Physics with Ultracold Neutrons at the Institut Laue-Langevin in Grenoble, France

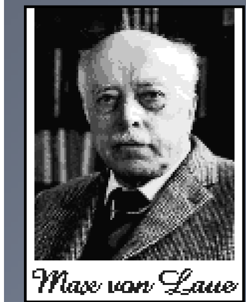
- Institut Laue-Langevin (ILL)
- Nuclear and Particle Physics Group (NPP)
- Ultra-Cold Neutrons (UCN)
- Neutron Lifetime
- Gravitational Levels
- Neutron Electric Dipole Moment (EDM)

ESRF
(6 GeV Synchrotron)

ILL
(High Flux Reactor)

Institut Laue-Langevin (ILL)

NEUTRONS FOR SCIENCE



H. Maier-Leibnitz

"A neutron factory and an user facility"

founded 17 January 1967

Internat. Convention (renewal) signed until end 2013

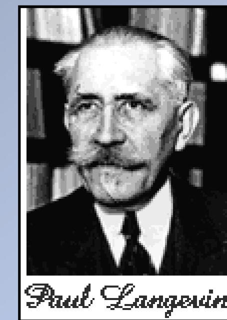
first neutrons in 1971

cold and hot neutrons sources started operation in 1972

general refit from 1991 - 94

Millennium Programme
phase M-0 nearly done
Phase M-1 kicked off

"earthquake" refit from 2003 - 07



L. Neel

Associates : France, Germany, United Kingdom
Scientific Member Countries : A, CZ, I, RUS, E, CH, S, H, B, PL

Further "Candidate" Countries: NL, N, DK, FIN, SLO, RO, …

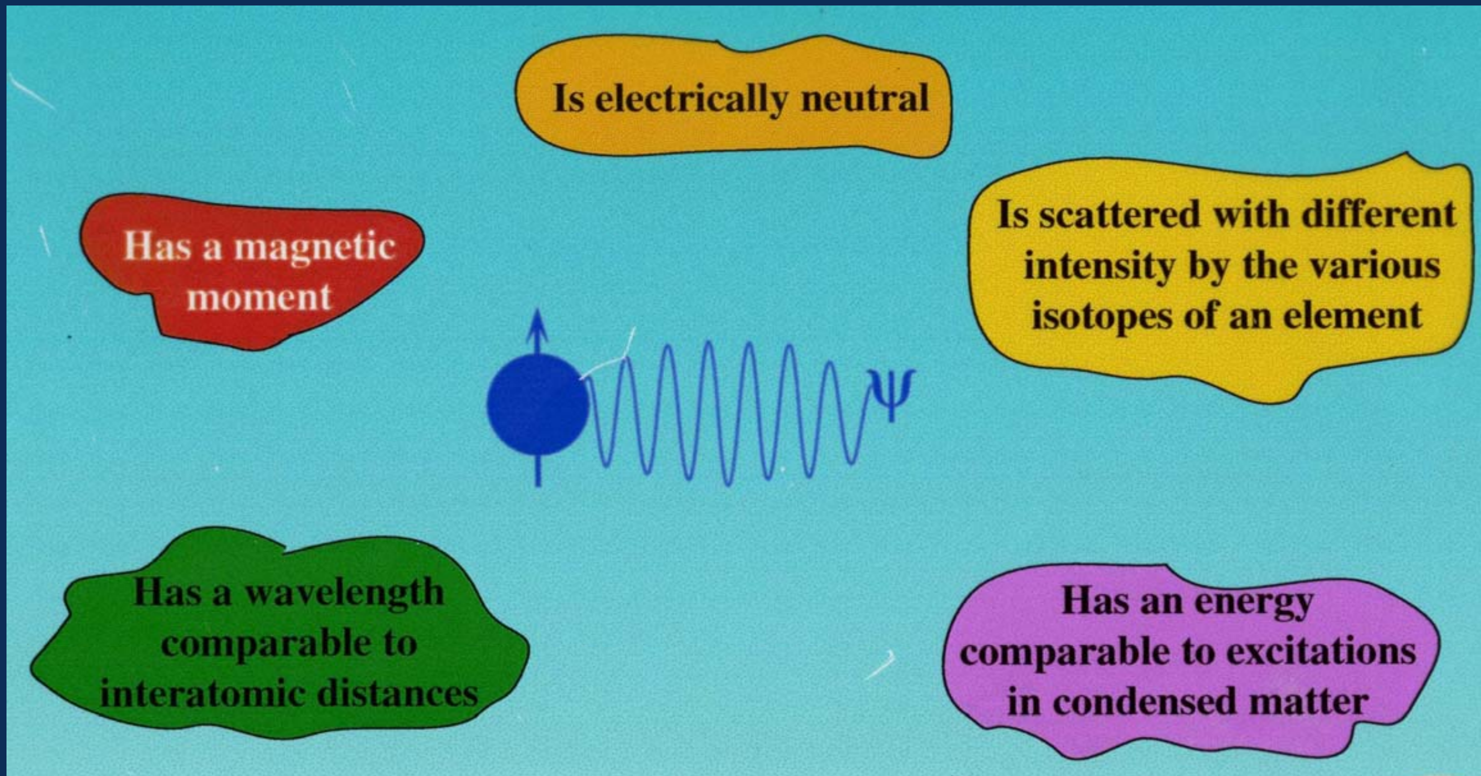
Experimental Programme in 2007
- 893 experiments (allocated by subcommittees) on 27 ILL-funded and 10 CRG instruments
- 1280 visitors coming from 36 countries
- 1109 proposals submitted and 811 accepted
- 562 publications by ILL staff and users

<u>Fields of research</u>

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

~475 staff; ~75 € annual budget (~18% investment)

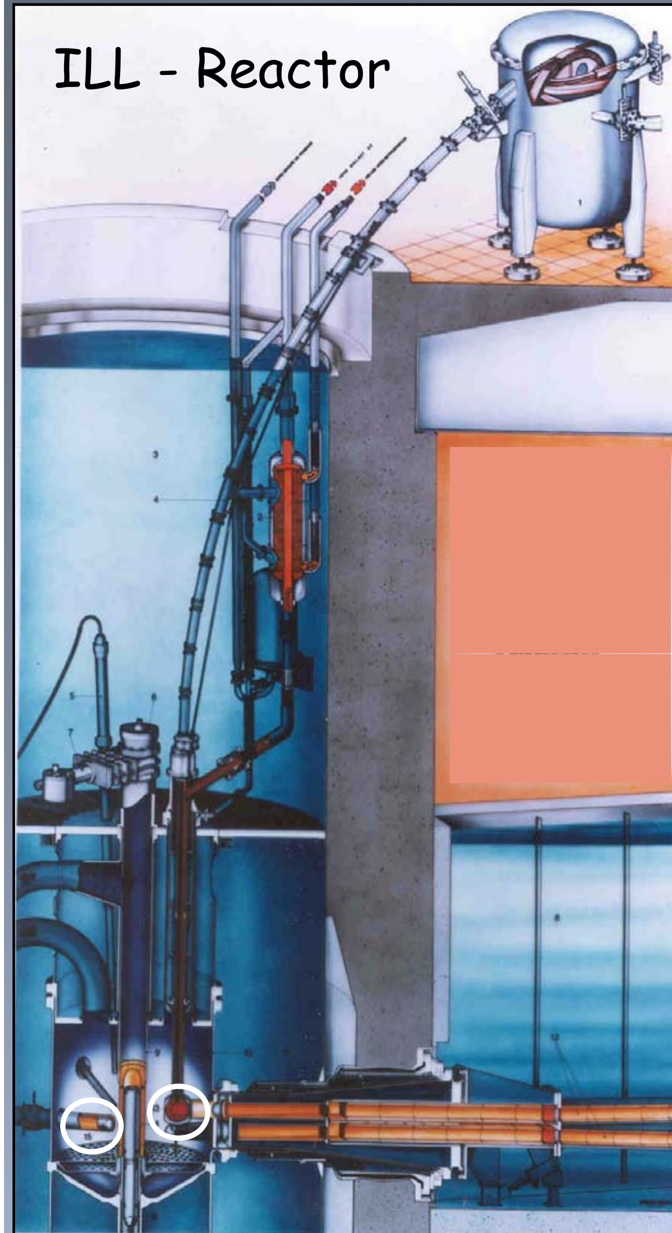
Neutron properties



Neutron Scattering on gases, liquids and solid matter gives information on their structure (elastic neutron scattering)
Neutron Excitation of atoms gives information about the binding energy within matter (inelastic neutron scattering)
Magnetic Moment μ_n —> determination of structure and dynamics of (unknown) magnetic matter
Neutron induced fission, neutron capture —> **gamma spectroscopy**, the **neutron** as a **particle** **and the** Neutron is COMPLEMENTARY to Synchrotron radiation

NEUTRONS FOR SCIENCE

Neutron source(s) at ILL



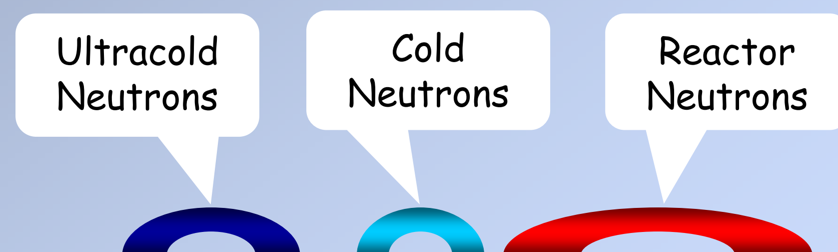
Fuel (chain reaction): $^{235}U(n_{th},f)$ → fission neutrons

Moderator: D_2O at 300K → 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	

The Nuclear and Particle Physics group (NPP)

NEUTRONS FOR SCIENCE

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

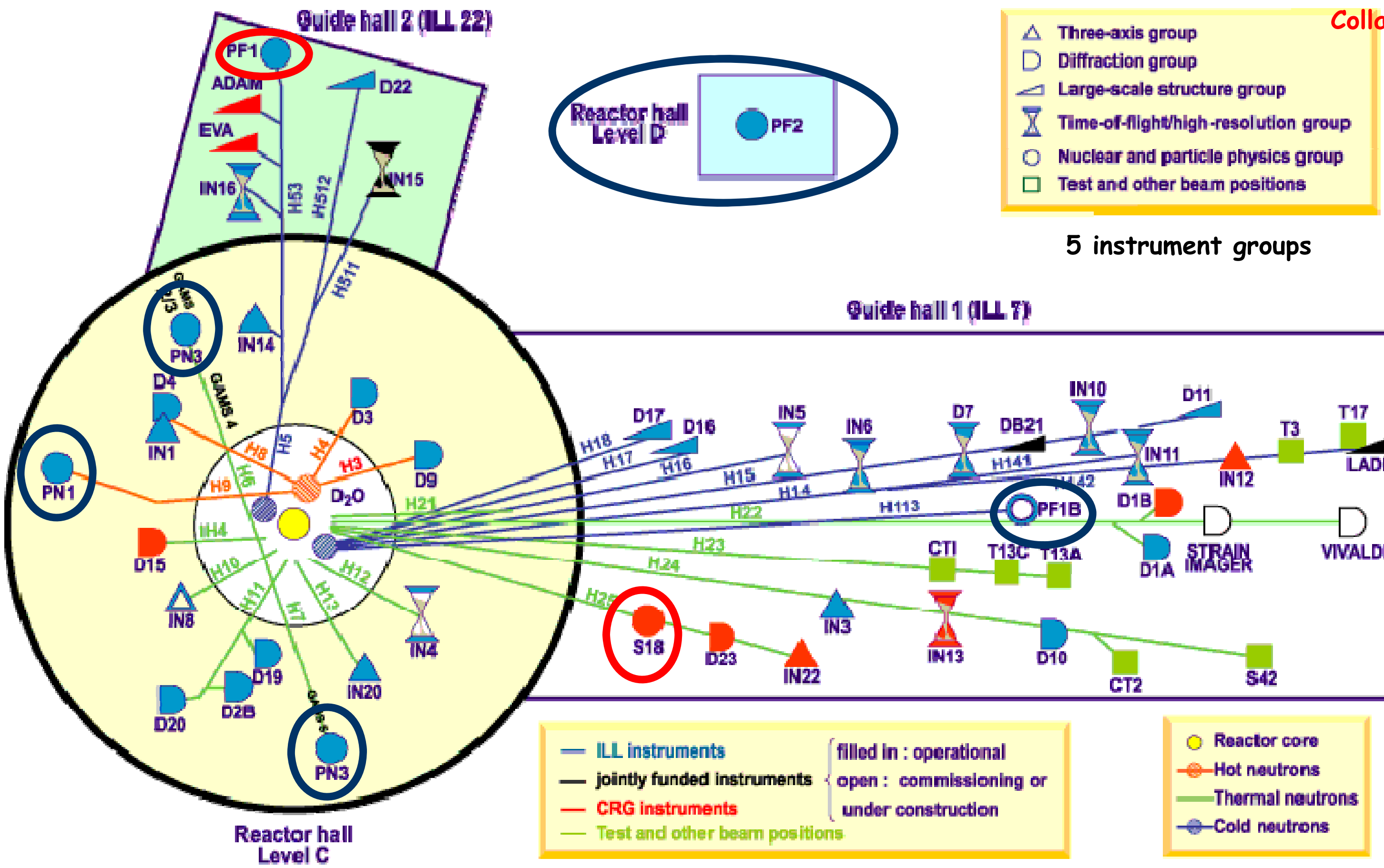
PF2
Facility for ultracold and very cold neutrons

