold Neutrons (UCN)

at the Institut Laue-Langevin (ILL)

in Grenoble, France

Peter Geltenbort

thanks to the beautiful slides of
V. Ezhov, P. Harris, V. Nesvizhevsky, C. Plonka, A. Steyerl, V. Varlamov, C. Vettier

Very Hot Neutrons

10^{7} eV

Ultracold Neutrons

10^{-7} eV

Physics with Spallation Ultracold Neutrons
-- RCNP-KEK workshop on fundamental neutron physics and related fields --

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Programme

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"UCN sources in Europe"	P. Geltenbort (ILL)	30 min but talked 50 min

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Dinner Party: "During and after dinner talk"	P. Geltenbort (ILL)	10 min

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For my todays' talk "Fundamental neutron physics at Grenoble"	P. Geltenbort (ILL)	30 min are allocated

but unfortunately now my TIME is already OVER!!

.

Therefore, do you have an questions????? Please do not hesitate ….

Thank you,
merci beaucoup et
besten Dank
for your attention!

Institut Laue-Langevin

"A neutron factory and a user facility"

founded in January 1967

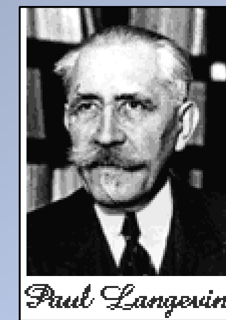
first neutrons in 1971

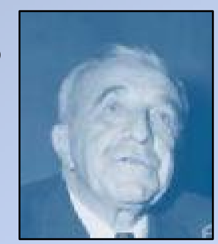
cold and hot neutrons sources started operation in 1972

general refit from 1991 - 94

Millennium Programme
just on the way

"earthquake" refit from 2003 - 05





Associates : France, Germany, United Kingdom
Scientific Member Countries : AU, CZ, I, RU, E, CH

Fields of research

solid-state physics, material science, chemistry, bio- and earth sciences, engineering,
nuclear and particle (fundamental) physics

In 2003

over 2000 visiting scientists

a total of 750 experiments at some 40 instruments

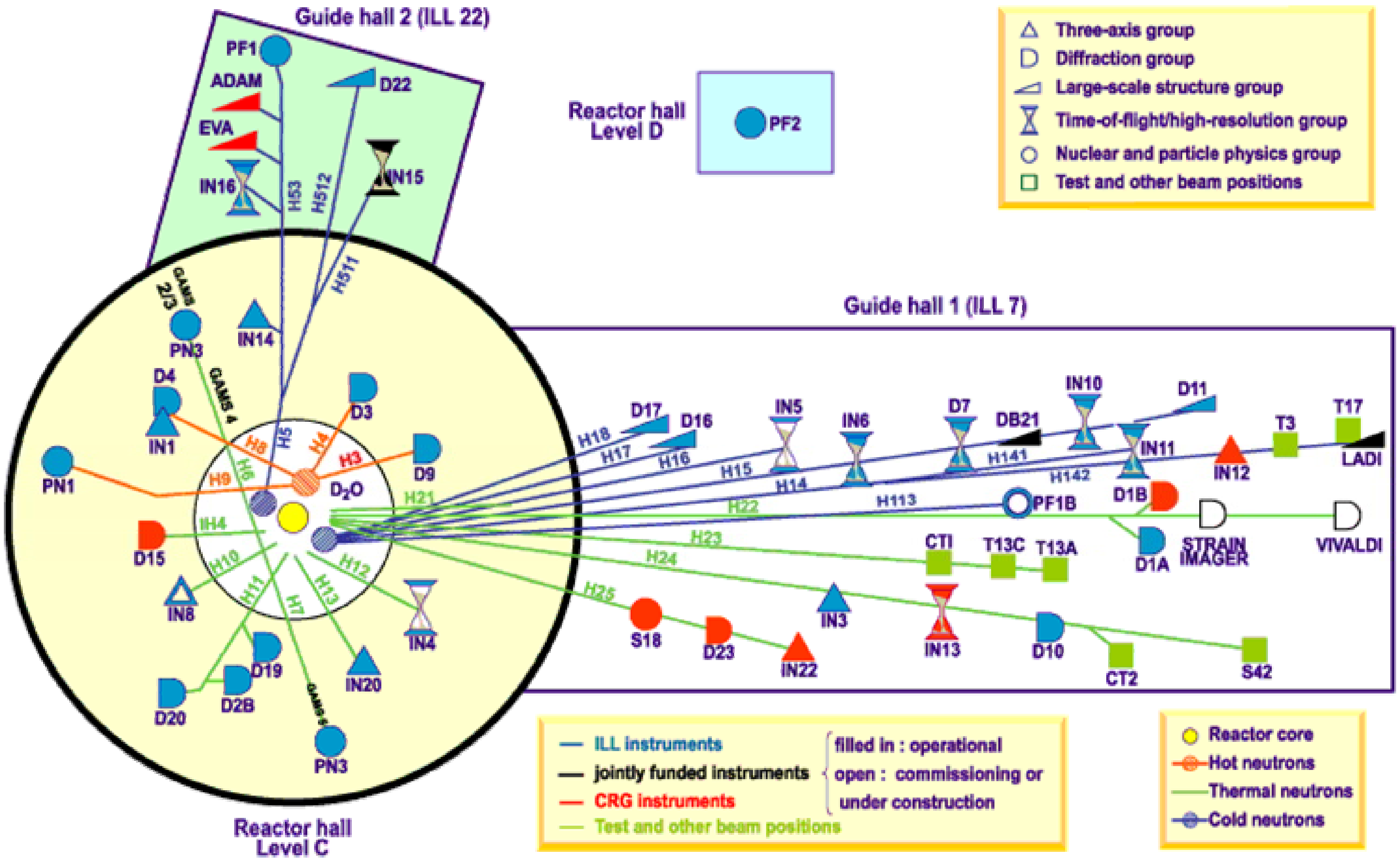
The Nuclear and Particle Physics group (NPP)

Nuclear physics

PN1 (LOHENGRIN) Recoil mass spectrometer for fission fragments
PN3 (GAMS) Ultra-high resolution gamma ray spectrometer

Particle physics

PF1B Facility for cold neutrons	(former PF1) cryoEDM experiment
PF2 Facility for ultracold and very cold neutrons	S18 - perfect crystal neutron interferometer



Nuclear and particle physics at ILL

nuclear physics and applied nuclear physics

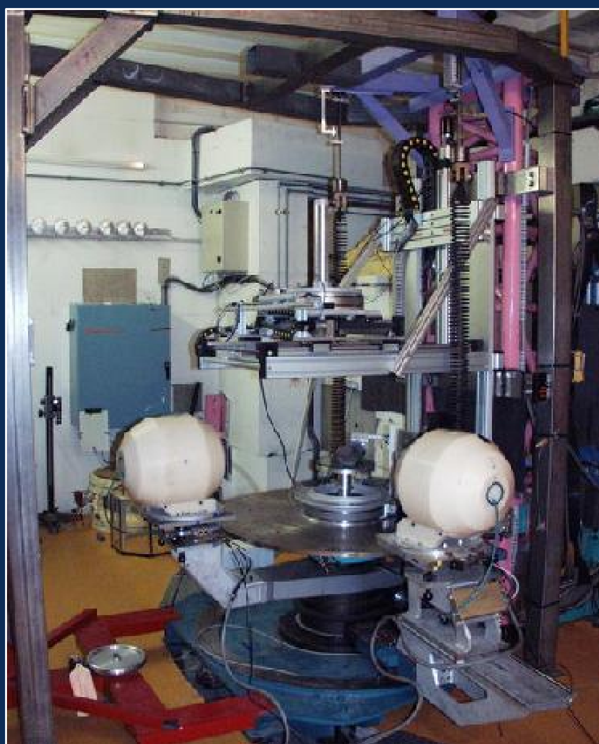
PN1 - Lohengrin : fission fragment spectrometer

PN3 - GAMS : high resolution gamma ray facility

S18 - CRG instrument

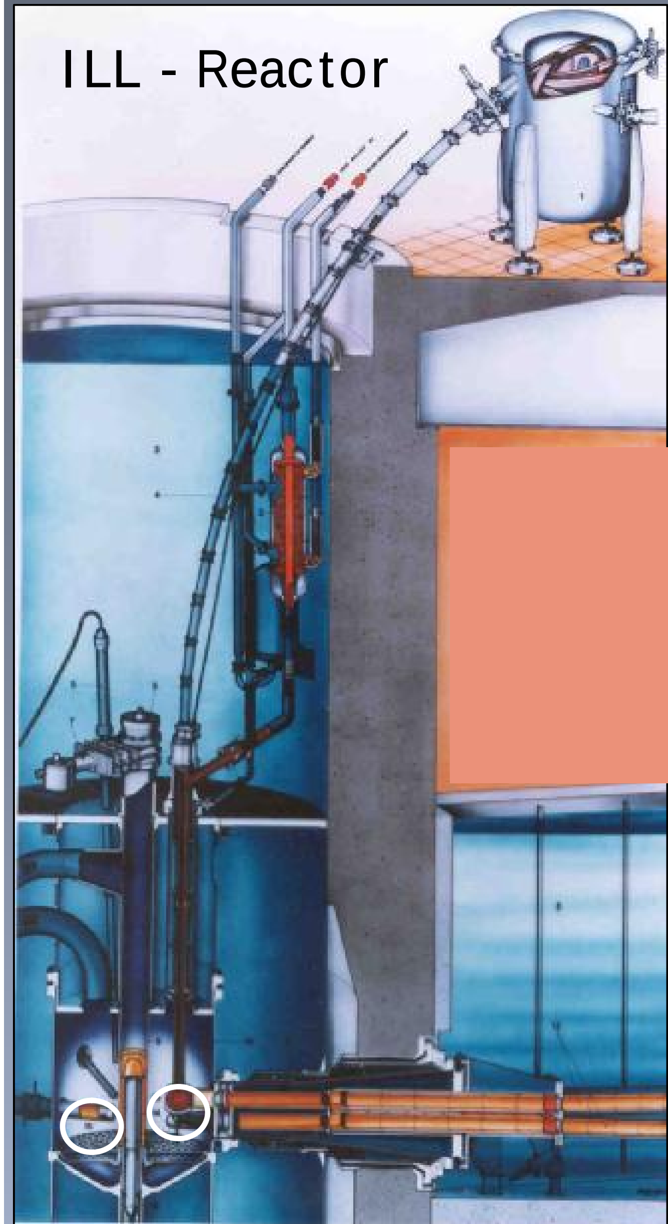
interferometer for basic neutron quantum optics

neutron scattering lengths



cryoEDM - CRG instrument

NEUTRONS FOR SCIENCE



Neutron sources at ILL

Fuel (chain reaction): $^{235}U(n_{th},f)$ à fission neutrons

Moderator: D_20 at 300K à thermal neutrons

Hot source: 10 dm^3 of graphite at 2400 K

Cold source (horizontal): 6 dm^3 of liquid D_2 at 25 K

Cold source (vertical): 20 dm^3 of liquid D_2 at 25 K

Temperature (K)	10^{-8}	10^{1}	10^{3}	
Energy (eV)	10^{-7}	10^{-3}	10^{-1}	10^{7}
Velocity (m/s)	5	800	2200	

Properties of UCN

E_{kin} (~ 5 ms^{-1}) = 100 neV (10^{-7} eV)

λ_{UCN} ~ 1000 Å

Interaction with matter:
UCN see a *Fermi-Potential* E_F

E_F ~ 10^{-7} eV for many materials, e.g.

- beryllium 252 neV
- stainless steel 200 neV

UCN are totally reflected from suitable materials at *any* angle of incidence, hence **storable**!

UCN are furthermore storable by gravity and/or magnetic fields

Long storage and observation times possible (up to several minutes)!

High precision measurements of the properties of the free neutron
(lifetime, electric dipole moment, gravitational levels, ...)

Fermi potential	~ 10^{-7} eV
Gravity $\Delta E = m_n g \Delta h$	~ 10^{-7} eV / Meter
Magnetic field $\Delta E = \mu_n B$	~ 10^{-7} eV / Tesla

The free neutron lifetime

$$\frac{1}{\tau_n} \propto G_F^2 V_{ud}^2, \; l^2 \qquad l = \frac{g_A}{g_V}$$

Together with measurements of *asymmetry coefficients* in neutron decay

Extraction of g_V, g_A and V_{ud}

Test of *Conserved Vector Current* (CVC: 'g_V' = 1)

Test of *Unitary of CKM* matrix ($V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$)

Weak interaction theory

Neutrino physics

Cosmology

Solar pp-process:

$$p + p \rightarrow d + e^+ + n_e \qquad s \propto g_A$$

Big bang:

Primordial elements' abundances

Neutrino induced reactions:

$$\bar{n}_m + p \rightarrow m^+ + n$$

Neutrino detectors:

$$p + \bar{n}_e + n \rightarrow n + e^+$$

$$s \propto \frac{1}{t_n}$$

Important input parameter for tests of the Standard Model of the weak interaction

Necessary to understand matter abundance in the Universe

Necessary to calibrate Neutrino Detectors and to predict event rates

V. Morozov (RRC Kurchatov Inst.) et al., Phys. Lett. B 483 (2000) 15-22

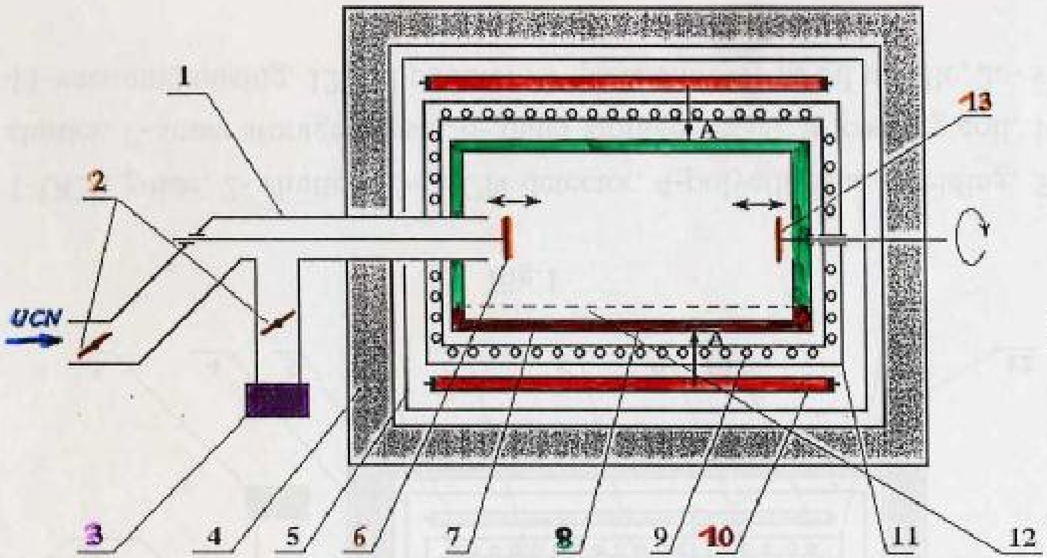


Fig.1

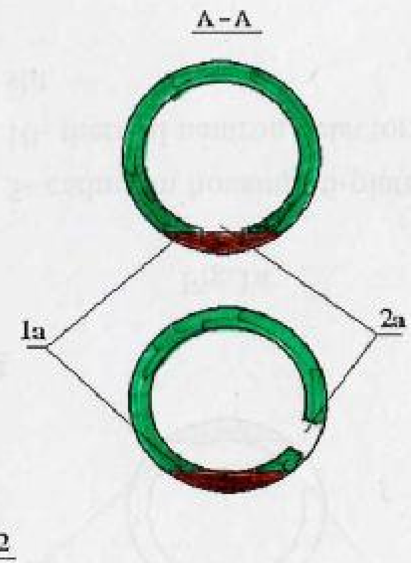


Fig.1a

Fomblin lake 3.5 ℓ

refresh surface once per day

1-UCN guide, 2- shutters, 3- UCN detector, 4-polyethylene shielding, 5- cadmium housing, 6-plate shutter, 7- inner storage vessel, 8- outer storage vessel, 9- cooling coil, 10- thermal neutron detector, 11-vacuum housing, 12- oil puddle, 13- plate shutter, 1a-oil puddle, 2a- slit.