(former PF1)
cryoEDM experiment

S18 - perfect crystal neutron interferometer

ILL-funded

Collab. Research Group



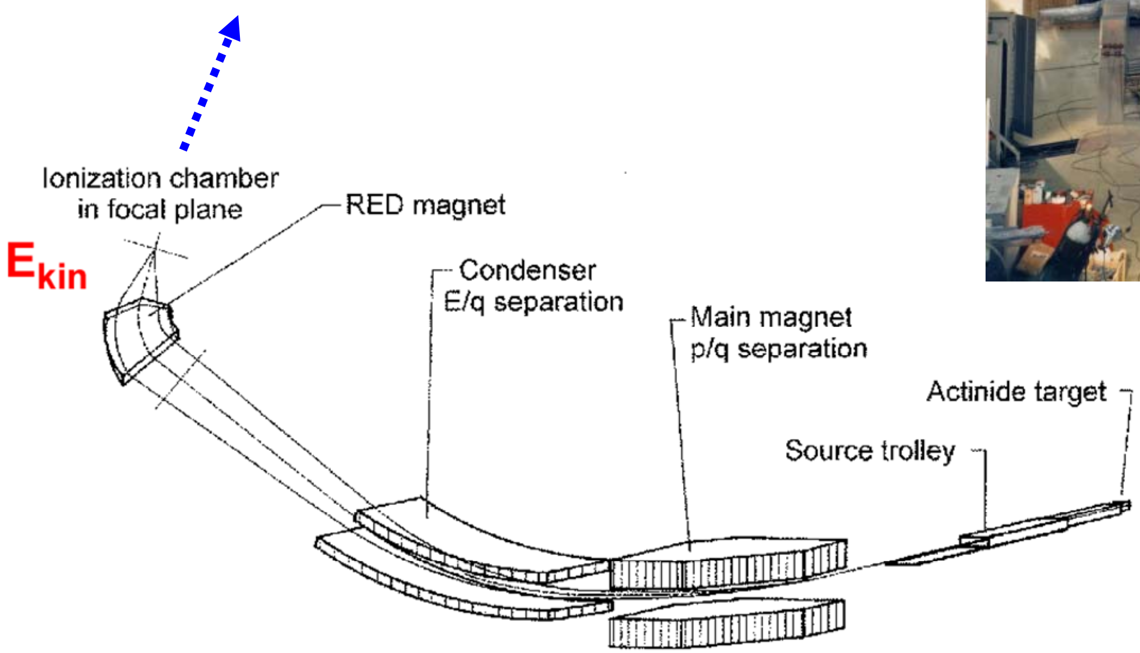
5 instrument groups

PN1: The fission fragment separator "Lohengrin"

H. Faust, U. Koester, T. Materna, N. Laurens

mass-separated fission fragments,

up to 10^5 per second, $T_{1/2} \geq \mu s$



$m v^2 / r_{el} = q E$ $m v^2 / r_{magn} = q v B$

$E_{kin} / q = E / 2 r_{el}$ $m v / q = B r_{magn}$

P. Armbruster et al., Nucl. Instr. Meth. 139 (1976) 213.

- **n-flux 5.5×10^{14} cm^{-2}/s**
- **few mg fission target (various materials)**
- **several 10^{12} fissions/s**

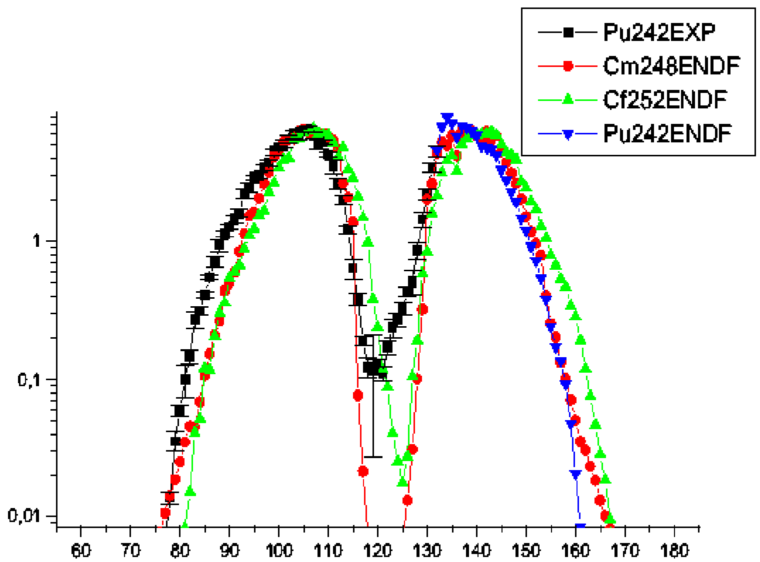
PN1: The fission fragment separator "Lohengrin"

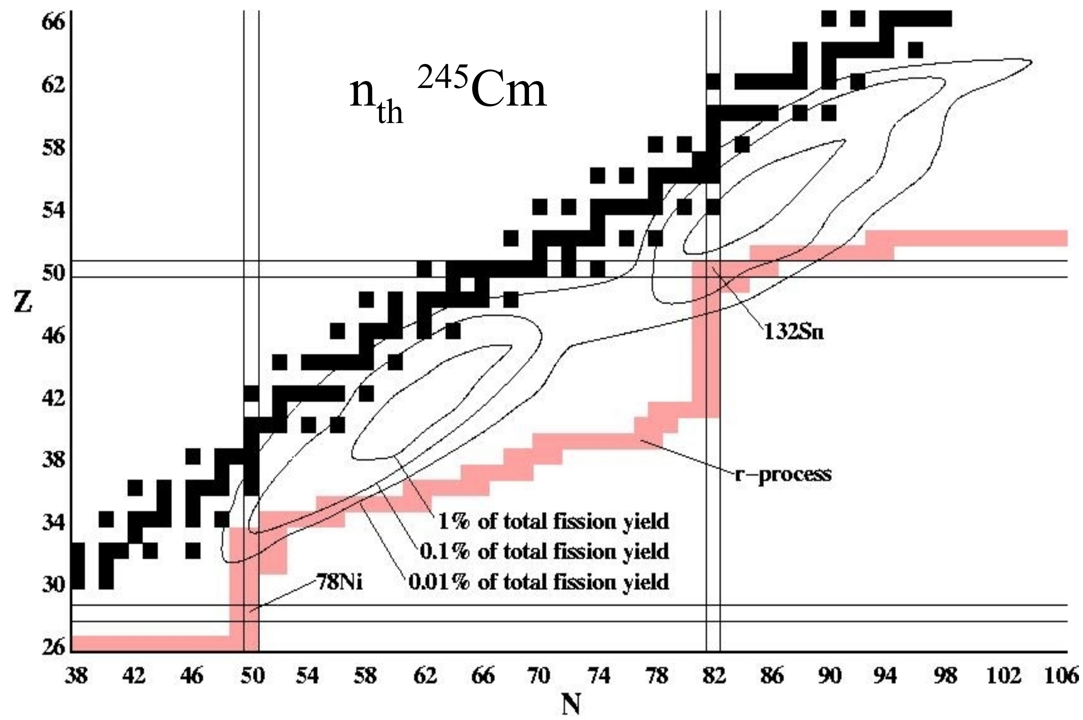
Applications:

- exotic, neutron-rich nuclides (production, decays, magnetic moments, r-process)
- fission yields

Typical duration of experiments:

- one to three weeks





PN3: The high resolution double crystal gamma ray spectrometer

NEUTRONS FOR SCIENCE

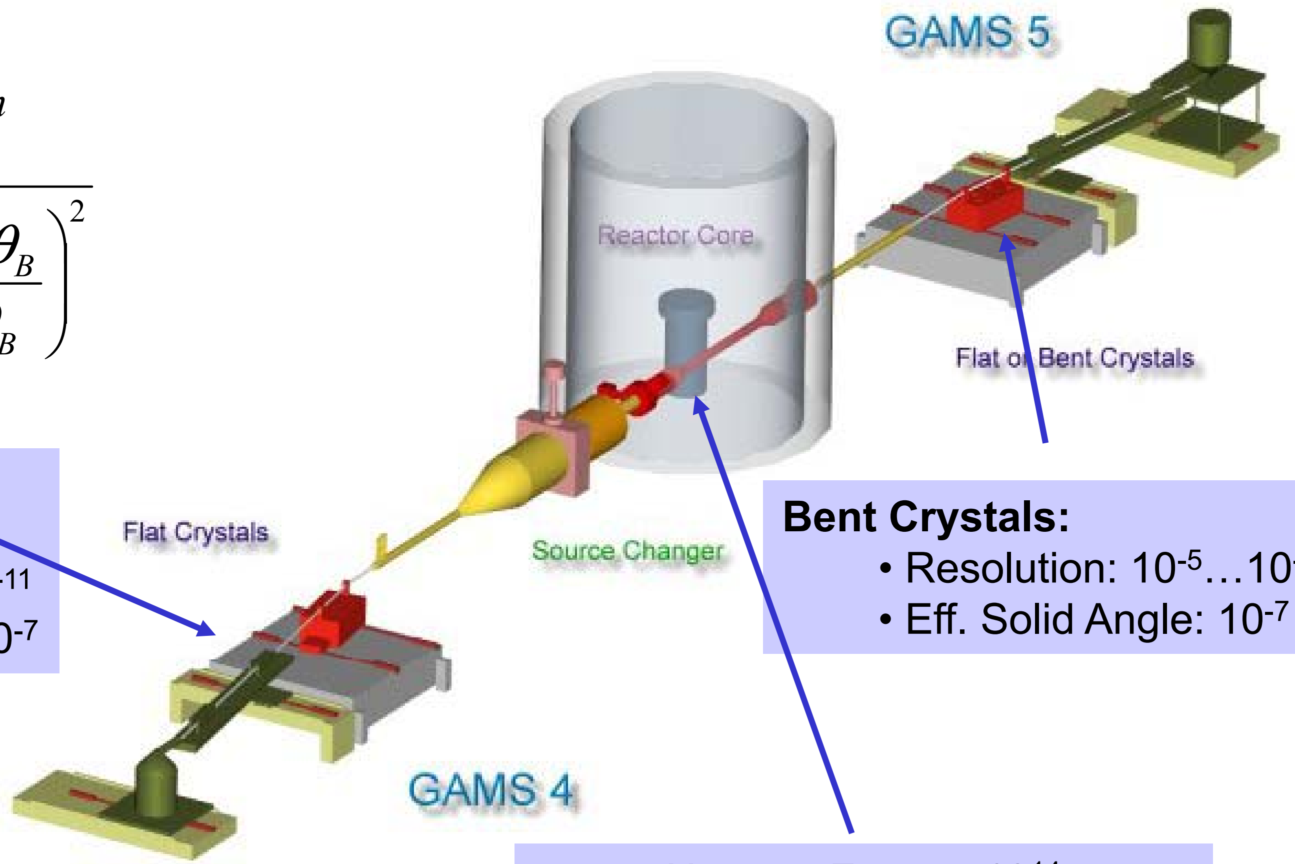
M. Jentschel, W. Urban, W. Clancy

Concept: Energy resolution via Bragg diffraction

$$n\lambda = 2d\sin\theta_n$$

$$\frac{\Delta\lambda}{\lambda} \cong \sqrt{\left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta\theta_B}{\theta_B}\right)^2}$$

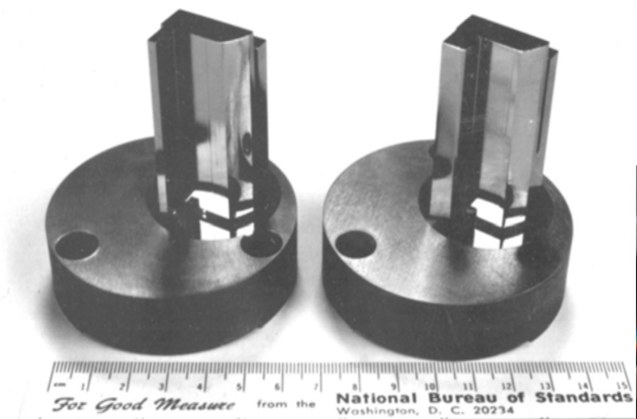
Flat Crystals:
- Resolution: 10^{-6}
- Eff. Solid Angle: 10^{-11}
- absolute Energy: 10^{-7}