$V_i = 65\ \ell$, Al 2 mm thick; ∅ 33 cm, ℓ = 90 cm

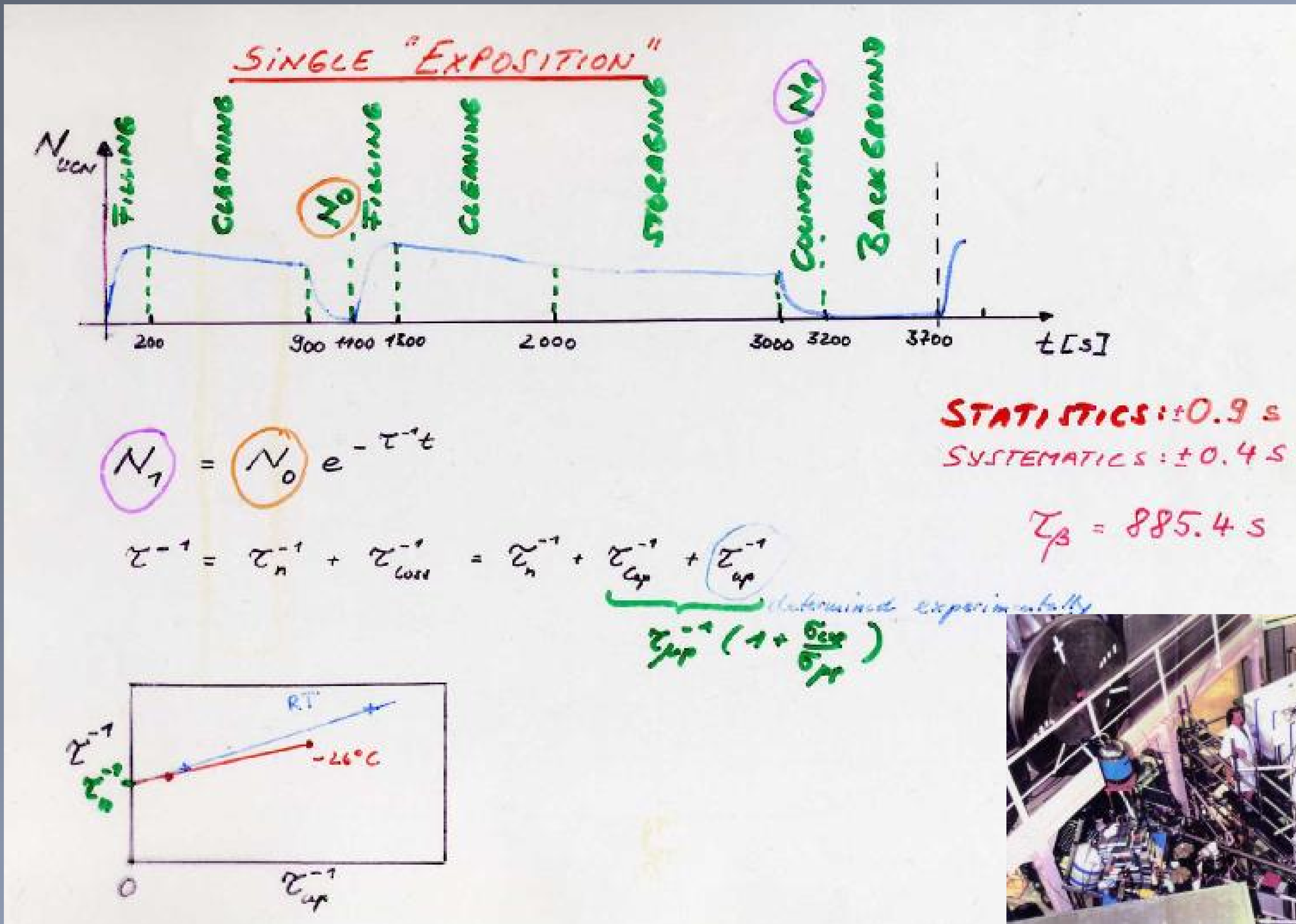
+2.5 cm

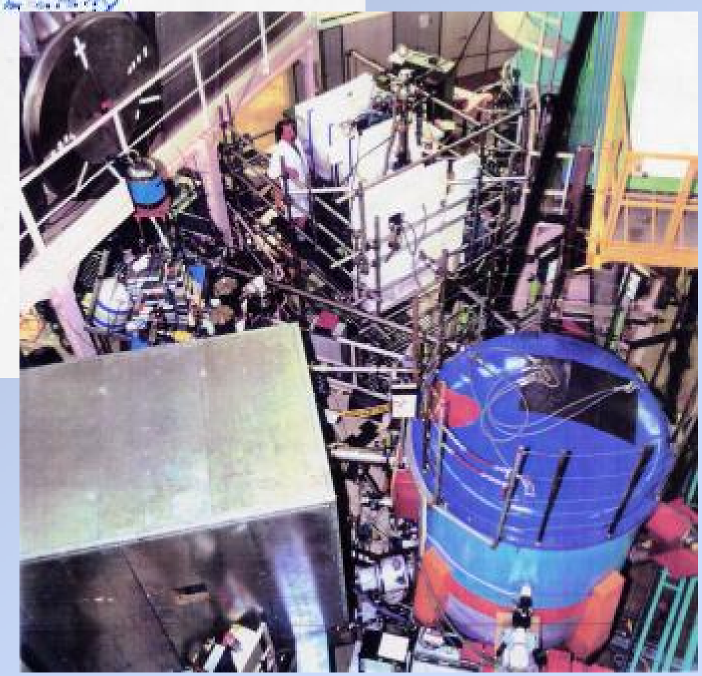
$V_o = 20\ \ell$

@ Room Temperature

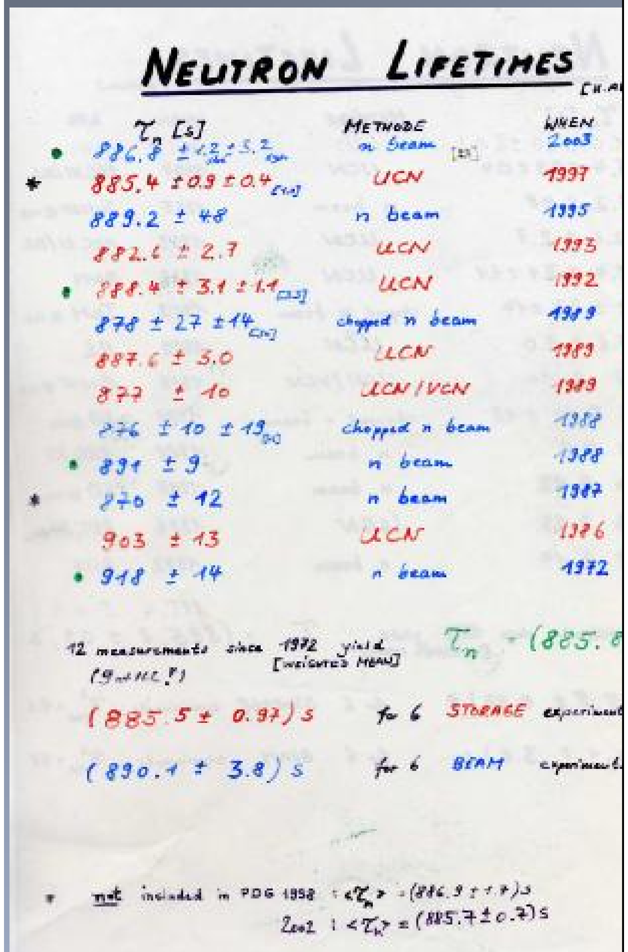
-9°C

-26°C


SINGLE "EXPOSITION"
N_{UCN}
FILLING
CLEANING
N_0
FILLING
CLEANING
STORAGING
COUNTING N_1
BACKGROUND
200
900
1100
1200
2000
3000
3200
3700
t [s]
STATISTICS: ±0.9 s
SYSTEMATICS: ±0.4 s
τ_β = 885.4 s
$N_1 = N_0 e^{-\tau^{-1} t}$
$\tau^{-1} = \tau_n^{-1} + \tau_{loss}^{-1} = \tau_n^{-1} + \tau_{cap}^{-1} + \tau_{up}^{-1}$
determined experimentally
$\tau_{cap}^{-1} = \tau_{\mu p}^{-1}\left(1 + \frac{\sigma_{cap}}{\sigma_{\mu p}}\right)$
τ^{-1}
τ_n^{-1}
R.T.
-26°C
0
τ_{up}^{-1}



Results of neutron lifetime experiments



NEUTRON LIFETIMES

τ_n [s]	METHODE	WHEN
• 886.8 ± 1.2 ± 3.2	n beam	2003
* 885.4 ± 0.9 ± 0.4	UCN	1997
889.2 ± 4.8	n beam	1995
882.6 ± 2.7	UCN	1993
• 888.4 ± 3.1 ± 1.1	UCN	1992
878 ± 27 ± 14	chopped n beam	1989
887.6 ± 3.0	UCN	1989
877 ± 10	UCN / VCN	1989
876 ± 10 ± 19	chopped n beam	1988
• 891 ± 9	n beam	1988
* 870 ± 12	n beam	1987
903 ± 13	UCN	1986
• 918 ± 14	n beam	1972

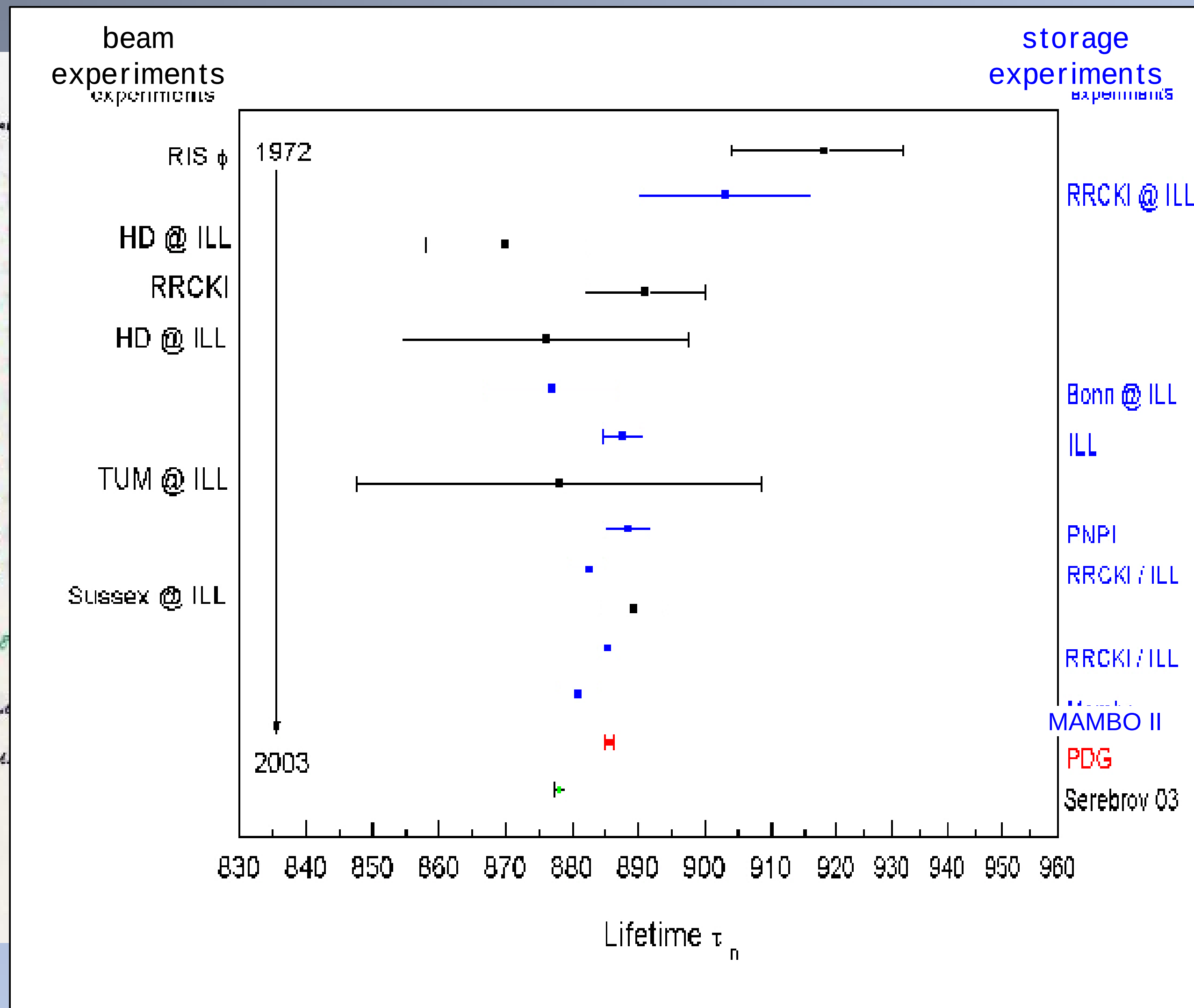
12 measurements since 1972 yield [weighted mean] τ_n = (885.[illegible]

(885.5 ± 0.97) s for 6 STORAGE experiments

(890.1 ± 3.8) s for 6 BEAM experiments

* not included in PDG 1998 : $\langle\tau_n\rangle$ = (886.7 ± 1.9) s

2002 : $\langle\tau_n\rangle$ = (885.7 ± 0.7) s



Neutron lifetime experiment with gravitational trap and with low temperature fomblin (LTF) coating

A.Serebrov [1,3], V.Varlamov [1], A.Kharitonov [1], A.Fomin [1], Yu.Pokotilovskii [2], P.Geltenbort [4], J.Butterworth [4], I.Krasnoschekova [1], M.Lasakov [1], K.Schreckenbach [5], R.Taldaev [1], A.Vassiljev [1], O.Zherebtsov [1]

[1] Petersburg Nuclear Physics Institute, Russia
[2] Joint Institute of Nuclear Research, Russia
[3] Paul Scherrer Institut, Switzerland
[4] Institute Max von Laue – Paul Langevin, France
[5] TU Munchen, Germany

Method of n-lifetime measurement

Total probability of UCN losses:

$$l_{tot} = l_n + l_{wall} + l_{other}$$

l_{other} ° $\mathbf{0}$ **(discussed later)**

probability of losses in trap walls: $l_{wall} = hg$

$$h = -\frac{\mathrm{Im}(V_F)}{\mathrm{Re}(V_F)}$$ **- wall loss coefficient**

g **- loss weighted wall collision frequency**

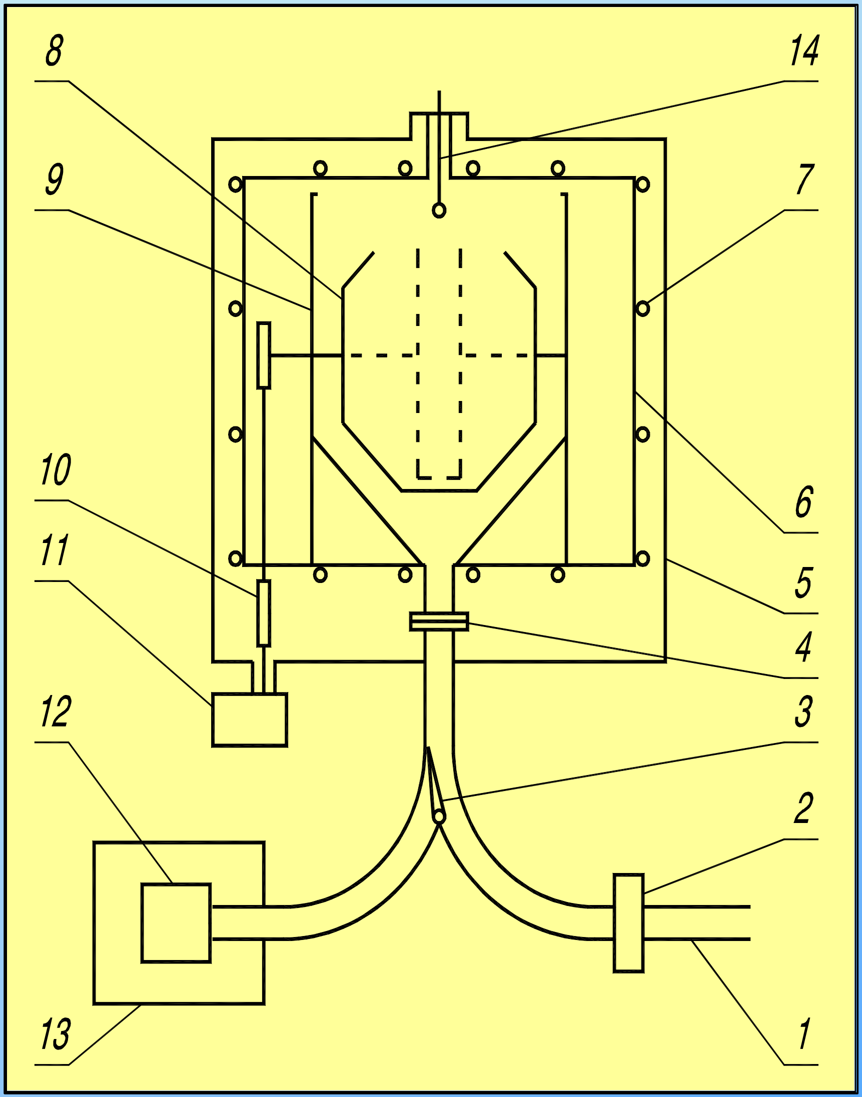
$$\begin{cases} l_{tot}^{(1)} = l_n + hg^{(1)} \\ l_{tot}^{(2)} = l_n + hg^{(2)} \end{cases} \Rightarrow \quad l_n = l_{tot}^{(1)} - \frac{l_{tot}^{(2)} - l_{tot}^{(1)}}{\frac{g^{(2)}}{g^{(1)}} - 1}$$

Plan of n-lifetime measurement in steps:

- **Measurement of** $l_{tot}^{(1)}$ **and** $l_{tot}^{(2)}$
- **Calculation of** $g^{(1)}$ **and** $g^{(2)}$
- **Extrapolation to n-lifetime (wall loss coefficient is the slope of extrapolation line)**

Using 2 traps we can reduce considerably an influence of some systematic errors on n-lifetime result, because l_n **depends only on ratio** $g^{(2)}$ **to** $g^{(1)}$

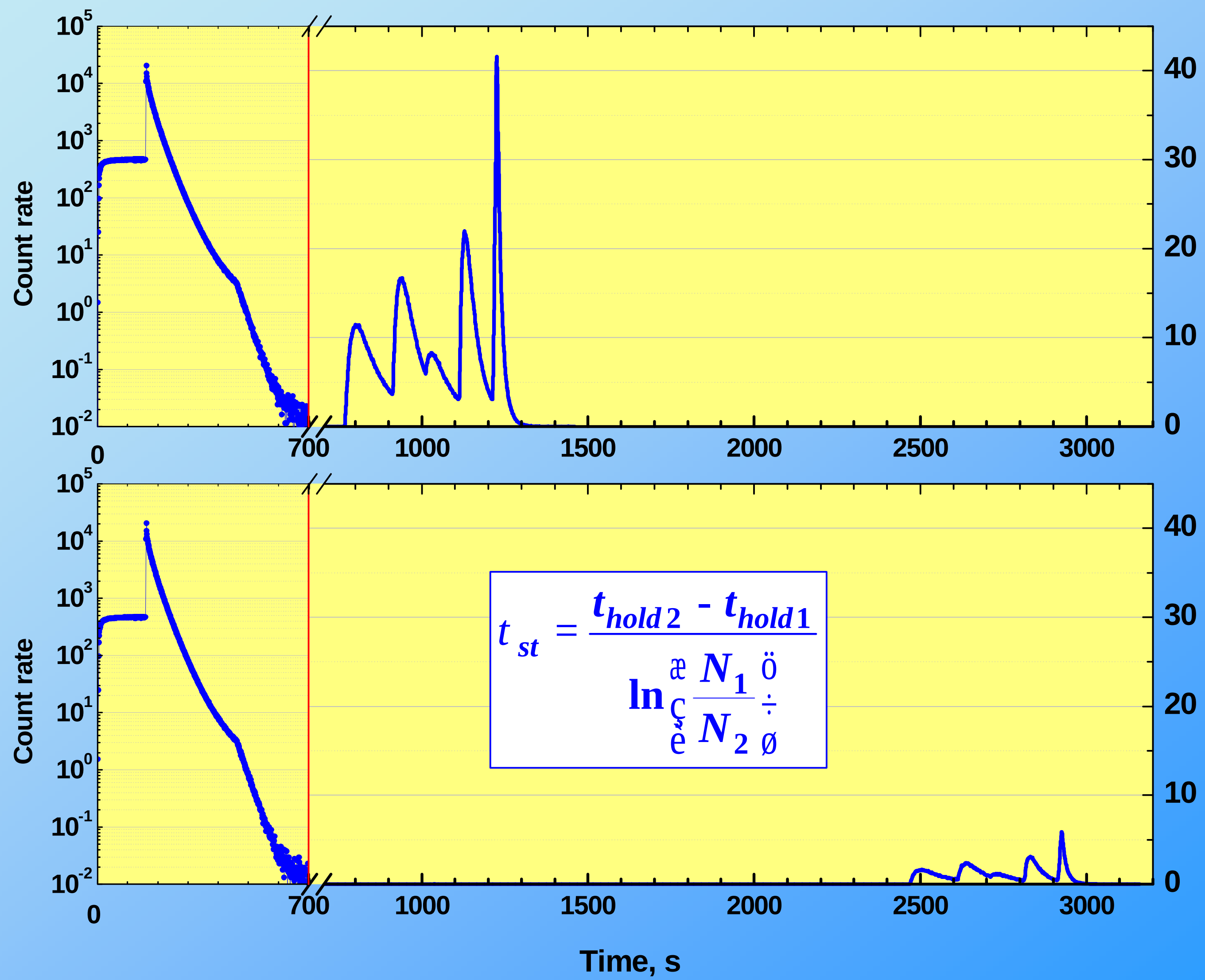
Scheme of “Gravitrap”, the gravitational UCN storage system



1 – neutron guide from UCN Turbine;
2 – UCN inlet valve;
3 – beam distribution flap valve;
4 – aluminium foil (now removed);
5 – “dirty” vacuum volume;
6 – “clean” (UHV) vacuum volume;
7 – cooling coils;
8 – UCN storage trap;
9 – cryostat;
10 – mechanics for trap rotation;
11 – stepping motor;
12 – UCN detector;
13 – detector shielding;
14 – evaporator

Setup for the measurement of n-lifetime at ILL (Grenoble, France)

Time diagram of measuring cycle

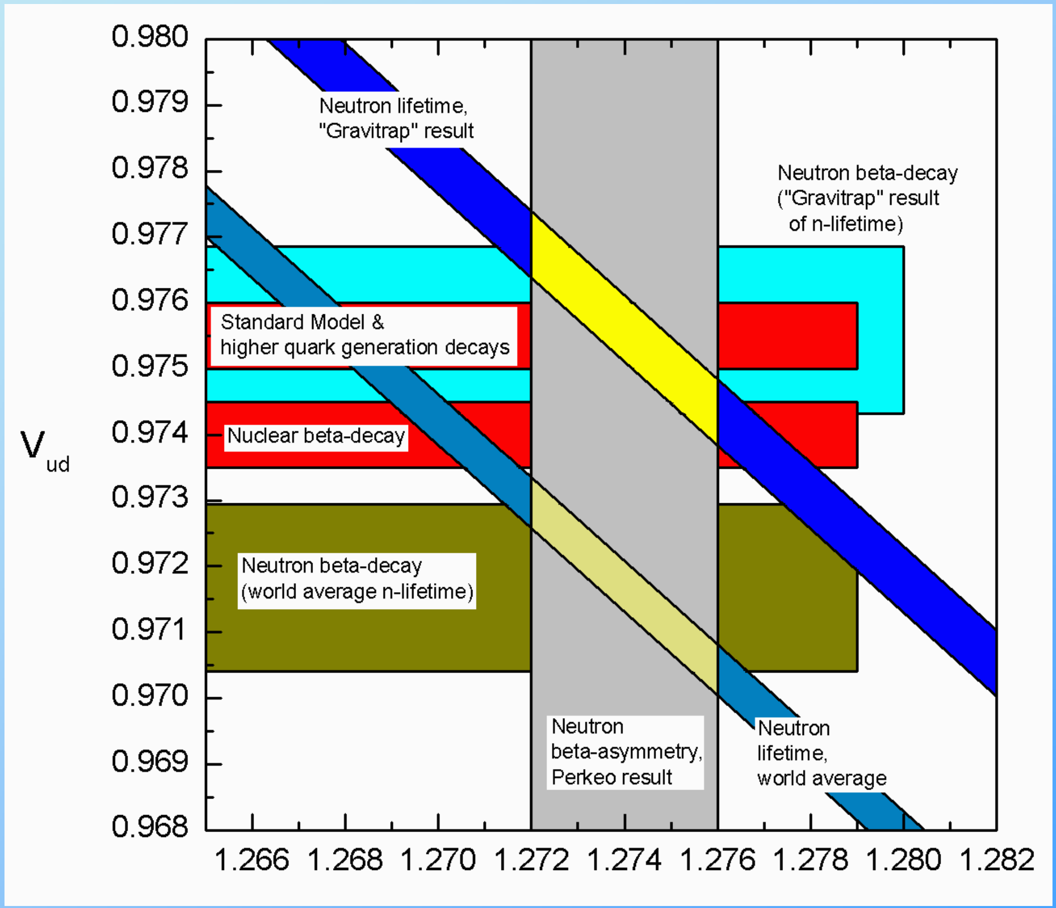


Final result and list of systematic corrections and uncertainties

Size extrapolation	Value,s	Uncertainty, s
n-lifetime	878,07	0,73
Systematic effect	**Value,s**	**Uncertainty, s**
Method of g values calculation	0	0,236
Influence of mu-function shape	0	0,144
Spectrum uncertainties	0	0,104
Uncertainties of traps sizes(1mm)	0	0,058
Influence of the residual gas	0,40	0,024
Uncertainty of LTF critical energy (20 neV)	0	0,004
Total systematic effect	0,40	0,30

$$t_n\,[s] = 878.5 \pm 0.7_{stat} \pm 0.3_{syst}$$

Test of Standard Model



$$\lambda = \frac{G_A}{G_V}$$

The new result is in agreement with Standard Model

NEUTRON LIFETIME EXPERIMENT BASED ON AN 'ACCORDION-LIKE' UCN STORAGE VOLUME COATED WITH 'LOW TEMPERATURE FOMBLIN'

B. Yerozolimsky[1], A. Steyerl[2], O. Kwon[2], V. Luschikov[3], E. Lychagin[3], A. Muzychka[3], A. Strelkov[3], P. Geltenbort[4], N. Achiwa[5], A. Pichlmaier[6], P. Fierlinger[6]

[1] Harvard University, Cambridge, MA, USA; [2] University of Rhode Island, Kingston, RI, USA; [3] Joint Institute for Nuclear Research, Dubna, Russia; [4] Institut Laue Langevin, Grenoble, France; [5] Osaka University, Japan; [6] Paul Scherrer Institut, Villigen, Switzerland