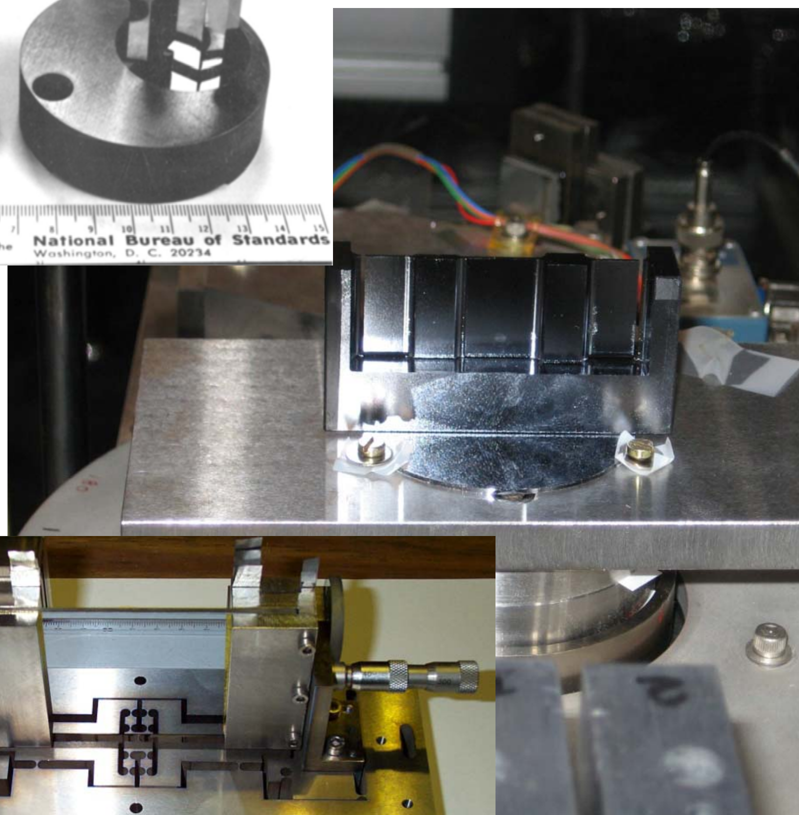


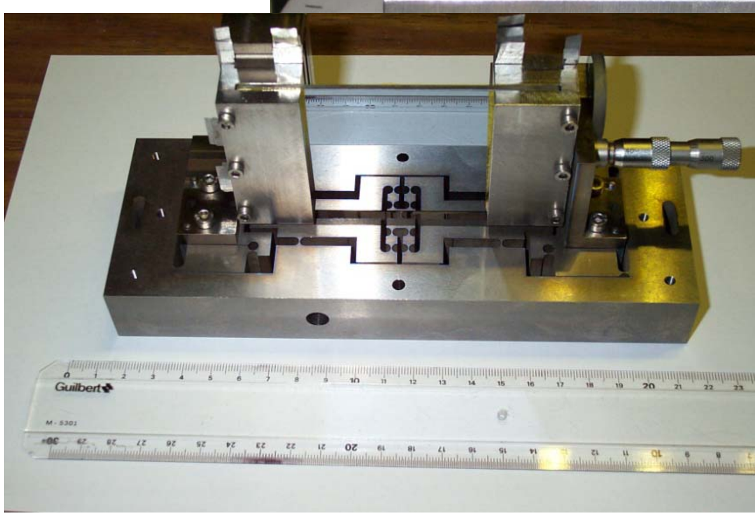
Bent Crystals:
- Resolution: $10^{-5}...10^{-4}$
- Eff. Solid Angle: 10^{-7}

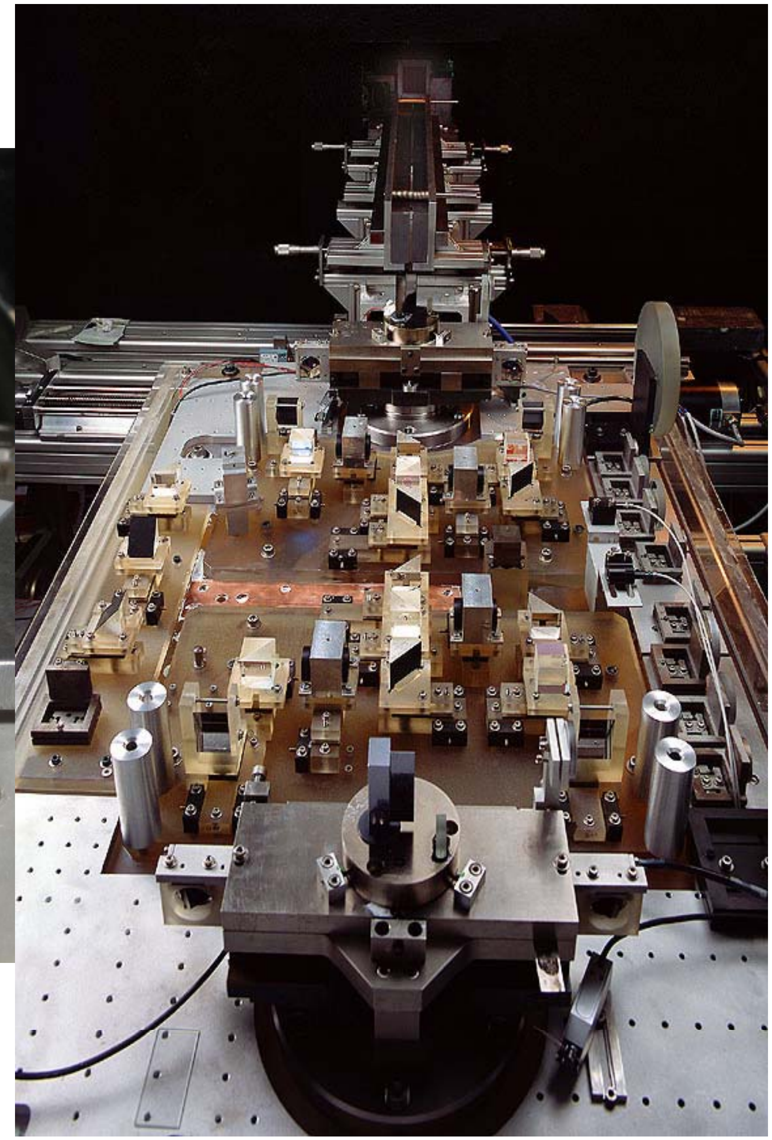
Neutron Flux: 5×10^{14}
Targets: 0.1 – 10g
Target change during reactor cycle

PN3: The high resolution double crystal gamma ray spectrometers









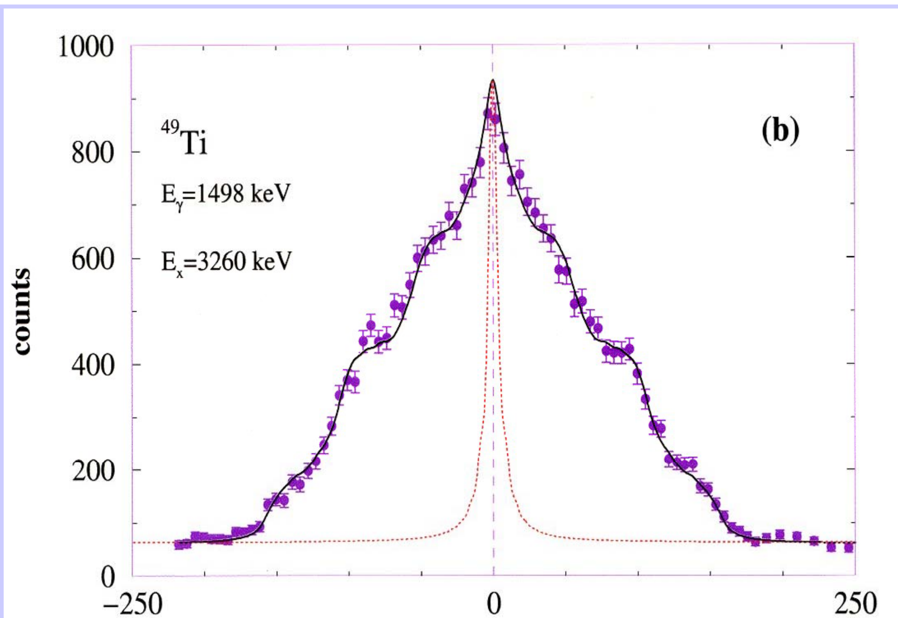
PN3: The high resolution double crystal gamma ray spectrometer

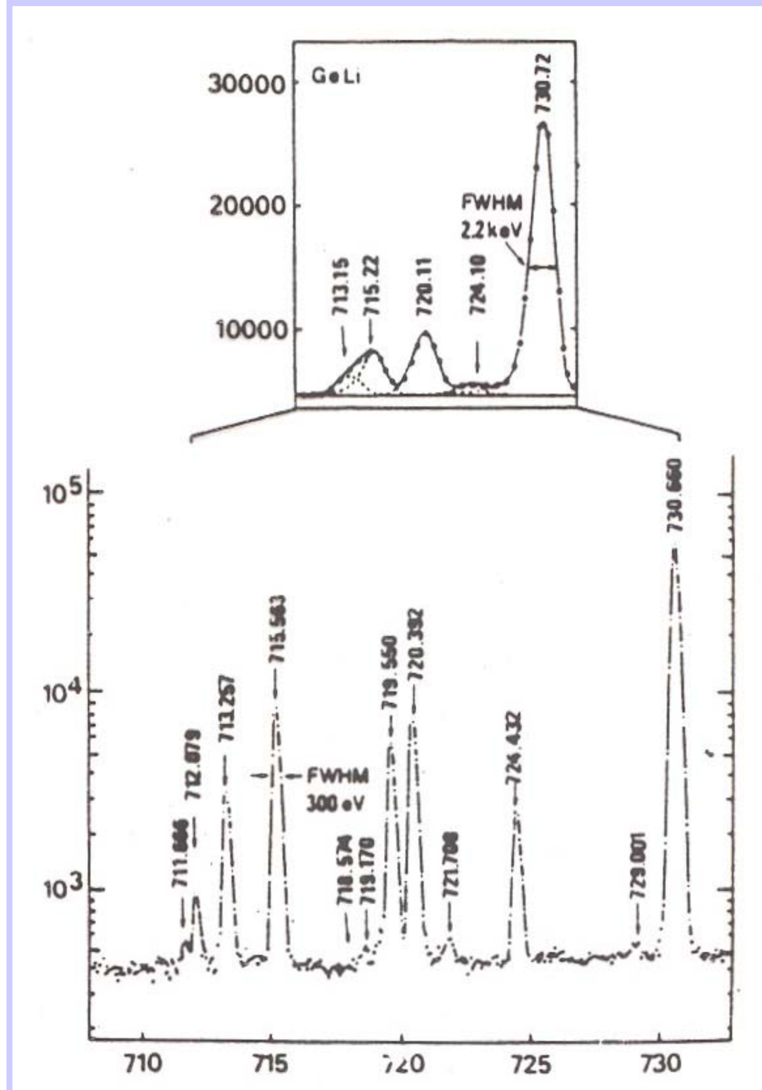
Applications:

- nuclear spectroscopy
- lifetimes of nuclear levels (10^{-16} ... 10^{-12} s)
- interatomic potentials (GRID technique)
- input to metrology (molar Planck constant)

Typical duration of experiments:

- two to four weeks

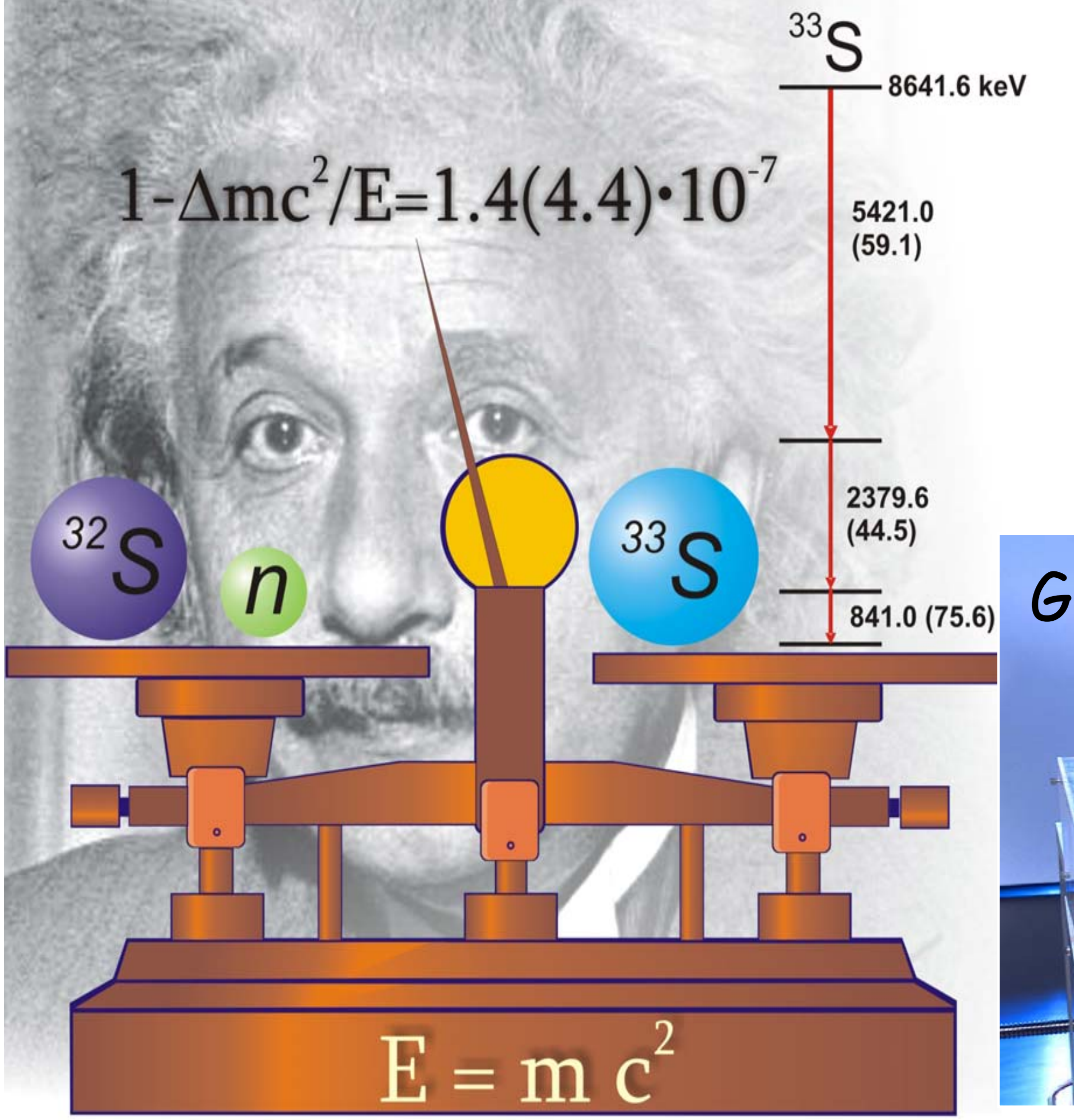


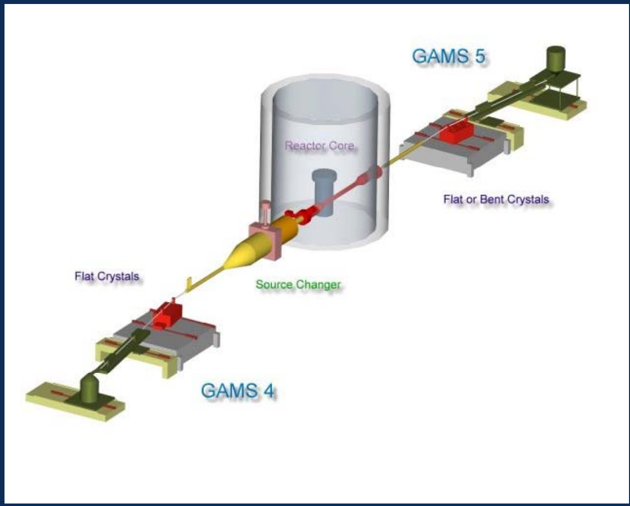


^{168}Er with Ge and GAMS (bent crystals)