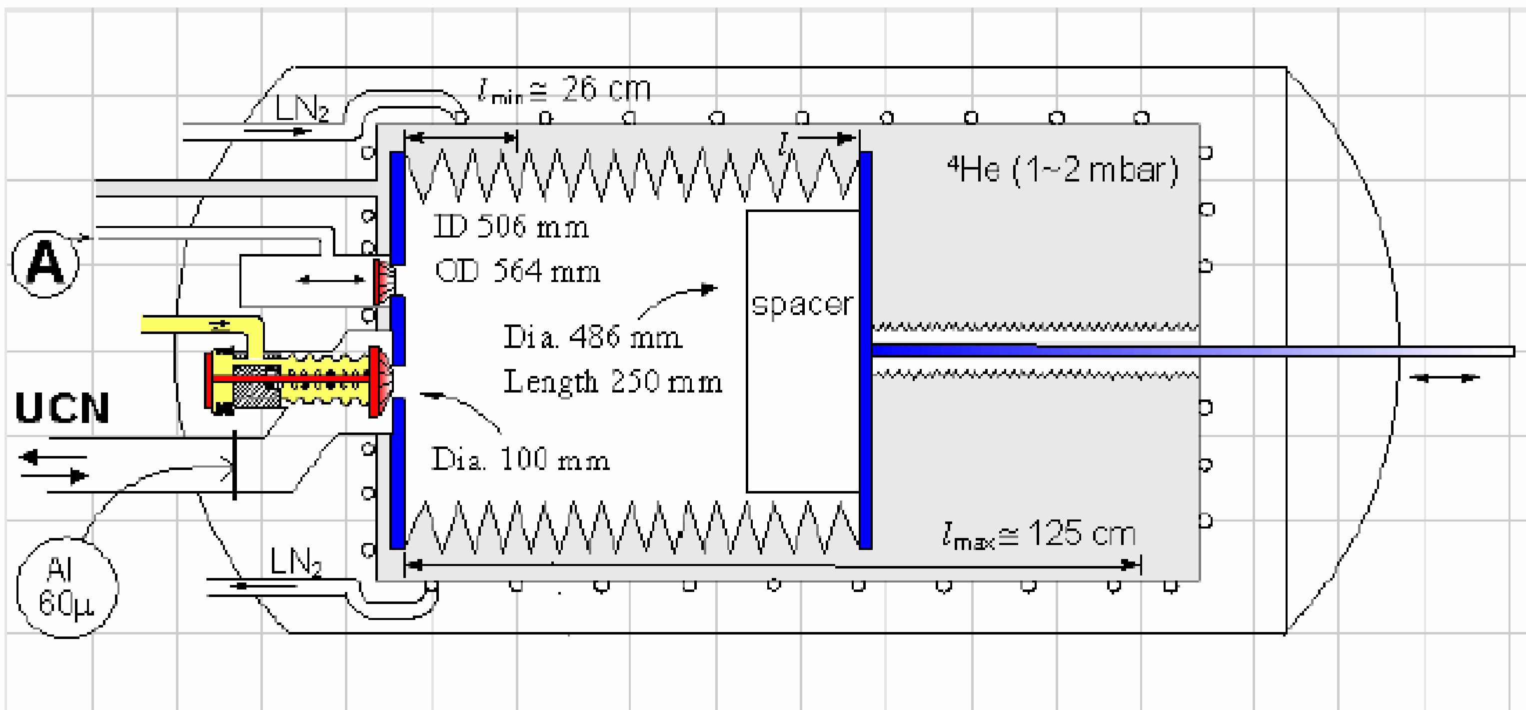


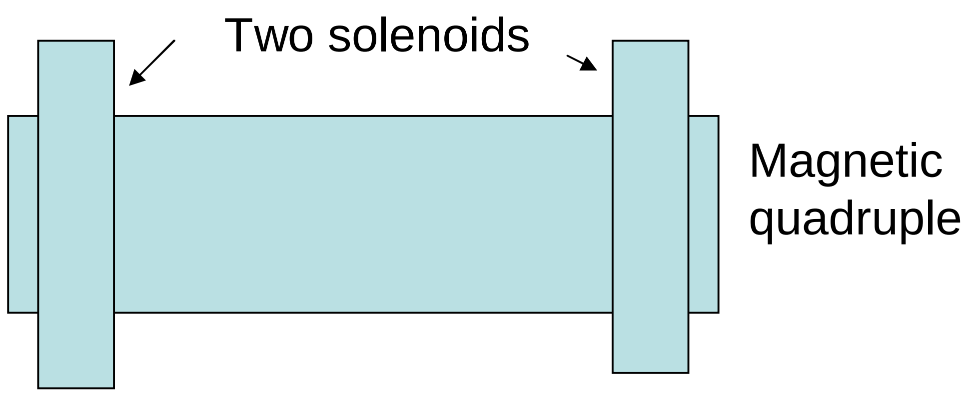
Fig. 1: Schematic view of the "accordion" system. It contains a UCN trap whose surface area remains constant while the volume is changeable by a factor 27. The inner surface will be coated with 'Low Temperature Fomblin' at temperatures in the range from 100-220 K to provide a low-loss UCN storage system for a neutron lifetime measurement.

UCN storage in the magnetic trap from permanent magnets

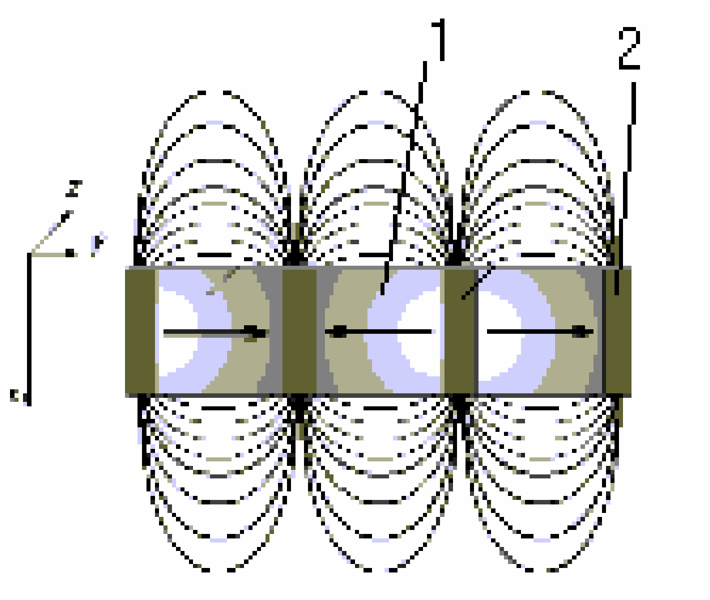
- V.F.Ezhov,[1] B.A.Bazarov,[2] P.Geltenbort,[3] F.J.Hartman,[4] N.A.Kovrizhnykh,[5] I.S.Altarev, [4] A.Z.Andreev, [1] A.A.Glushkov, [1] A.G.Glushkov, [1] M.G.Groshev, [1] V.A.Knyazkov, [1] G.D.Krygin, [1] S.Paul, [4] R.Picker, [4] V.L.Ryabov, [1] A.P.Serebrov, [1] O.Zimmer[4]
- 1 Petersburg Nuclear Physics Institute, Gatchina, Russia.
- 2 Research Center "Domen", S-Petersburg, Russia.
- 3 Institut Laue-Langevin, Grenoble, France.
- 4 Technical University, Munich, Germany.

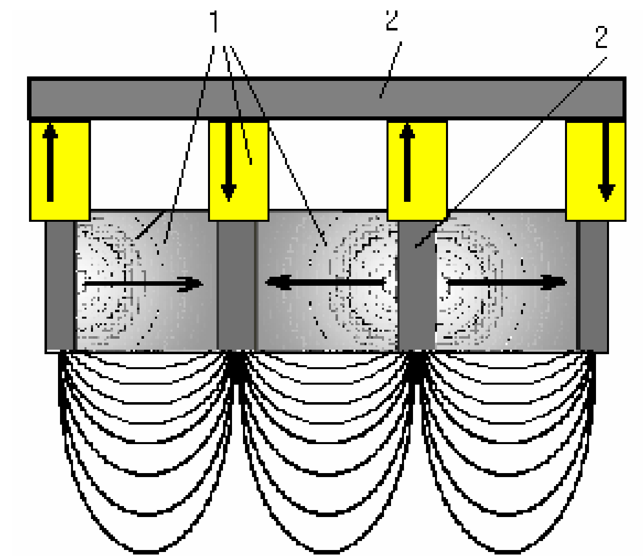
- The first "real" magnetic trap for neutrons was tested in the eighties at the ILL by W. Paul, F. Anton, L. Paul, S. Paul and W. Mampe, Z. Phys. C45, 25, 1989

  This trap used a superconducting ring from sixpoles magnets
- It was not possible at that time and even nowadays is not easy to change the current in the magnetic entrance shutter of such superconducting systems with a speed needed for the lifetime measurements
- Hence a complicated experimental setup was used to produce UCN inside the trap (P.R. Huffman *et al.,* Nature 403, 62, 2000), using inelastic scattering of neutrons in superfluid He (Ioffe-Pritchard trap)

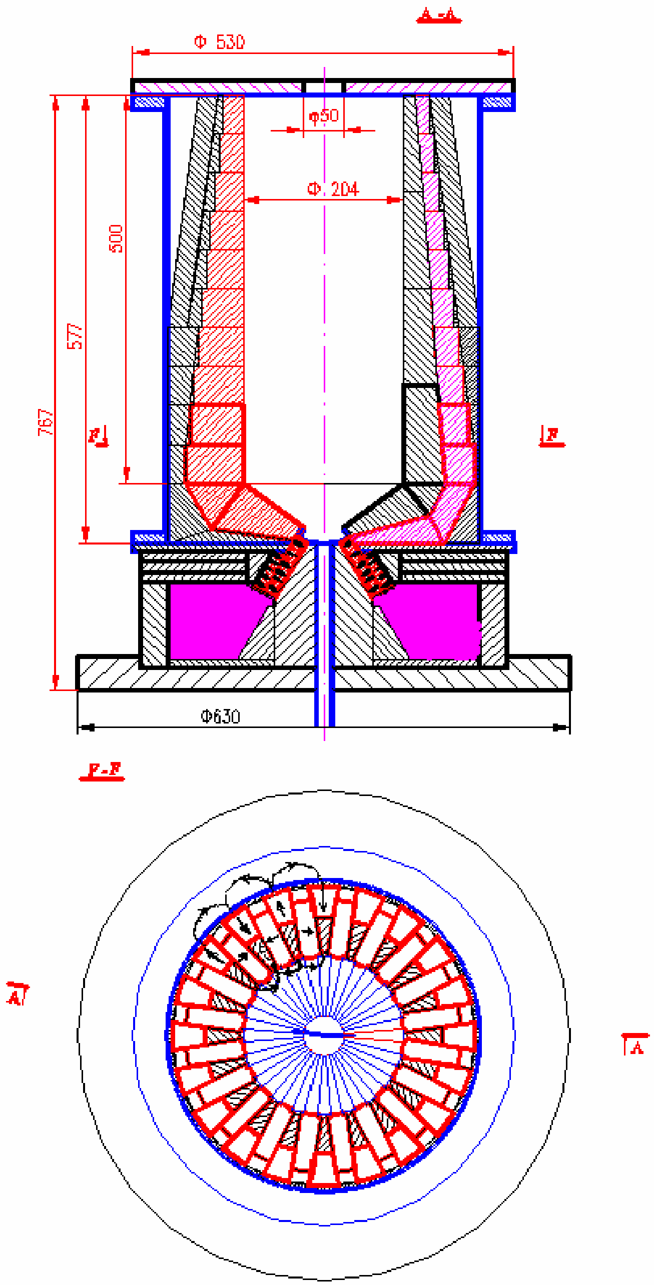


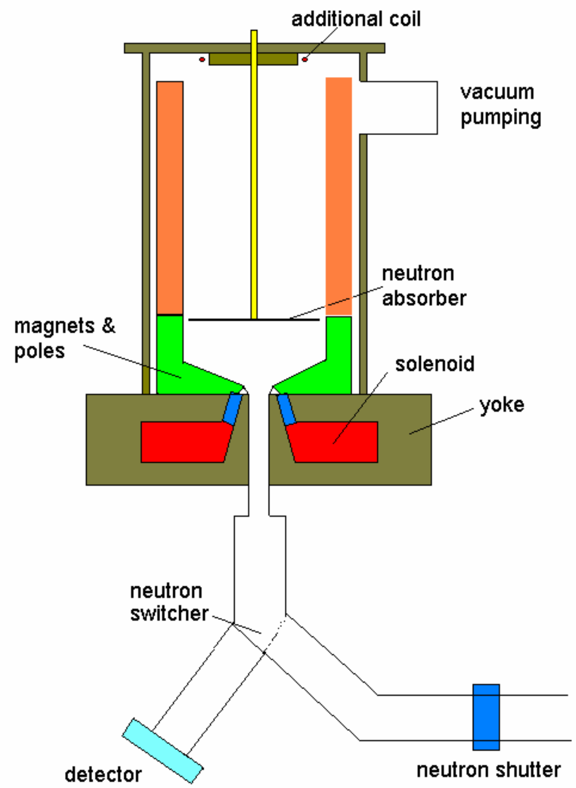
Magnetic wall





1 – permanent magnet
2 – magnetic field guide





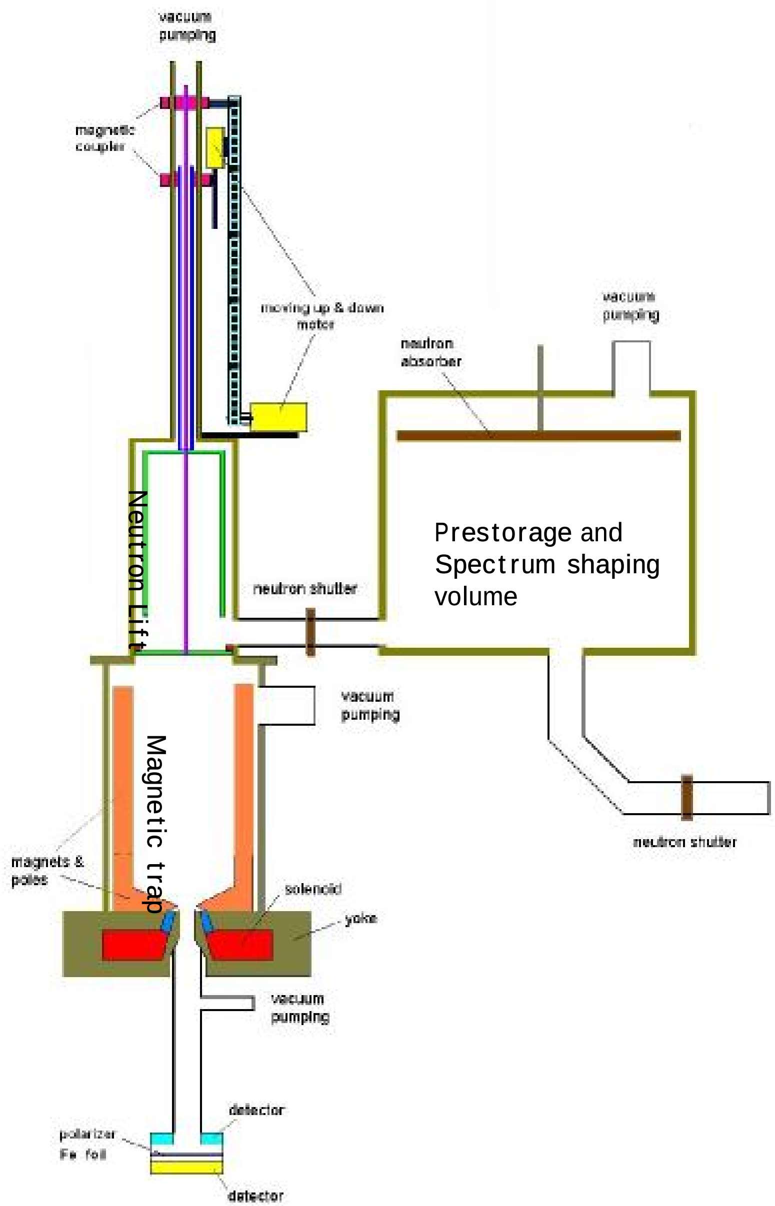
MAGNETIC TRAP FROM PERMANENT MAGNETS

- The trap walls consist of a periodic structure with a characteristic period of ~1cm. The magnetic field decreases quite fast (gradient ~ 2 T/cm).
- The UCN are transferred to the trap through a neutron guide inside the solenoid at the bottom. After loading the trap this entrance is closed by switching on the current in the solenoid. To facilitate fast operation we use a normal-conducting solenoid with iron core and permanent magnets.
- UCN with energies exceeding the solenoid magnetic barrier will penetrate the barrier and disappear. Thus changing the current in the solenoid easily modifies the spectrum of trapped UCN.
- By applying a magnetic barrier at the entrance during trap loading, the spectrum may be cut from the low-energy side. This flexibility in the choice of the UCN spectrum is very useful for eliminating systematic errors in the neutron lifetime measurement.
- To avoid UCN depolarization at the points of zero magnetic fields we use the field generated by the lower solenoid, which is orthogonal to the magnetic field from the permanent magnets. For this purpose an iron yoke guides the magnetic field from the solenoid to the top of the trap.
- To control the depolarization of UCN we can cover the inner trap walls with thin nickel foil that reflects depolarized UCN. In this case the depolarized UCN penetrate the magnetic barrier inside the solenoid and are measured by the UCN detector installed below the solenoid. Hence this detector may be used as monitor for depolarization losses during neutron storage.