Direct test of mass/energy relationship $E = mc^2$

ILL-MIT-NIST, Nature 430, 58 (2005)

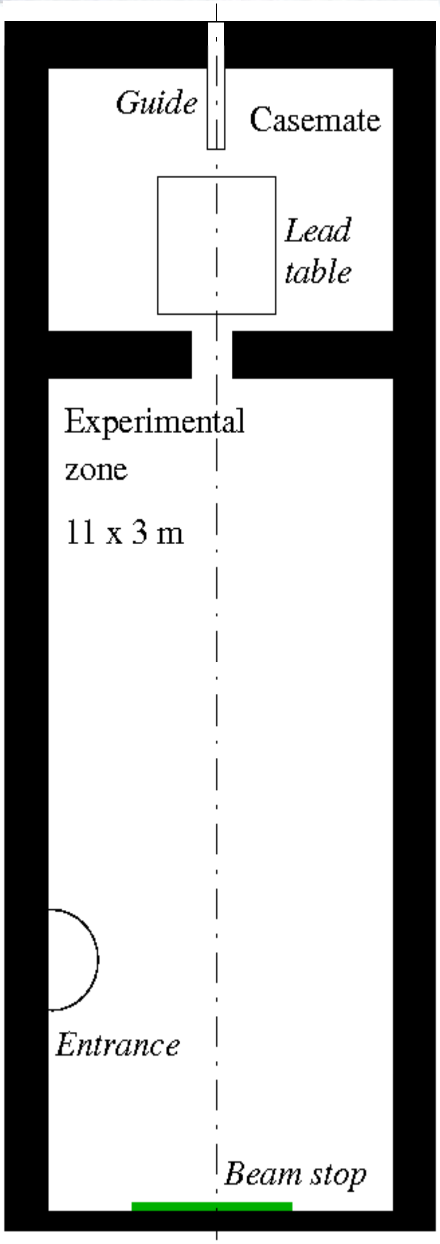




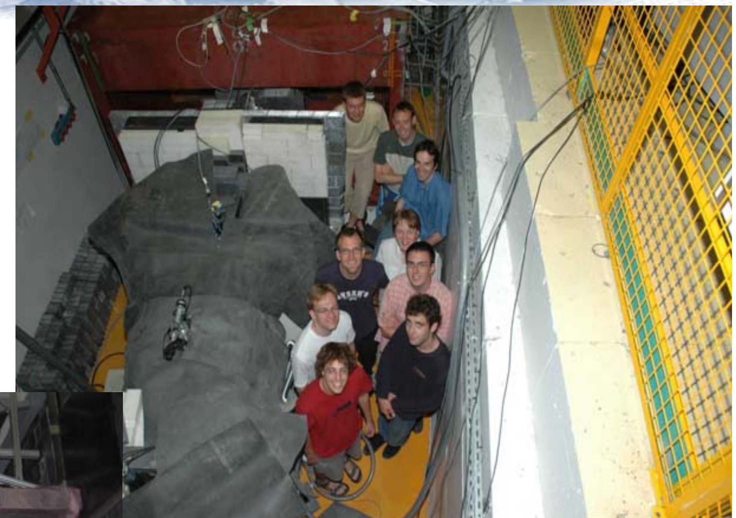
GAMS Interferometer ILL

PF1B

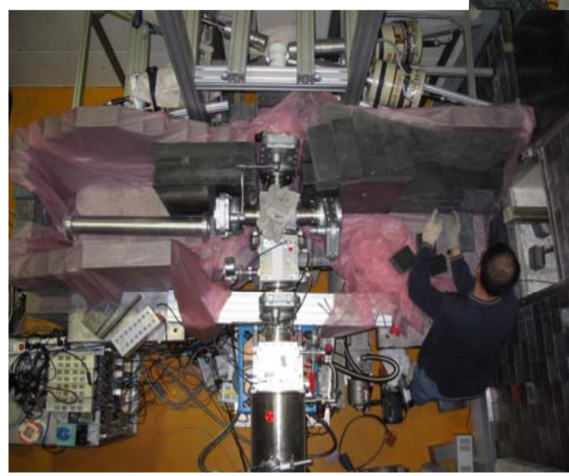
Guide hall n1 (ILL7)
Neutron source
Vertical liquid deuterium cold source
Neutron guide
super-mirror (m=2) ballistic neutron guide H113, 76 m length
Un-polarized beam cross-section
6 cm by 20 cm
Height of the neutron beam above the floor level
PF1B: 140 cm
Mean neutron wavelength
4.0-4.5 A
Un-polarized equivalent flux
$1.8*10^{10}$ n/cm^2/s
Polarized beam cross-section
3 cm by 4.5 cm or 6 cm by 8 cm
Polarized equivalent flux
$3*10^{9}$ n/cm^2/s
Polarizers
Curved stack of glass plates with double sided super-mirror coating, polarization 98% Crossed geometry of two super-mirror polarizers, polarization 99.7%
Spin-flippers
"Current-sheet" and adiabatic radio-frequency flippers; efficiency >99.5%



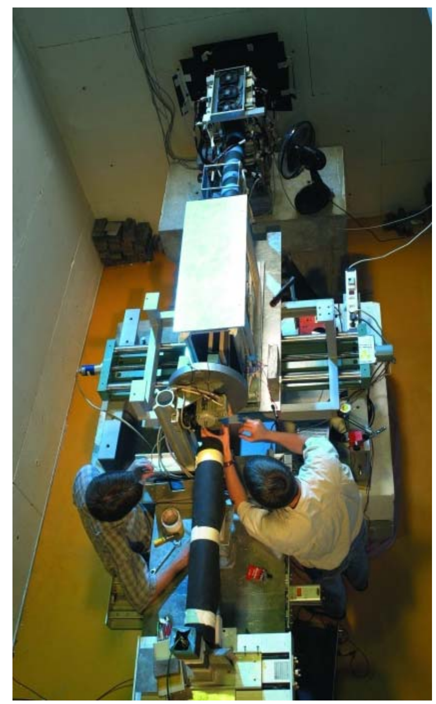
Physics at PF1B



- Neutron decay
  correlation measurements
  (V_{ud}, right-handed currents, T violation)
- Neutron properties
  CrystalEDM



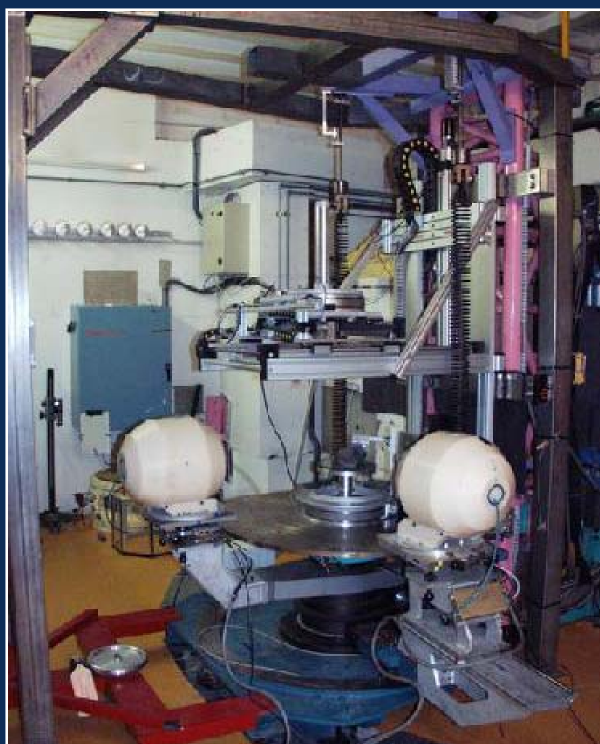
- Fission studies
  Asymmetries in fission
  Cross-sections
- Nuclear spectroscopy
  of neutron-rich nuclei produced by fission



- Developments of new techniques
  polarisation techniques, UCN production

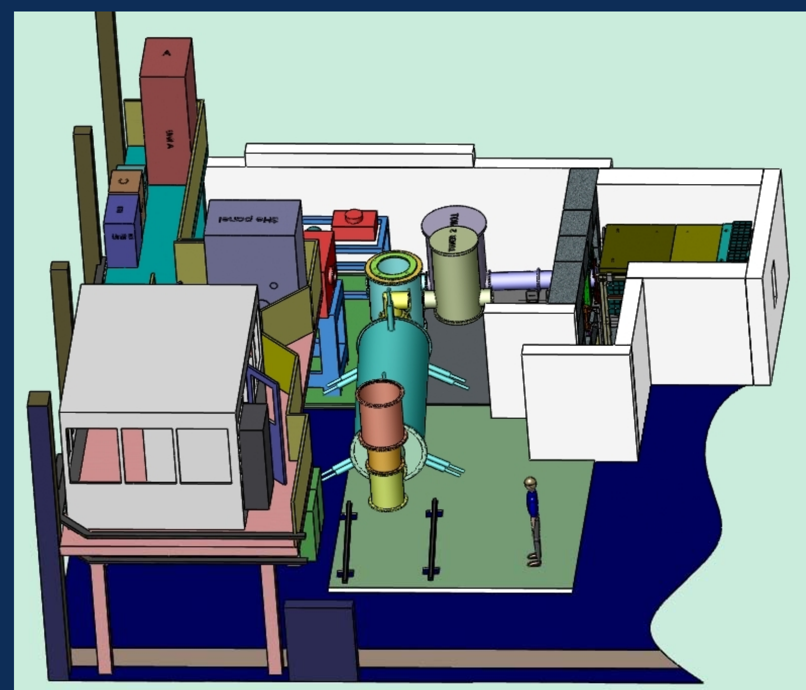
S18 - CRG instrument

interferometer (perfect Si crystals) for basic neutron quantum optics, neutron scattering lengths and USANS



cryoEDM - CRG instrument

UCN in superfluid He



Properties of UCN

Ultracold neutrons, that is, neutrons whose energy is so low that they can be contained for long periods of time in material and magnetic bottles

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

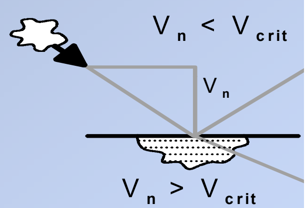
λ_{UCN} ~ 1000 Å

T_{UCN} ~ 2 mK

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

UCN discovery

OBSERVATION OF ULTRACOLD NEUTRONS

V. I. Lushchikov, Yu. N. Pokotilovskii, A. V. Strelkov, and F. L. Sh
Joint Institute for Nuclear Research

Submitted 18 November 1968
ZhETF Pis. Red. 9, No. 1, 40 - 45 (5 January 1969)

Ya. B. Zel'dovich showed in 1959 [1] that neutrons with velocities u
experience total reflection from the walls at all incidence angles, can be
cavity. As was noted recently [2], the idea of storing neutrons points to
the accuracy of measurement of the neutron dipole moment, an important fac
of

… by extracting neutrons from the low energy tail of the distribution in the source

the tube. The neutron detectors 11 and 12 were FEU-13 photomultipliers c

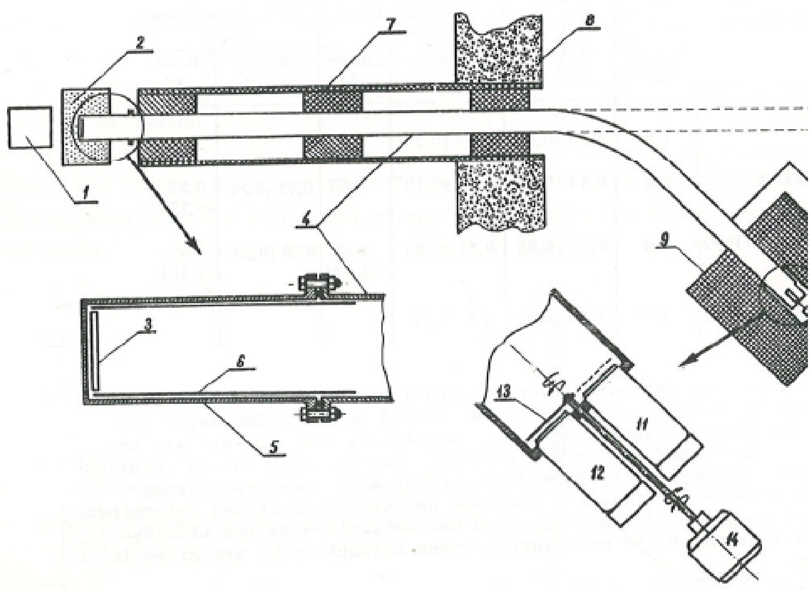


Fig. 1. Diagram of setup. 1- IBR reactor; 2, 3 - moderator (2 - paraffi layer 1 mm thick); 4 - copper tube, 9.4 cm i.d., total length 10.5 m; 5 - copper-foil cylinder; 7 - shield (paraffin with boron carbide); 8 - 2-m c actor chamber; 9 - detector shield (paraffin); 10 - tube filling and evac 12 - detectors (FEU-13 with layers of ZnS or ZnS + Li compound); 13 - cop between shutter and detector < 1 mm); 14 - shutter mechanism; 15 - trap f

Volume 29B, number 1 PHYSICS LETTERS 31 March 1969

MEASUREMENTS OF TOTAL CROSS SECTIONS FOR VERY SLOW NEUTRONS WITH VELOCITIES FROM 100 m/sec TO 5 m/sec

A. STEYERL
Physik-Department, Technische Hochschule München, Munich, Germany

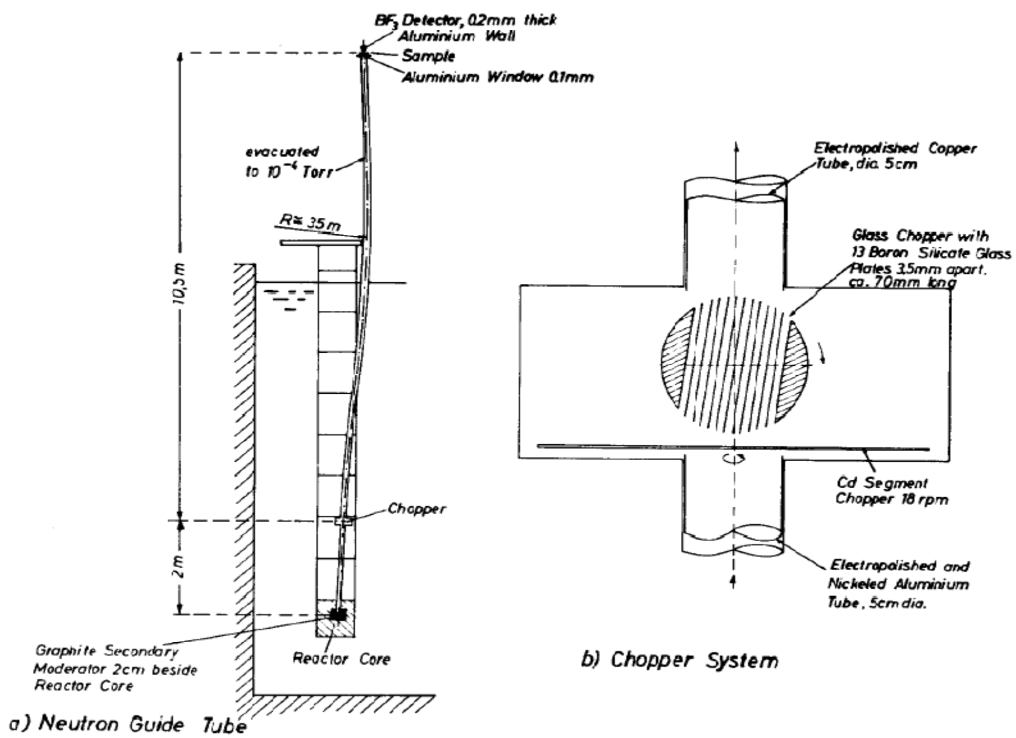
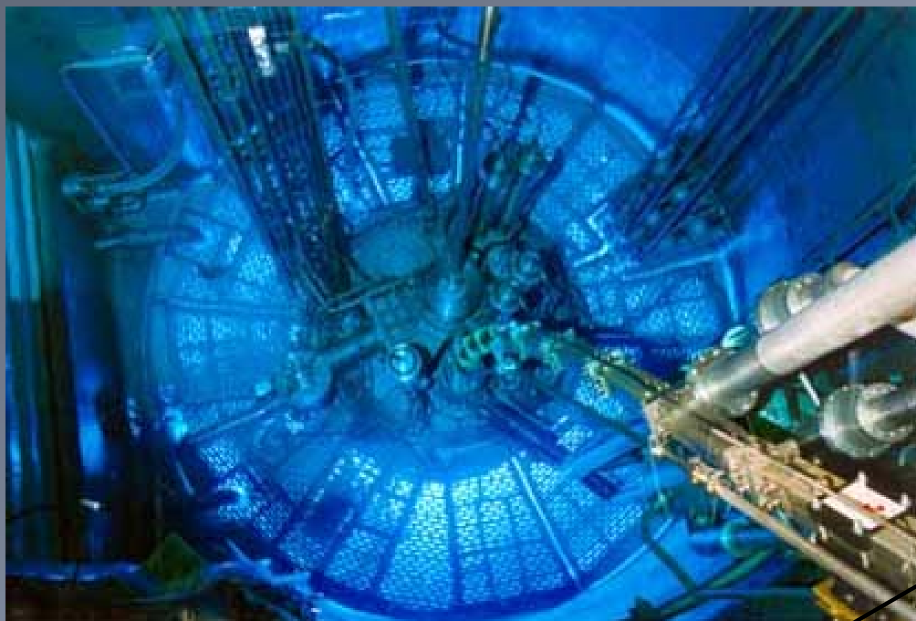
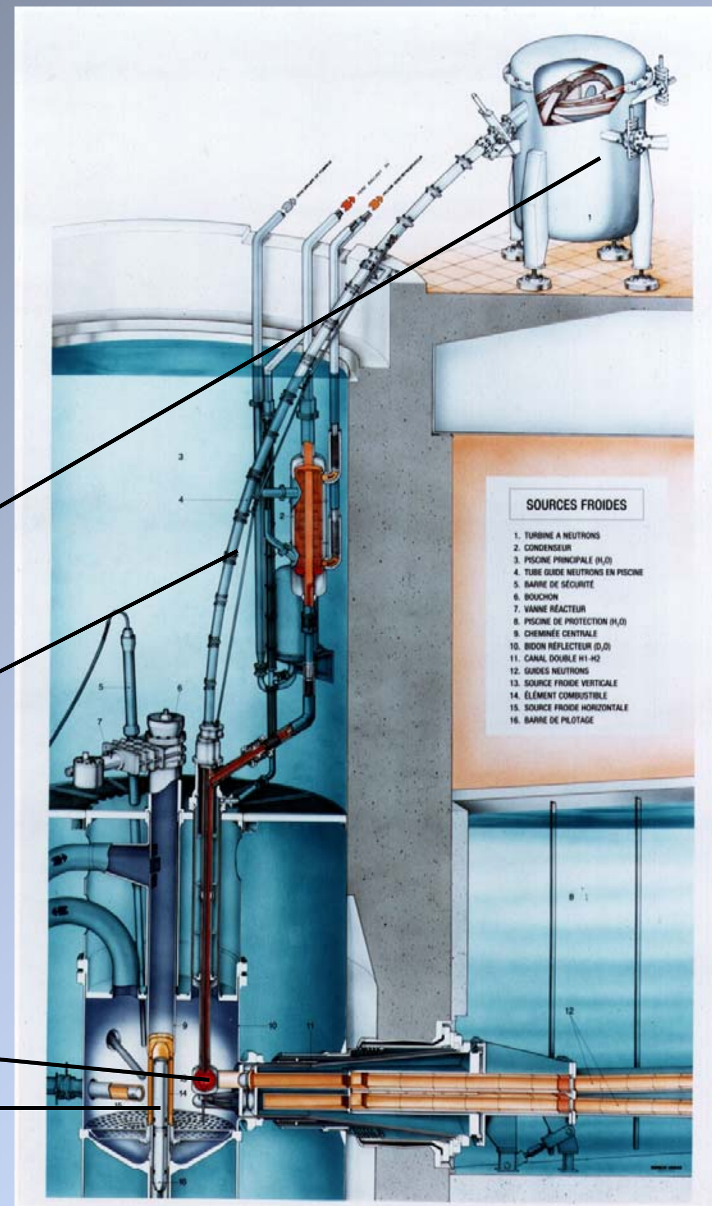


Fig. 1. Vertical beam tube for very slow neutrons.

The UCN/VCN facility PF2





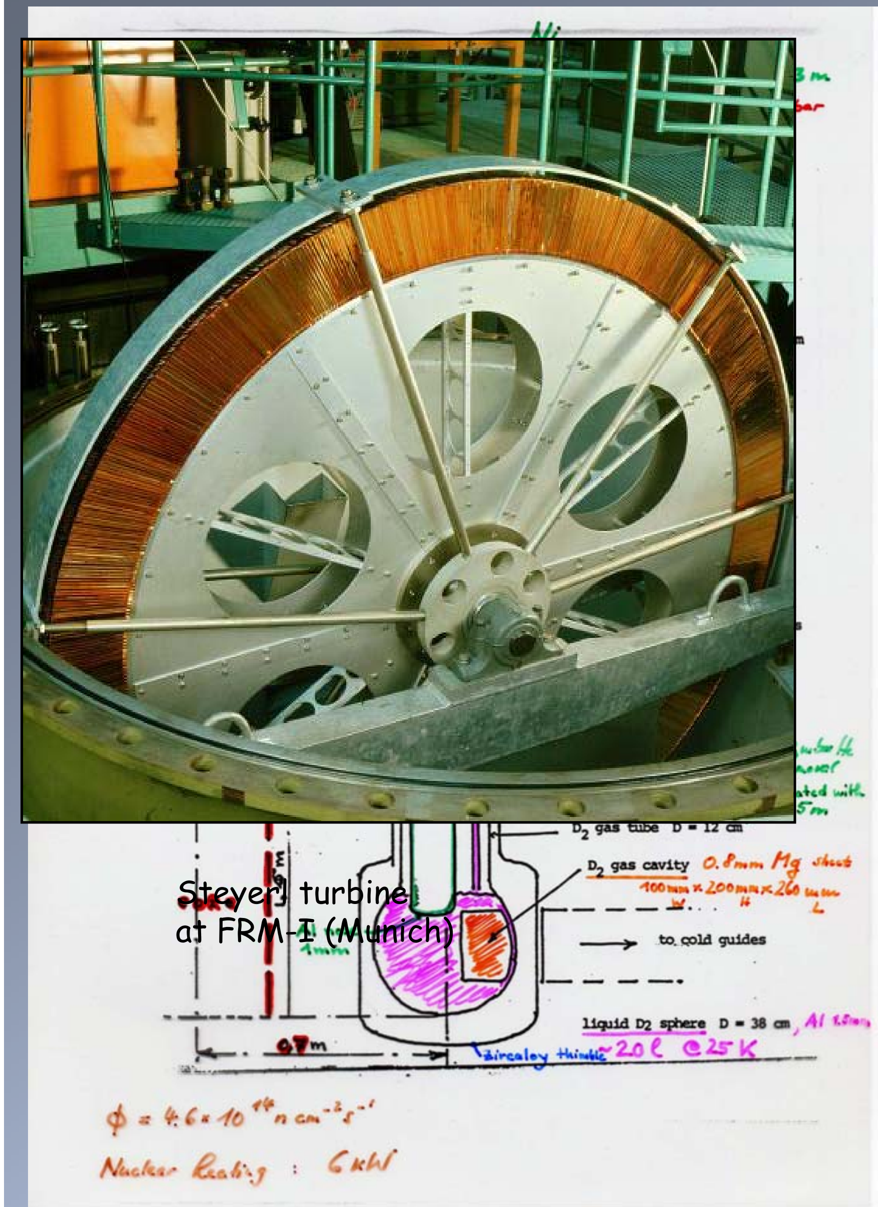
Neutron turbine
A. Steyerl (TUM - 1985)