Storage time for lower part (height: 15 cm): 882 ± 16 s

Storage time for medium part (height: ?? cm): 878 ± 6 s

	Existing lower part of trap	Upper part of trap	Trap of larger diameter
Volume (l)	3.6	15.6 (7)	62.4
Neutrons after 50 sec of cleaning time	62.6±2.0	1770±11	7000
Neutron density after 50 sec of cleaning time	0.017 n/cm3	0.11 n/cm3	0.11 n/cm3
Accuracy of lifetime measuring	16 sec in 6 days	3.1 sec in 6 days (10 s in 4 days)	1.6 sec in 6 days



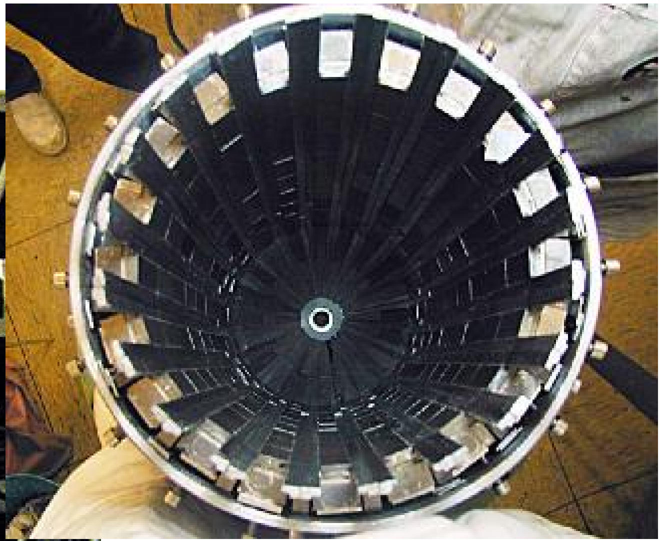
Modified

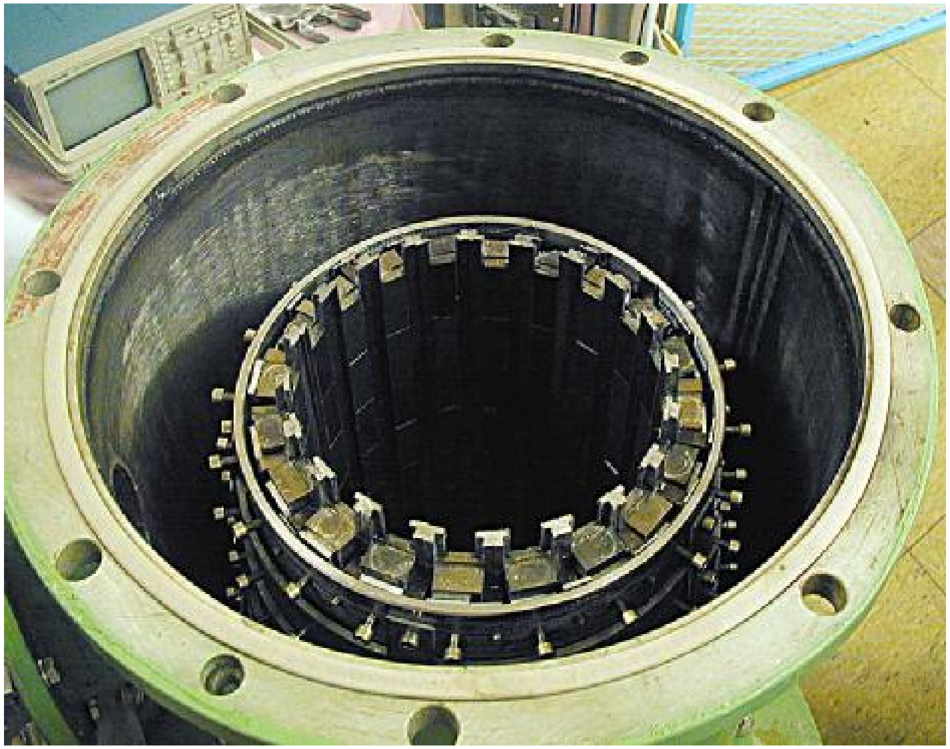
Experimental set-up

for the next run in April 2005

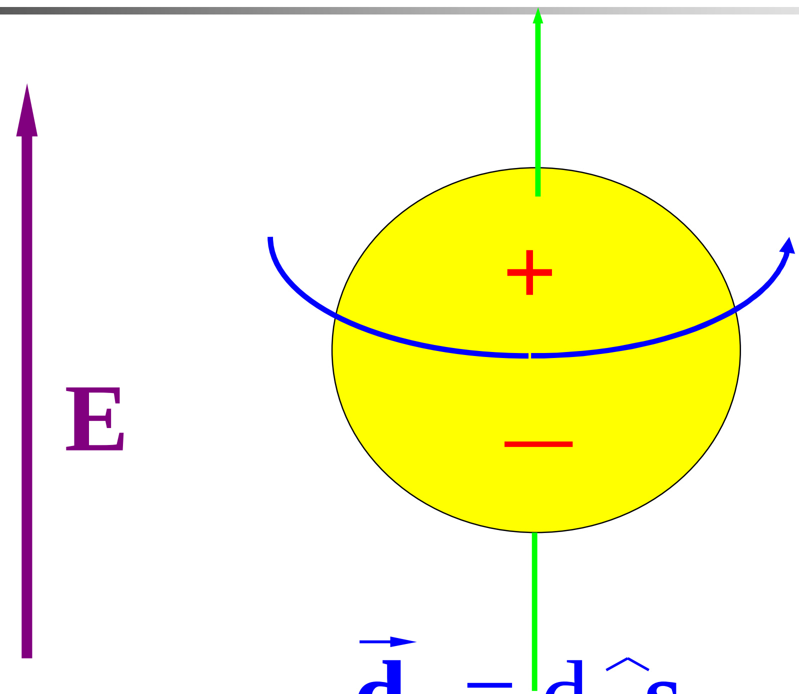
So in order to cut the spectrum of stored neutrons an additonal titanium absorber was installed inside the trap. After 400 s of cleaning the absorber was lifted up. This absorber works well (i.e. there are many collisions of neutrons with its surface) if its diameter is larger than the distance between absorber and trap bottom. Otherwise the number of neutron collisions with the absorber are decreased drastically. In our case the ratio of trap height to diameter is 2.8. As a result only half of trap height can be used effectively. The absorber was placed only at the height of 25 cm above trap bottom This resulted in an effective volume of the trap of only 7 dmi instead of possible 16 dmi. In this case the statistical error was decreased to 10 s in a four-day run. The measured storage time in such trap was 878±6 s. By searching for an increase of the background counts in the detector during storage we were able to detect leaked neutrons. Our measured leakage time is 24100±1400 s. These statistical errors were obtained during 10 days in 243 runs. We did not see any losses in our trap at the given level of accuracy. Nevertheless we treat our result as the low limit to the neutron lifetime. In order to estimate the upper limit we have to perform analogous measurement with different energy spectra of the trapped neutrons.

ATTENTION!   your fingers ….





What's an EDM?



$$\vec{\mathbf{d}}_n = d_n \hat{\mathbf{s}}$$

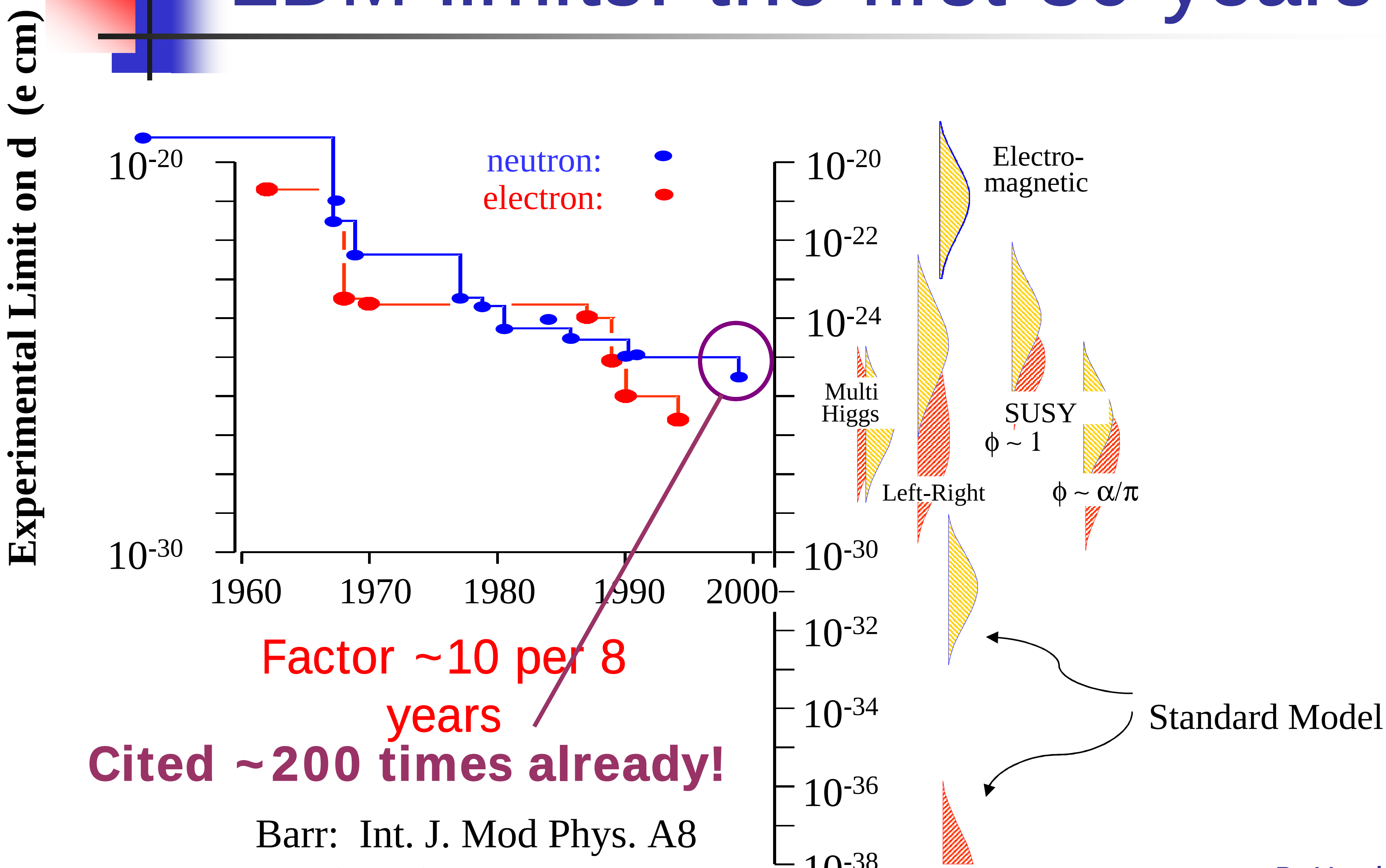
- EDMs are
  - P odd
  - T odd

and therefore CP violating.

- New insight to CP violation and to physics beyond the standard model

P. Harris
University of Sussex

EDM limits: the first 50 years



Factor ~10 per 8 years

Cited ~200 times already!

Barr: Int. J. Mod Phys. A8 208 (1993)

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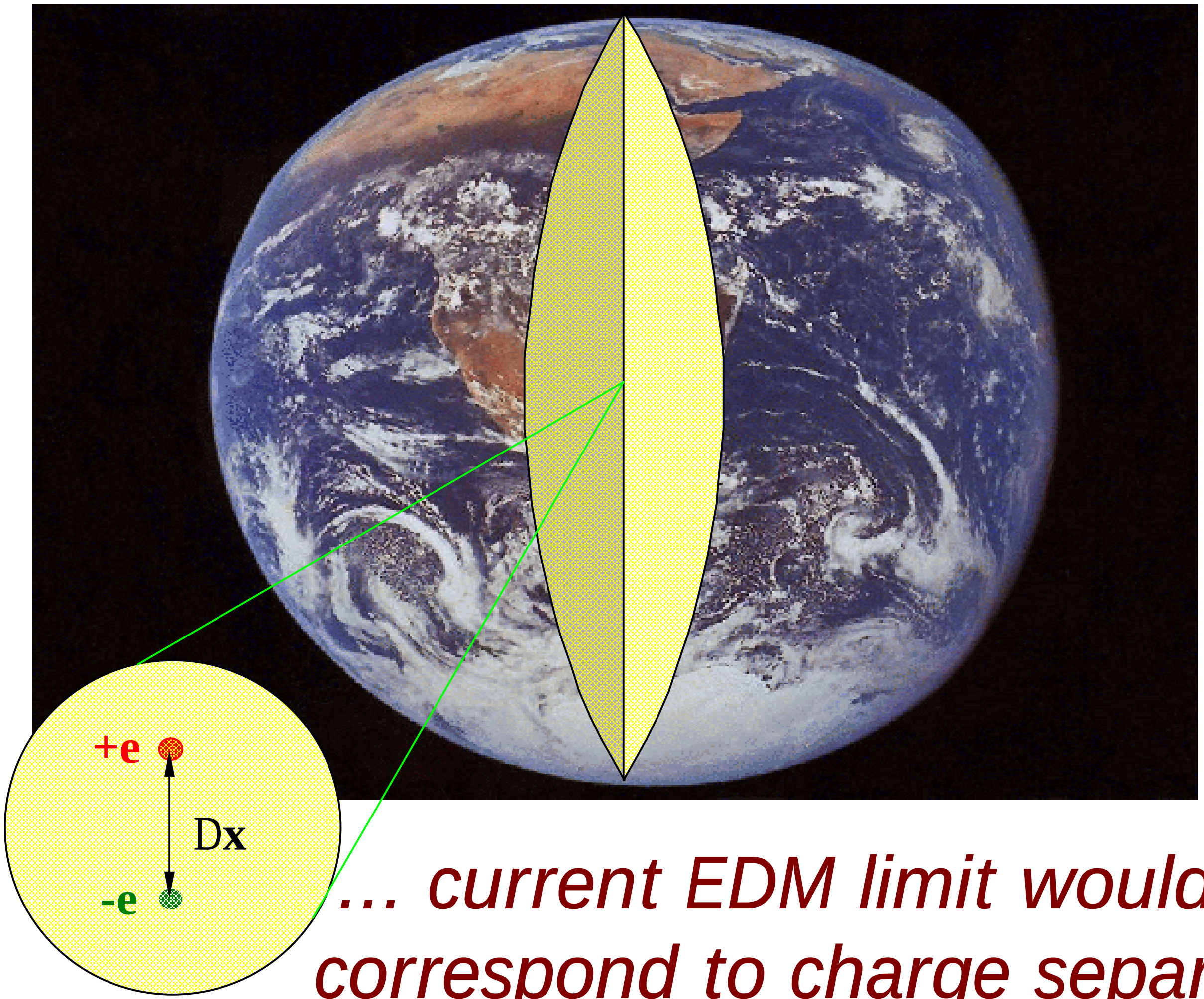
University of Sussex