Vertical guide tube

Cold source

Reactor core

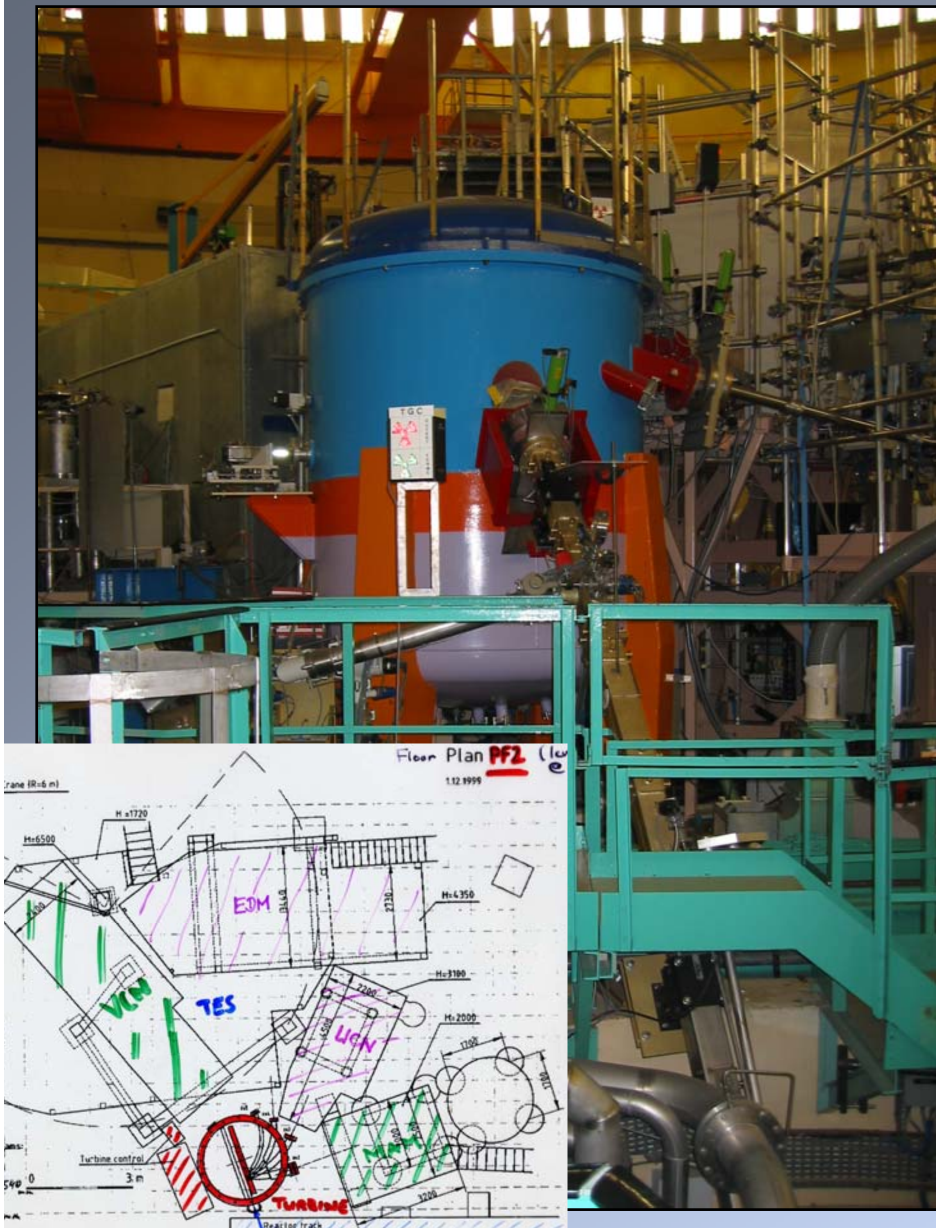
The Vertical Cold Source (VCS)



Steyerl turbine at FRM-II (Munich)

Steyerl turbine (2nd generation)
at PF2 / ILL
10 years later

The PF2 beam facility



PF2: Physique Fondamentale 2

2nd installation for fundamental physics

4 positions for Ultracold Neutrons (UCN)

- *MAM*
- *EDM*
- *UCN*

$v = 5\ ms^{-1}$

$\rho = \sim 50\ cm^{-3}$ (at the experiment)

- *TES*

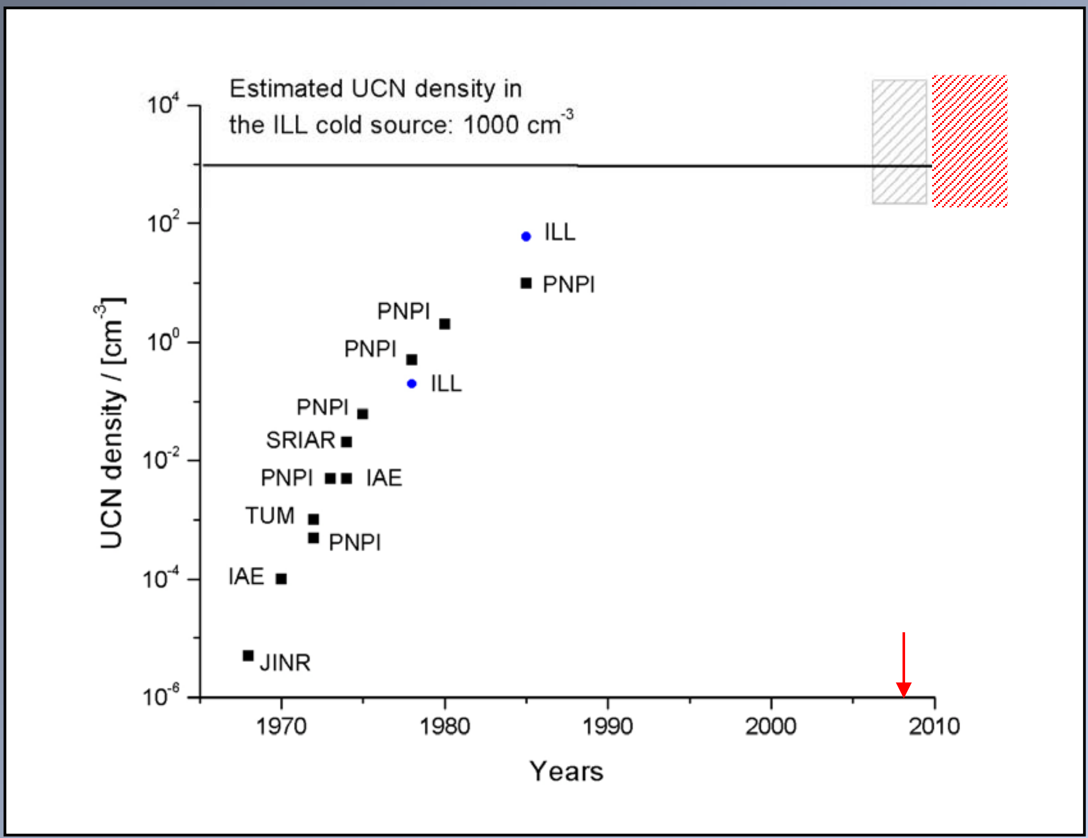
1 position for Very Cold Neutrons (VCN)

- *VCN beam*

$v = 50\ ms^{-1}$

$\Phi = 10^8\ cm^{-2}\ s^{-1}$

UCN facilities – Status and Future

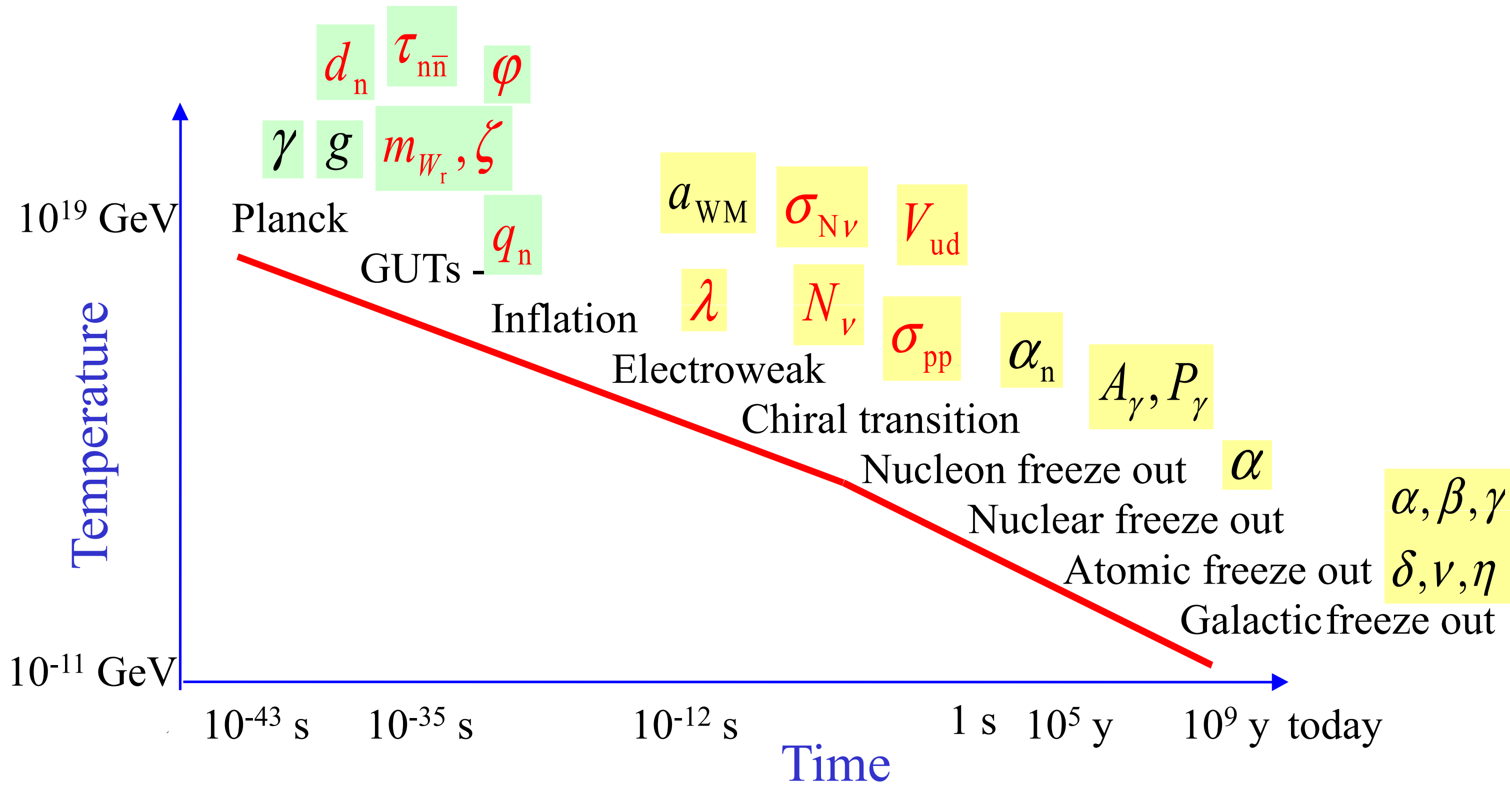


More and stronger UCN facilities in the future worldwide

- **PSI (CH)**
- **Mainz / Munich (D)**
- **ILL (F)**
- **LANL / NIST / SNS / NCSU / LENS (USA)**
- **RCNP (J)** then (?) TRIUMF (Canada) then (?) JPARC (J)
- **PNPI (?) (RUS)**

The Neutron Guide to the Universe

New Physics Standard Model

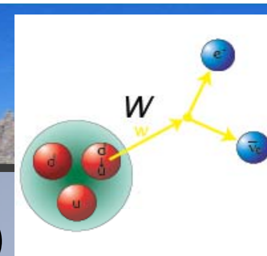


Neutron energies: peV…meV
Decay energy: 780 keV

Instead of $E \rightarrow \infty$
$\Delta E/E \rightarrow 0$

Diagram from D. Dubbers

NEUTRONS FOR SCIENCE



The free neutron lifetime: $n \rightarrow p + e^- + \bar{\nu}_e \; (+782\,\text{keV})$

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

$n \rightarrow p + e^- + \bar{\nu}_e + \gamma \qquad BR(15keV) \approx 3 \times 10^{-3}$

$n \rightarrow H^\circ + \bar{\nu}_e \qquad BR \approx 4 \times 10^{-6}$

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:

$$p + p \rightarrow d + e^+ + \nu_e \qquad \sigma \propto g_A^2$$

Big bang:

Primordial elements' abundances

Neutrino induced reactions:

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

$$\nu_\mu + n \rightarrow \mu^- + p$$

Neutrino detectors:

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

$$\sigma \propto \frac{1}{\tau_n}$$

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

Big-Bang Nucleosynthesis (BNN) crucial in constraining cosmological models

Essentially the only probe of physics in the early universe (~1 – 10^4 s; "radiation dominated epoch")

Single unknown parameter for standard BBN is baryon-to-photon ration during the nucleosynthesis epoch. All light abundances are a simple function of this parameter.

Those yields are particularly sensitive to the neutron lifetime τ_n which affects BBN in 2 ways:

i) τ_n enters in weak reaction rate which ceases at freeze –out temperature T_F, then n/p ratio fixed except for neutron decay

ii) Neutron decay between weak freeze-out (t~1s) and nucleosynthesis (t~200s)

These effects imply that **the shorter the neutron lifetime, the lower the predicted helium abundance**

See "BBN with a new neutron lifetime", G.J. Mathews et al, Phys. Rev. D71, 021302(R) (2005)

Measurements of the neutron lifetime τ_n

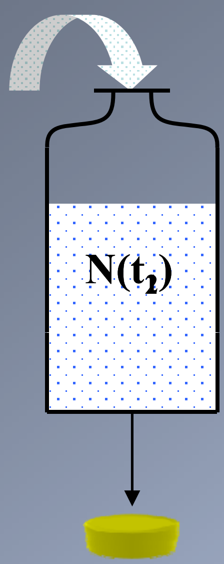
exponential decay law: $N = N_0 e^{-\lambda t}$

or, ultimately, measure the exponential decay directly

Storage experiments with UCN

"counting the surviving neutrons"

"UCN bottle"



$$\frac{1}{\tau_m} = \frac{1}{t_2 - t_1} \cdot \ln \frac{N(t_1)}{N(t_2)}$$

$$\frac{1}{\tau_m} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{wall}} + \frac{1}{\tau_{leak}} + \frac{1}{\tau_{vacuum}} + \ldots$$

→ 0 (experiment)

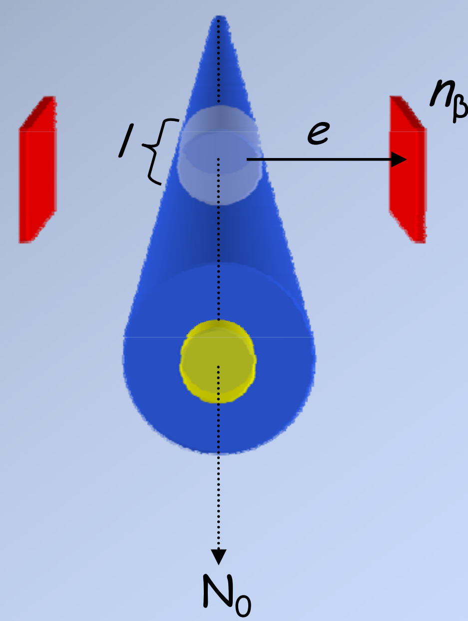
$$\frac{1}{\tau_{wall}} = \mu \cdot v_{eff}$$ → 0 (extrapolation)

$$\Rightarrow \quad \frac{1}{\tau_m} = \frac{1}{\tau_\beta}$$

Two relative measurements

Beam experiments with cold neutrons

"counting the dead neutrons"



$$n_\beta = \frac{dN}{dt} = -\frac{N_0}{\tau_n} e^{-\frac{l}{v \cdot \tau_n}}$$

Two absolute measurements

MAMBO-I

The early days

It took many years from the discovery of the neutron by Chadwick in 1932 and the conjecture of its instability by Chadwick & Goldhaber in 1935 until its radioactive decay was observed …….