Reality check

If neutron were the size of the Earth…

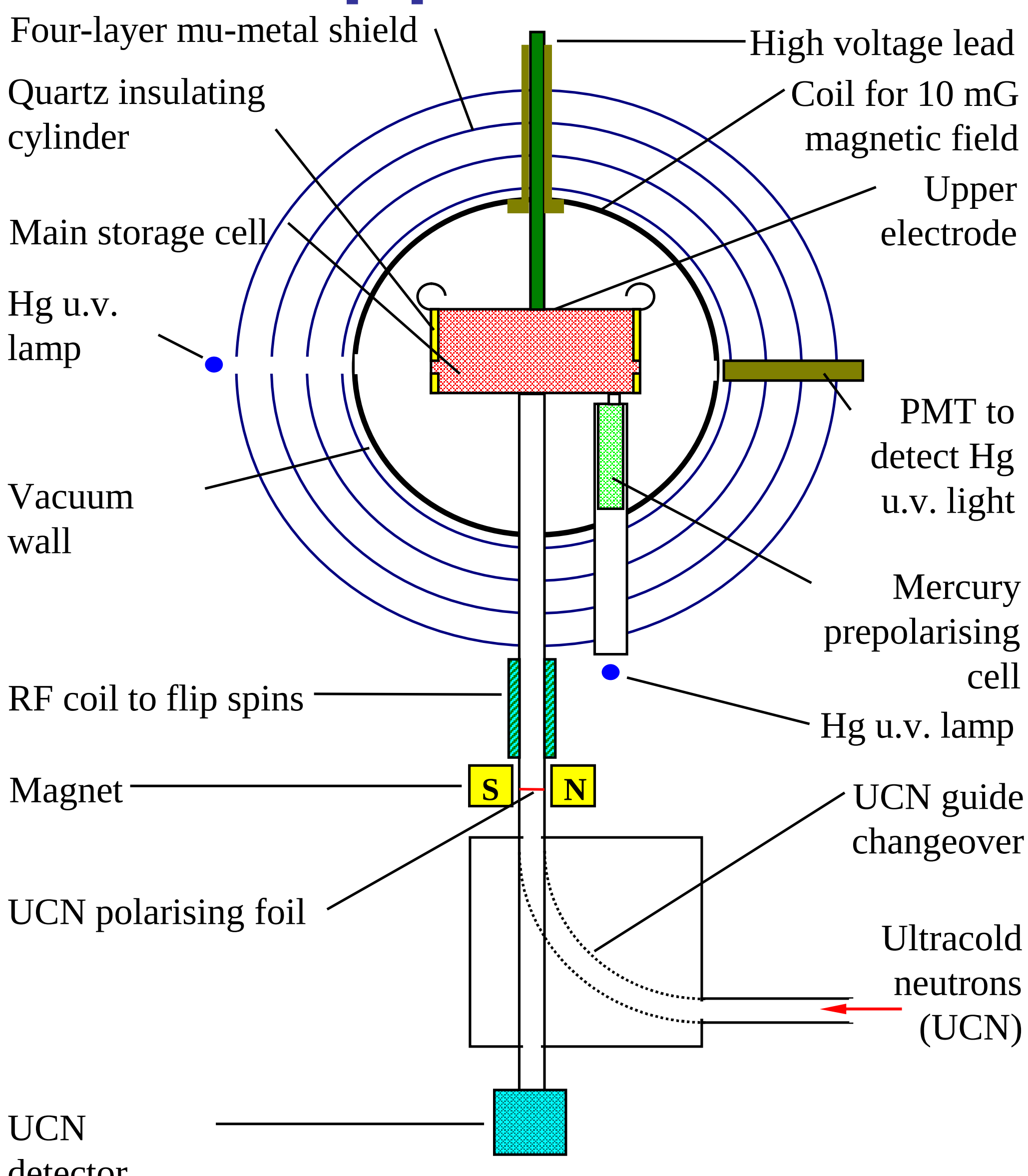


… current EDM limit would correspond to charge separation of

Dx » 10m

P. Harris
University of Sussex

nEDM apparatus



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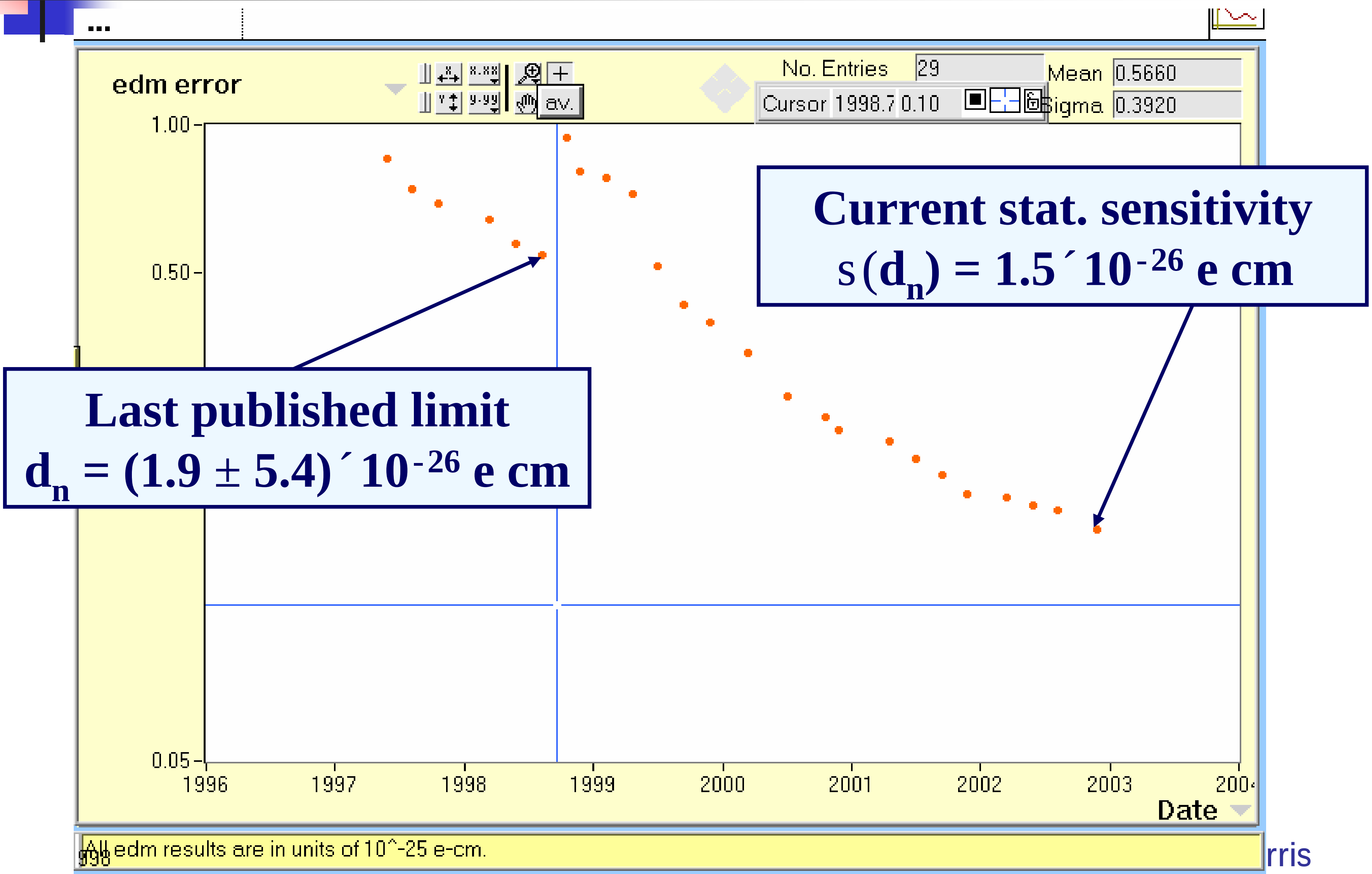
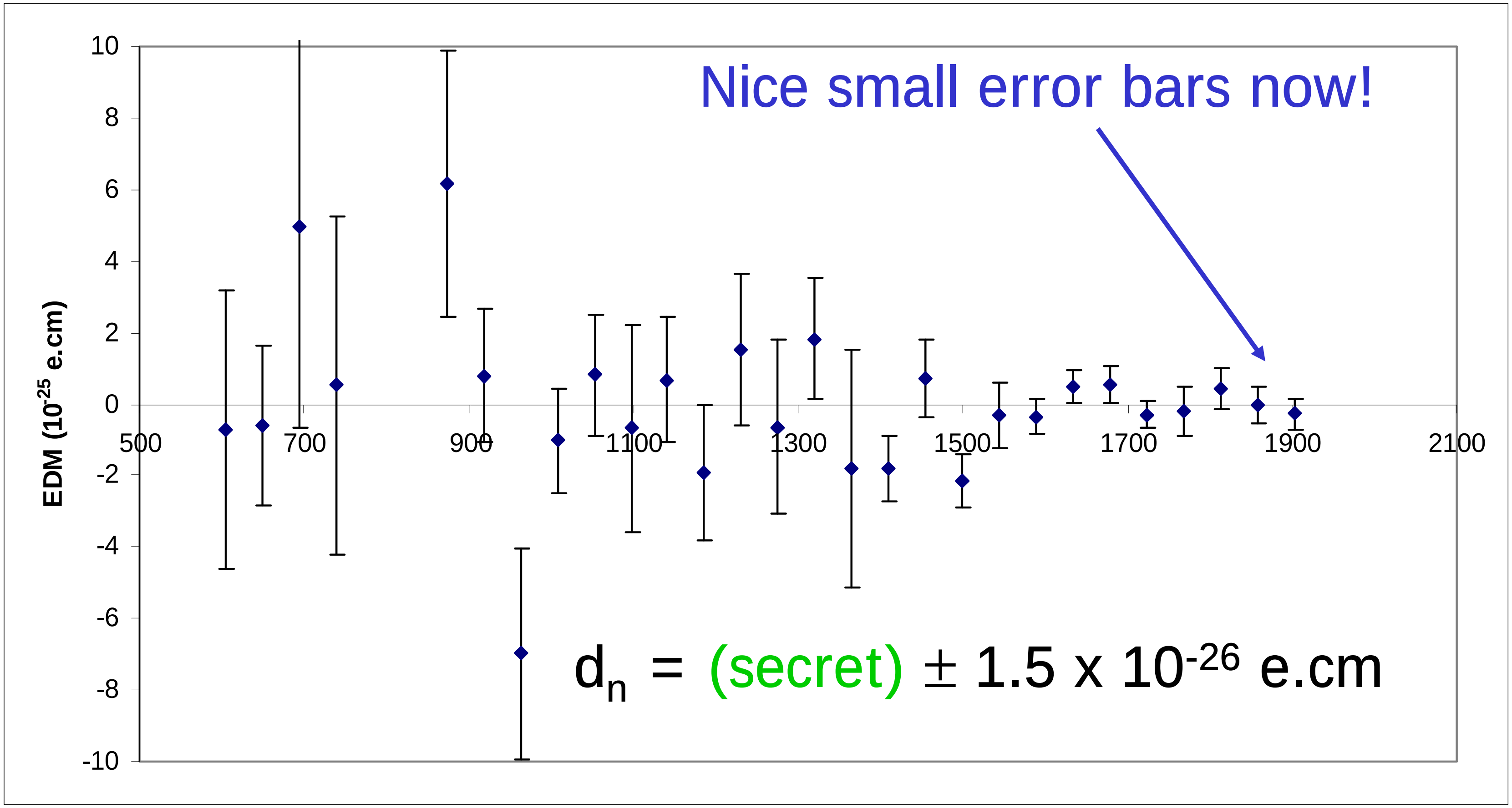
University of Sussex

Neutron EDM sensitivity



rris
University of Sussex

Neutron EDM results (binned)

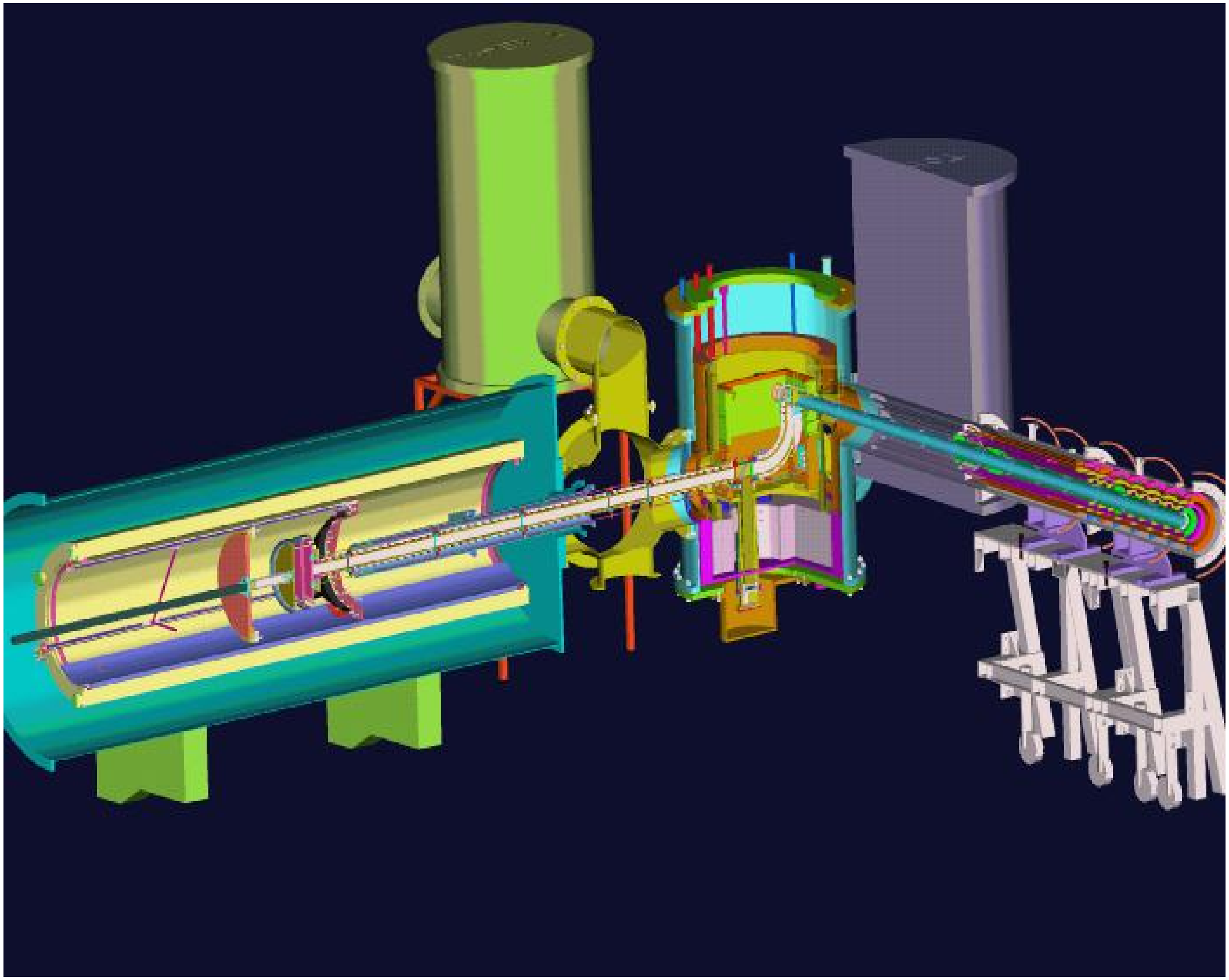


P. Harris
University of Sussex

cryoEDM apparatus as planned for the ILL

A CAD overview of the apparatus as now planned for the ILL.