PHYSICAL REVIEW VOLUME 74, NUMBER 9 NOVEMBER 1, 1948

Proceedings of the American Physical Society

MINUTES OF THE MEETING AT WASHINGTON, APRIL 29 TO MAY 1, 1948

F12. On the Radioactive Decay of the Neutron. ARTHUR H. SNELL AND L. C. MILLER, *Clinton National Laboratories.*—A collimated beam of neutrons, three inches in diameter, emerges from the nuclear reactor and passes axially through a thin-walled, aluminum, evacuated cylindrical tank. A transverse magnetic field behind the thin entrance window cleans the beam of secondary electrons. Inside the vacuum, axially arranged, an open-sided cylindrical electrode is held at +4000 volts with respect to ground. Opposite the open side a smoothed graphite plate is held at −4400 volts. The field between these electrodes accelerates and focuses protons which may result from decay of neutrons, so that they pass through a $2\frac{1}{4}\times 1\frac{1}{4}$ inch aperture in the center of the graphite plate, and strike the first dynode of a secondary electron multiplier. The first dynode is specially enlarged so as to cover the aperture. Readings are taken (1) with and without a thin B^{10} shutter [illegible]

the foil (2) in, operation (1) does not change the counting rate. Assuming all of the 100 c.p.m. to be due to decay protons, preliminary estimates of the collecting and counting efficiency (10 percent) and of the number of neutrons in the sample (4×10^4) give for the neutron a half-life of about 30 minutes. It is at present much safer however to say that the neutron half-life must exceed 15 minutes. Coincidences are presently being sought between the disintegration betas and the collected protons.

proton counter
n lifetime must exceed 21 minutes

PHYSICAL REVIEW VOLUME 77, NUMBER 5 MARCH 1, 1950

Proceedings of the American Physical Society

MINUTES OF THE MEETING AT CHICAGO, NOVEMBER 25 AND 26, 1949

H6. Radioactive Decay of the Neutron. J. M. ROBSON, *Chalk River Laboratory.*—The positive particle from the radioactive decay of the neutron has been identified as a proton from a measurement of charge to mass. A collimated beam of neutrons emerging from the Chalk River pile passes between two electrodes in an evacuated tank. One electrode is held at a positive potential, up to 20 kev, while the other electrode is grounded and forms the entrance aperture to a thin lens magnetic spectrometer, the axis of which is perpendicular to the beam of neutrons. The positive decay particles can be focused on the first electrode of an electron multiplier. The background counting rate is 60 c.p.m. A peak of 80 c.p.m. is observed above background when the magnetic field is adjusted for protons of energy expected from the electrostatic field. When a thin boron shutter is placed in the neutron beam, the proton peak disappears. Preliminary estimates of the collecting and focusing efficiency and the neutron flux indicate a minimum half-life of 9 minutes and a maximum of 18 minutes for the neutron.

proton counter
n lifetime between 13 and 26 minutes

Measurement of the Neutron Lifetime Using a Proton Trap

F. E. Wietfeldt
Tulane University

M.S. Dewey, D.M. Gilliam, and J.S. Nico
National Institute of Standards and Technology

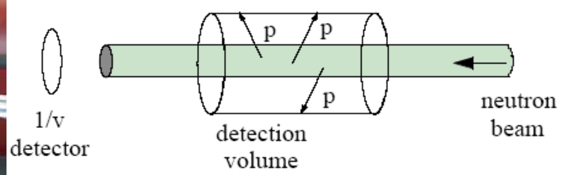
X. Fei and W.M. Snow
Indiana University

G.L. Greene
University of Tennessee

J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel
Institute for Reference Materials and Measurements, Belgium

April 5, 2004

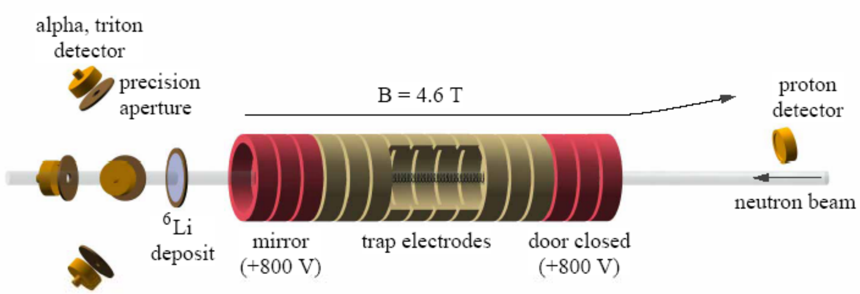
In-Beam Method

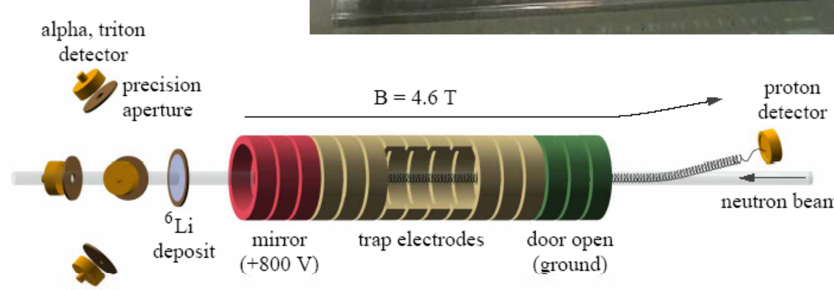


neutron decay rate $\Gamma = \frac{N}{\tau}$

$$\text{so } \tau = \frac{\phi\, V_{det}}{v\, \Gamma}$$

Need to measure:
1. decay rate Γ
2. effective decay volume V_{det}
   - *use linear extrapolation vs. trap length*
3. neutron flux weighted by inverse velocity
   - *use 1/v neutron flux monitor*





Result: $\tau = 886.8 \pm 1.2\ (\text{stat}) \pm 3.2\ (\text{syst})$ s

Phys. Rev. Lett. 91, 152302 (2003)

A "typical" UCN storage experiment at ILL – MamBo I

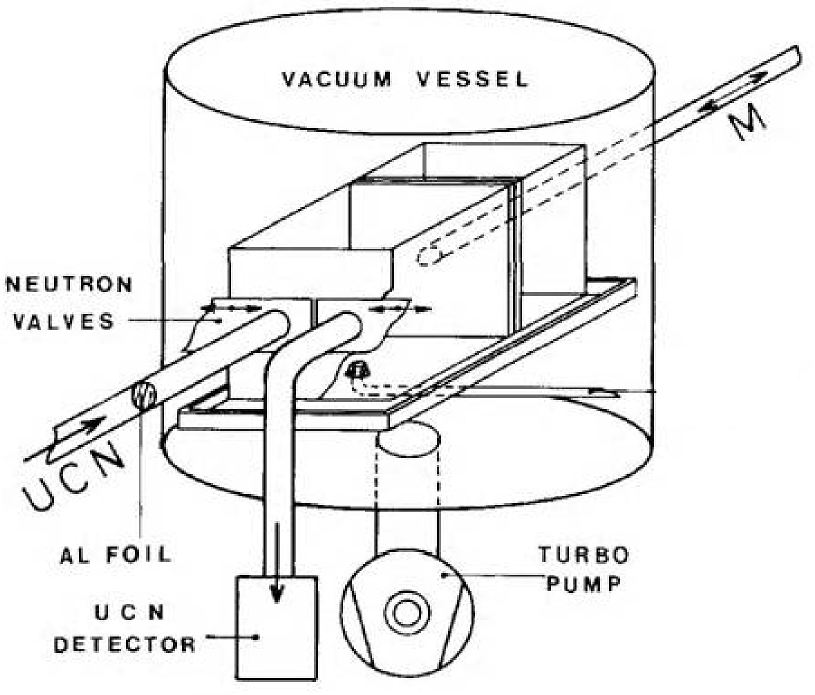


FIG. 1. Sketch of the apparatus.

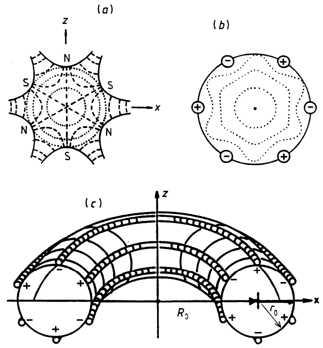
Glass walls:
H=0.3 m, W=0.4 m
L=0.5m … 0.01 m
(surface *A* and volume *V* sizeable)

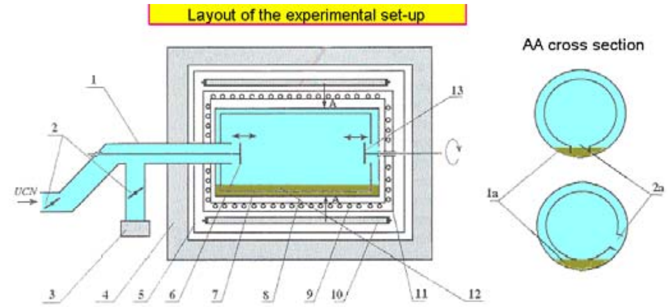
$$\frac{1}{\tau_m} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\text{wall}}} + \ldots$$

$\tau_{\text{wall}} \rightarrow$ number of wall collisions, i.e. mean free path λ

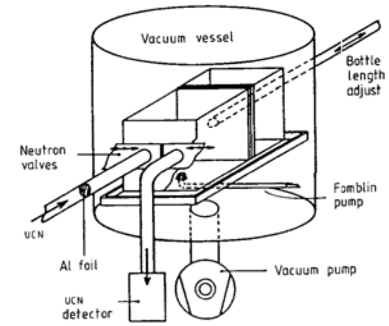
Measure storage lifetime τ_{st}
for different volume to surface ratios *V/A*
and extrapolate for $V \rightarrow \infty$