On the right is Cooling Tower II, which supplies superfluid LHe to the entire neutron volume, over Phase I of the new cryostat construction. On the left are the large magnetic shields surround the Ramsey cell, behind which is Cooling Tower I which supplies the cooling power to the shields. Next to Tower I is Phase II of the cryostat, which contains the UCN transfer section and the vertical detector section. Between the shields and Phase II is the 6-way cryogenic section needed for access and construction and in which we will mount the SQUIDs



Quantum states of neutrons in the gravitational field

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(17 January 2002)

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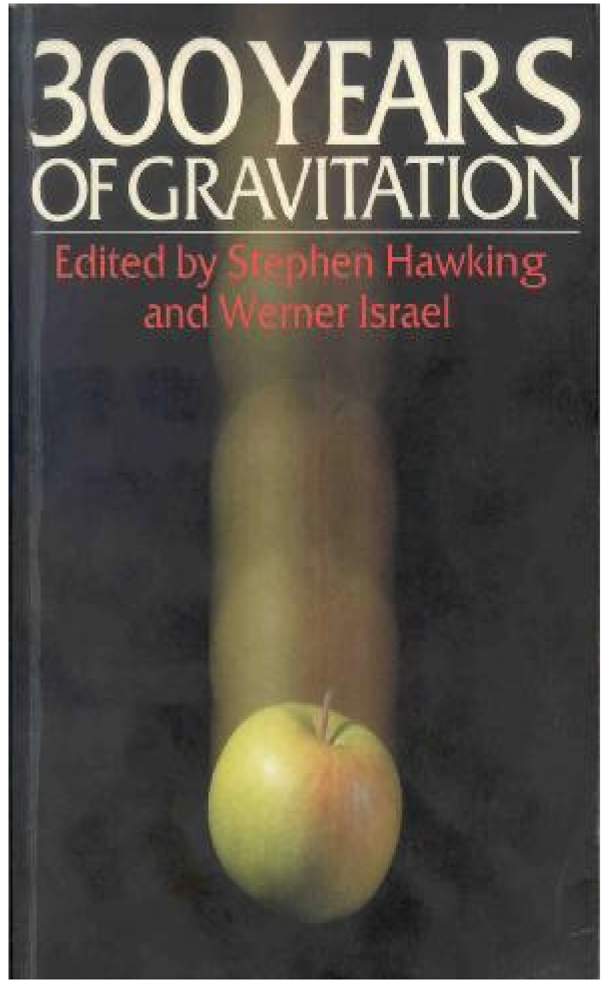
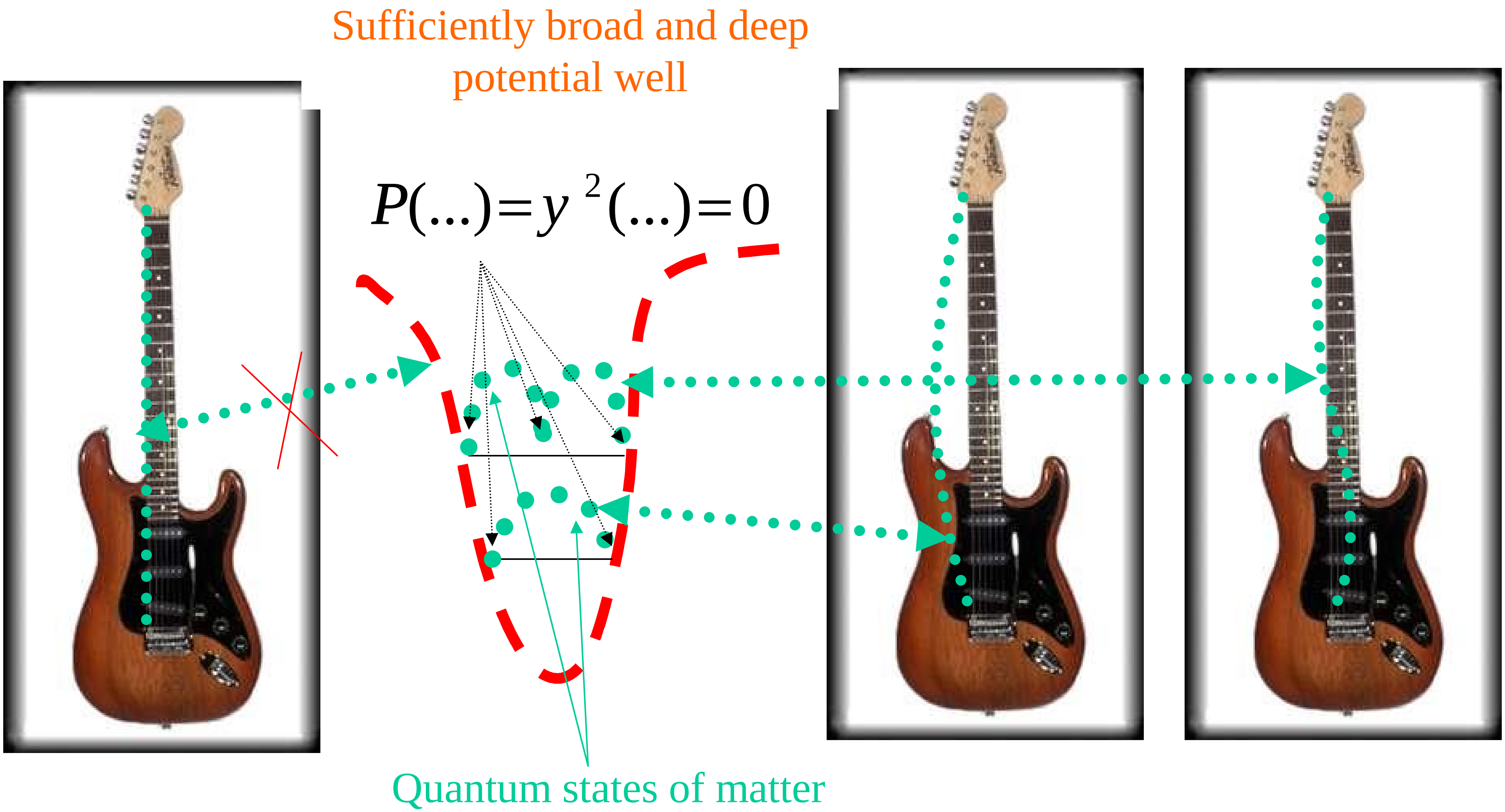
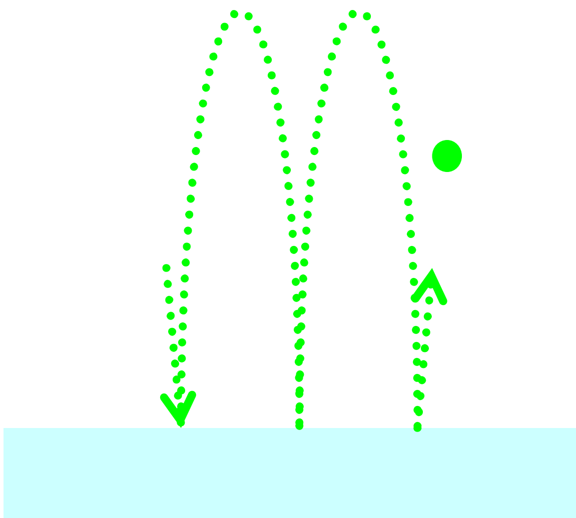


Quantum states of matter in a potential well



How to observe quantum states in a gravitational field ?



A neutron, which is trapped
in the Earth's gravitational field
above a horizontal mirror

1) Electric neutrality (usually the gravitational interaction is weaker than the others)

2) Long life time $\left(\Delta E \approx \frac{\eta}{\Delta t}\right)$

3) Small mass $\left(\Delta \mathrm{v} \cdot \Delta x \approx \frac{\eta}{m}\right)$

4) Energy (temperature) of UCN is extremely small and it is not equal to the installation temperature

$$E_n \approx \sqrt[3]{\left(\frac{9 \cdot m_n}{8}\right) \cdot \left(p \cdot \eta \cdot g \cdot \left(n - \frac{1}{4}\right)\right)^2}$$

Spatial distribution of neutron density

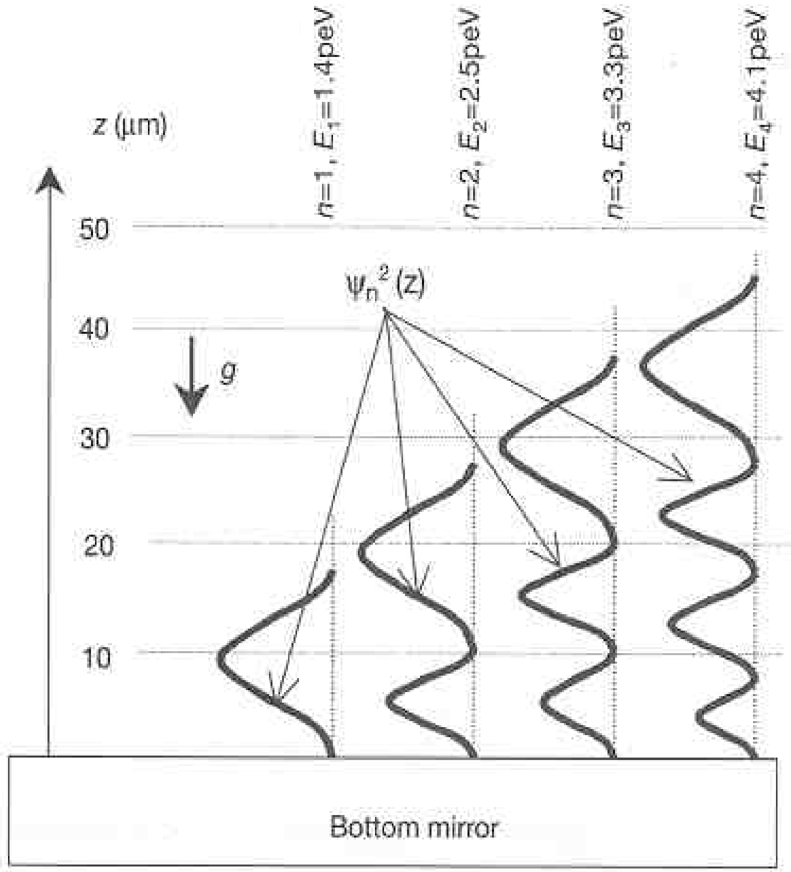


Figure 1 Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height *z*, corresponding to the *n*th quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$. The vertical axis *z* provides the length scale for this phenomenon. E_n is the energy of the *n*th quantum state.

General scheme of the experiment

$V_{horizont}$~4-15 m/s

V_{vertic}~2 cm/s

$$\Delta E \approx \frac{\eta}{\Delta t}$$

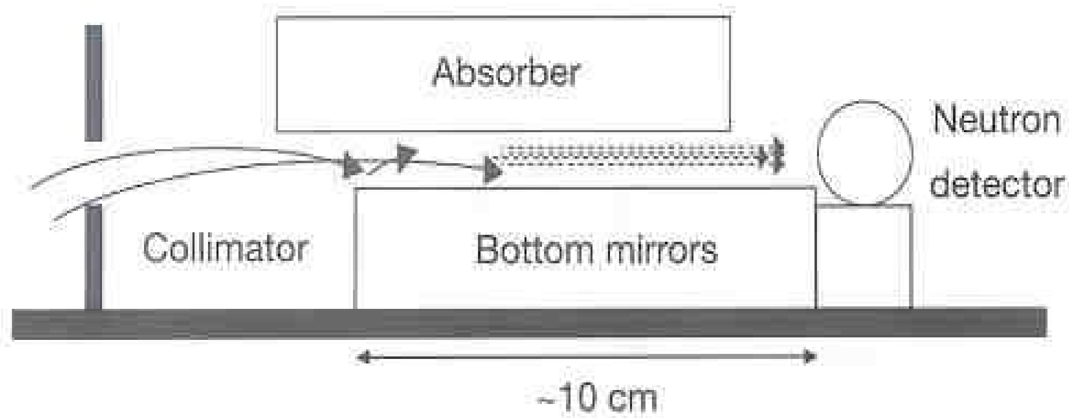


Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

Choice of the vertical and horizontal velocity components

Results (first run) and further steps

To increase statistics

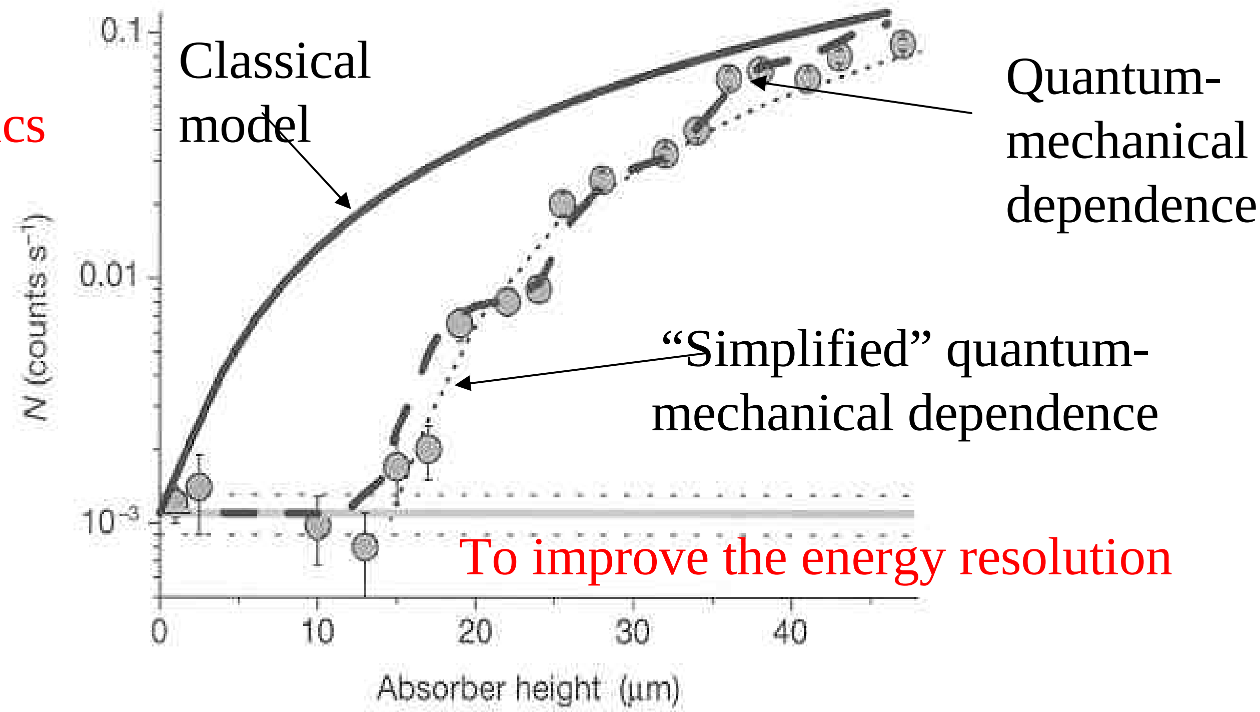
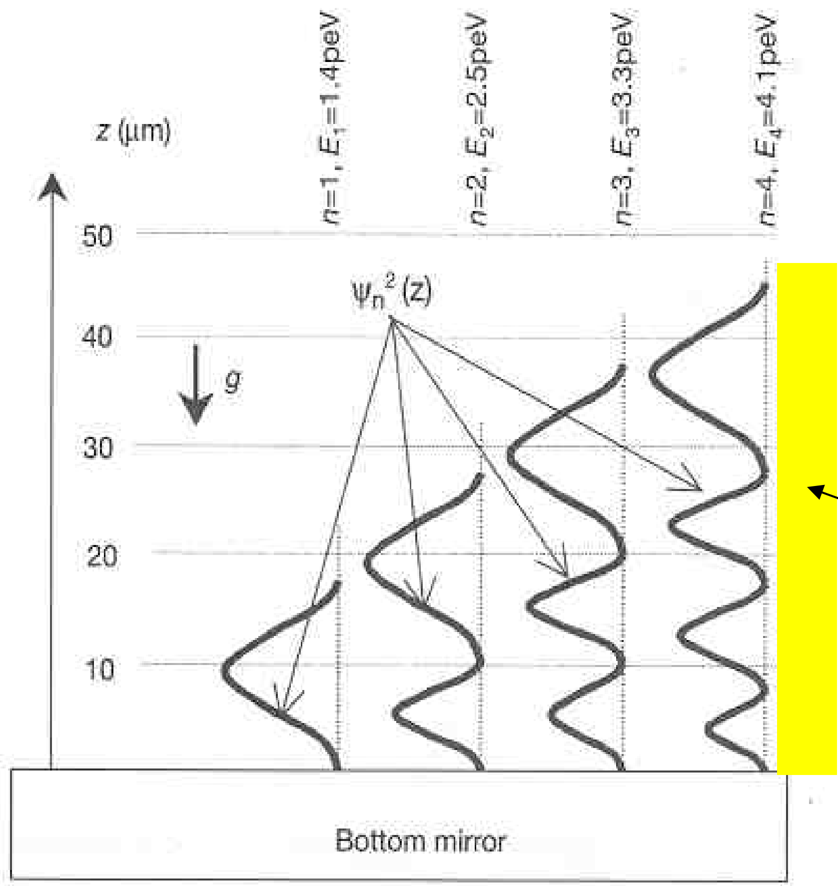


Figure 4 The neutron throughput versus the absorber height at low height values. The data points are summed up in intervals of 2 μm. The dashed curve corresponds to a fit using the quantum-mechanical calculation, in which all level populations and the height resolution are fitted from the experimental data. The solid curve is again the full classical treatment. The dotted line is a truncated fit in which it is assumed that only the lowest quantum state—which leads to the first step—exists.

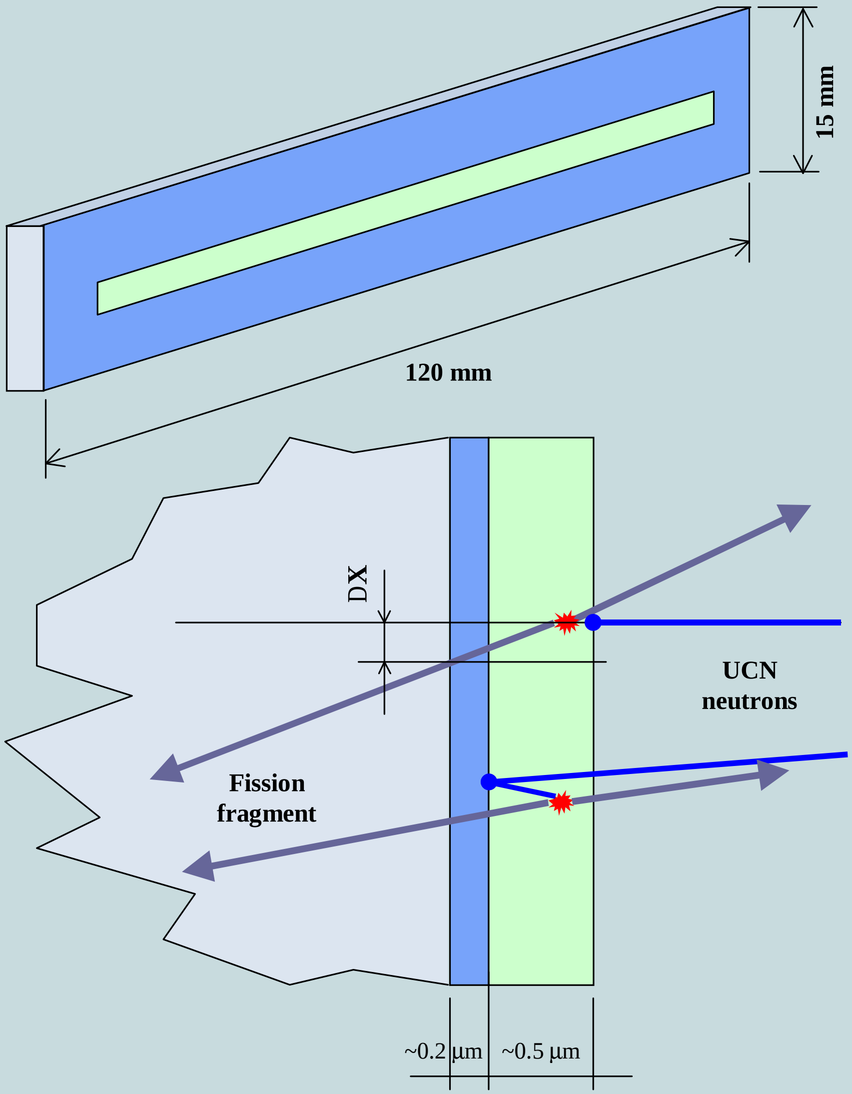
Spatial distribution of neutron density

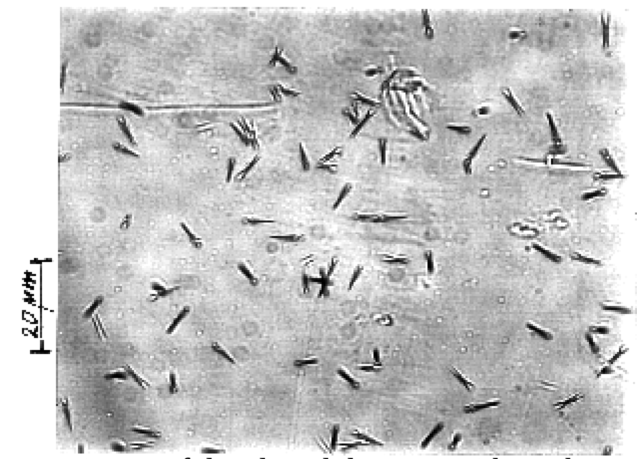


Position-sensitive detector with the spatial resolution of 1 micron

Figure 1 Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height z, corresponding to the nth quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$. The vertical axis z provides the length scale for this phenomenon. E_n is the energy of the nth quantum state.

An example of such position-sensitive detector

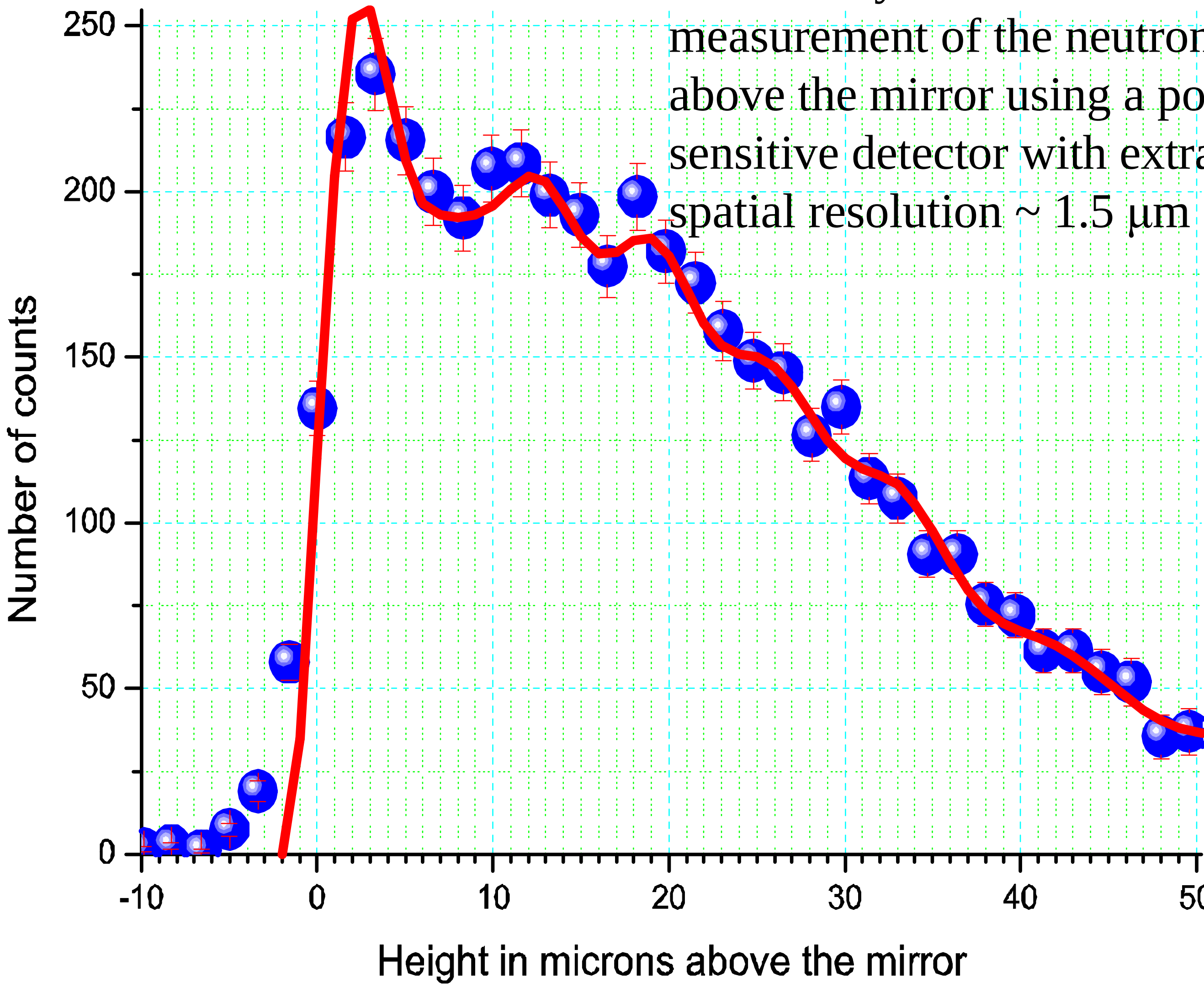




Picture of developed detector with tracks

An example of such position-sensitive detector

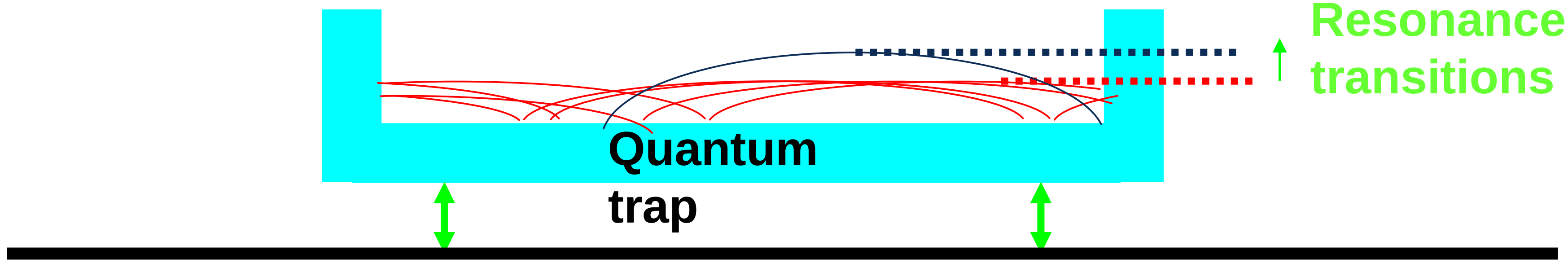
Preliminary results of the measurement of the neutron density above the mirror using a position-sensitive detector with extra-high spatial resolution ~ 1.5 μm

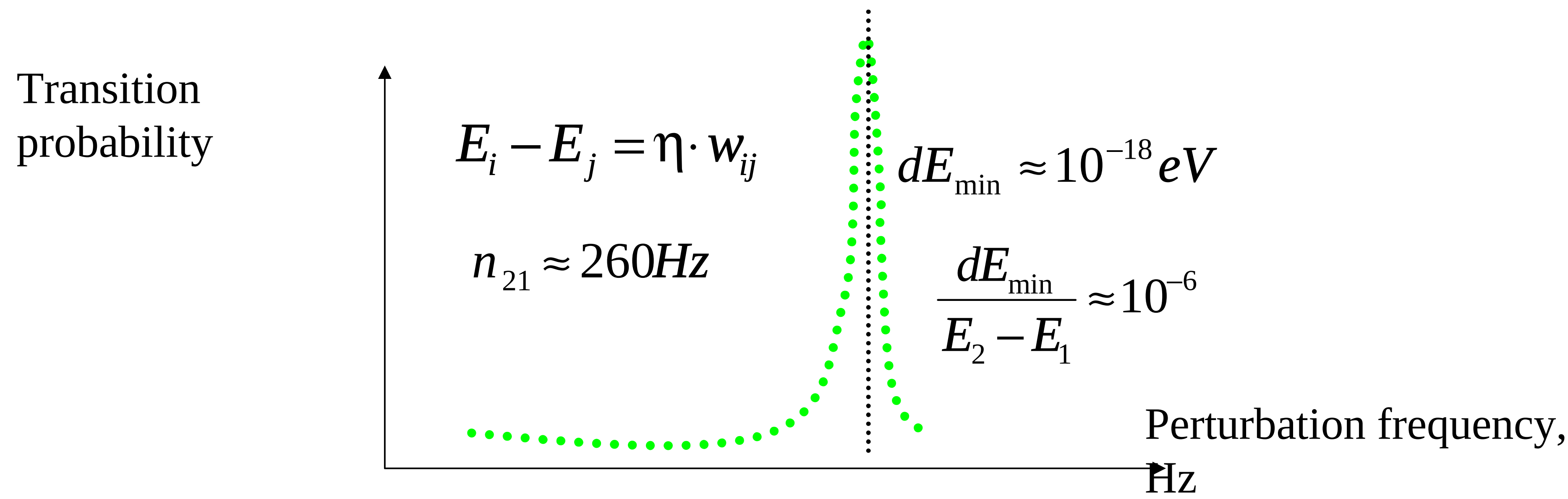


Applications in fundamental physics

- Search for extra fundamental forces at short distances of 1 nm - 10 μm

-Verification of electrical neutrality of neutrons





$$E_i - E_j = \eta \cdot w_{ij}$$

$$n_{21} \approx 260 Hz$$

$$dE_{\min} \approx 10^{-18} eV$$

$$\frac{dE_{\min}}{E_2 - E_1} \approx 10^{-6}$$

Near future programme for UCN physics at PF2

- Lifetime
- Magnetometers for EDM
- Quantum states continued
- Neutron optics
- Test of detectors, guides, coatings, etc. for UCN physics
- Double differential cross sections
- ….

I hope I could convince you

that **ultracold neutrons** are

– due to the fact that they are storable –
and despite the fact there are only few of them available in the experiment

a fancy and powerful tool in fundamental physics!!

Thank you,
merci beaucoup et
besten Dank
for your attention!