$$\frac{1}{\tau_{\text{wall}}} \rightarrow 0$$

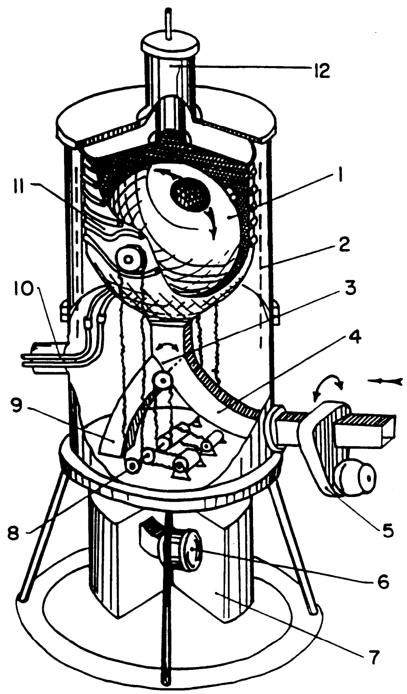


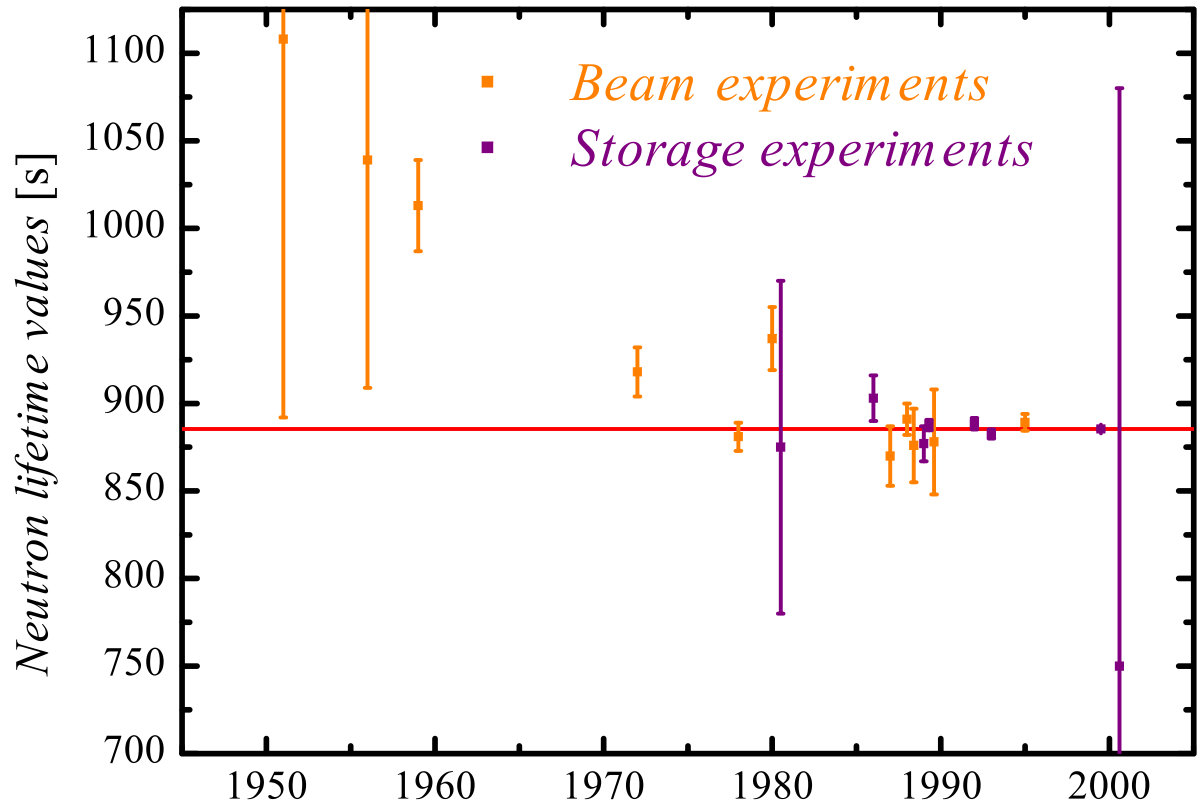


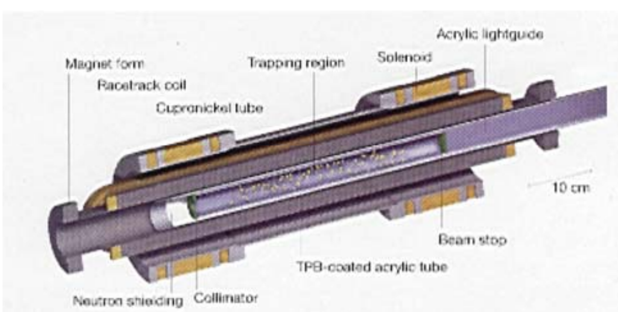
(1) UCN guide; (2) shutters; (3) UCN detector; (4) polyethylene shielding; (5) cadmium housing; (6) entrance shutter of the inner vessel; (7) inner storage vessel; (8) outer storage vessel; (9) cooling coil; (10) thermal neutron detector; (11) vacuum housing; (12) oil puddle; (13) entrance shutter of the annular vessel; (1a) oil puddle; (2a) slit.



$885.4 \pm 0.9_{stat} \pm 0.4_{sys}$

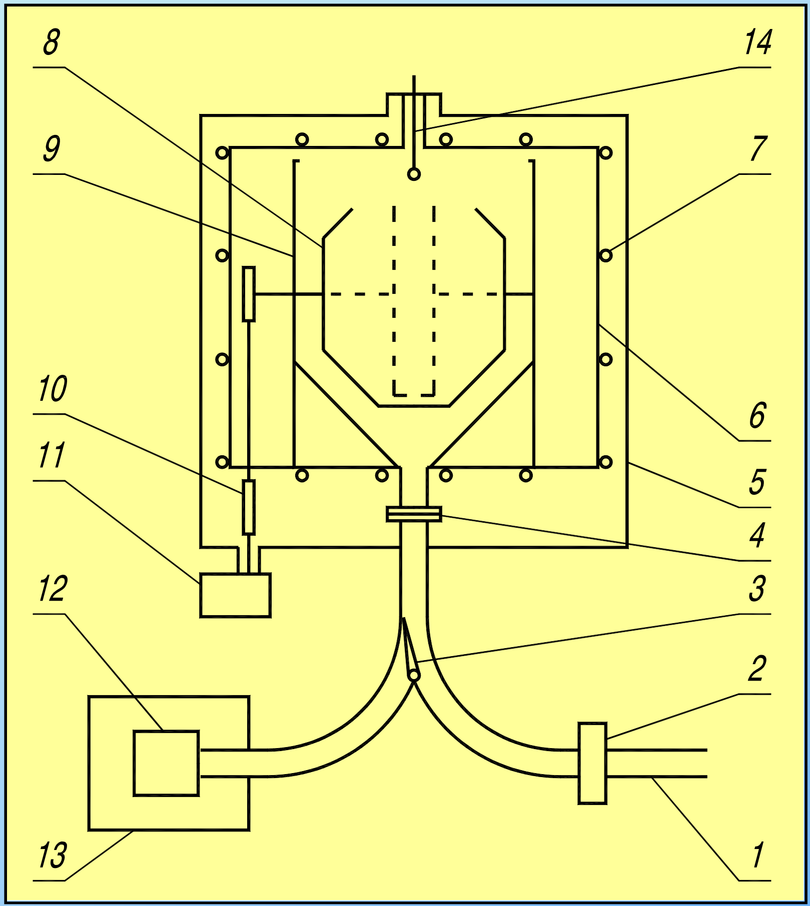






World average: $\tau_n = 885.7(8)$ s [PDG 2002]

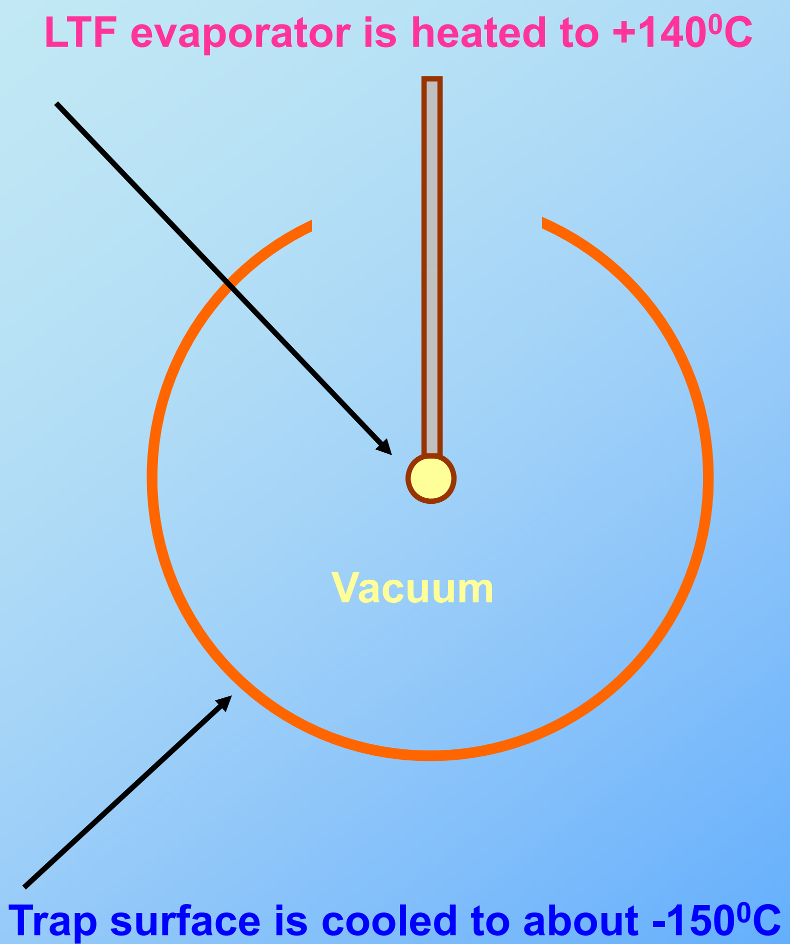
Scheme of "Gravitrap", the gravitational UCN storage system



UCN traps are made from copper:

1. quasi-spherical (cylinder + 2 truncated cones) trap, inner
2. narrow (14 cm) cylindrical trap, inner surface - sputtered
3. wide (50 cm) cylindrical trap, inner surface - sputtered tita

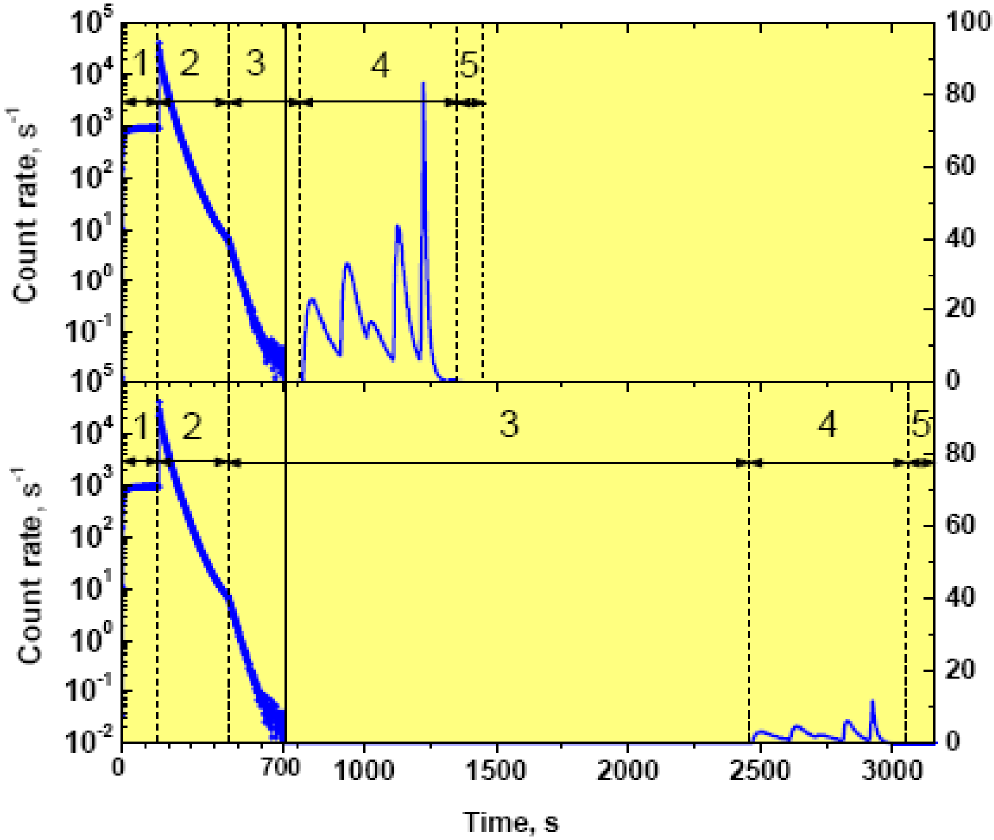
Deposition of LTF on the trap surface



The chemical formula of LTF contains only C, O and F.
Molecular weight - 2354
Density at r.t. 1.825 g/ml
Vapour pressure at r.t. $1.5*10^{-3}$ mbar
Fermi potential 102.8 neV

Calculation based on cold neutron transmission data predicts for LTF at 190K $\eta=2*10^{-6}$ (Yu.N.Pokotilovski, JETP 96, 2003)
confirmed in a recent experiment at PF2/TES by V. Morozov et al.

Typical measuring cycle

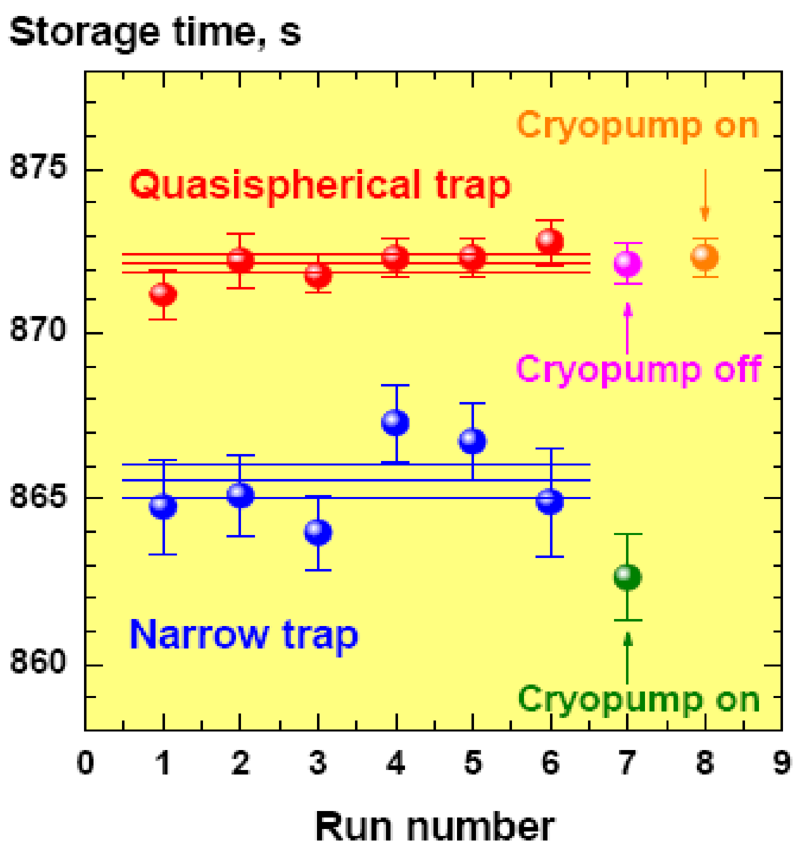


1. filling 160 s (time of trap rotation (35 s) to monitoring position is included);
2. monitoring 300 s;
3. holding 300 s or 2000 s (time of trap rotation (7 s) to holding position is included);
4. emptying has 5 periods 150 s, 100 s, 100 s, 100 s, 150 s (time of trap rotation (2.3 s, 2.3 s, 2.3 s, 3.5 s, 24.5 s) to each position is included);
5. measurement of background 100 s.

$$N(t_2) = N(t_1) \cdot \exp\left(-\frac{t - t_1}{\tau_{st}}\right)$$

$$\tau_{st} = \frac{t_2 - t_1}{ln\left(N(t_1)/N(t_2)\right)}$$

Measurement of UCN storage times



Results:

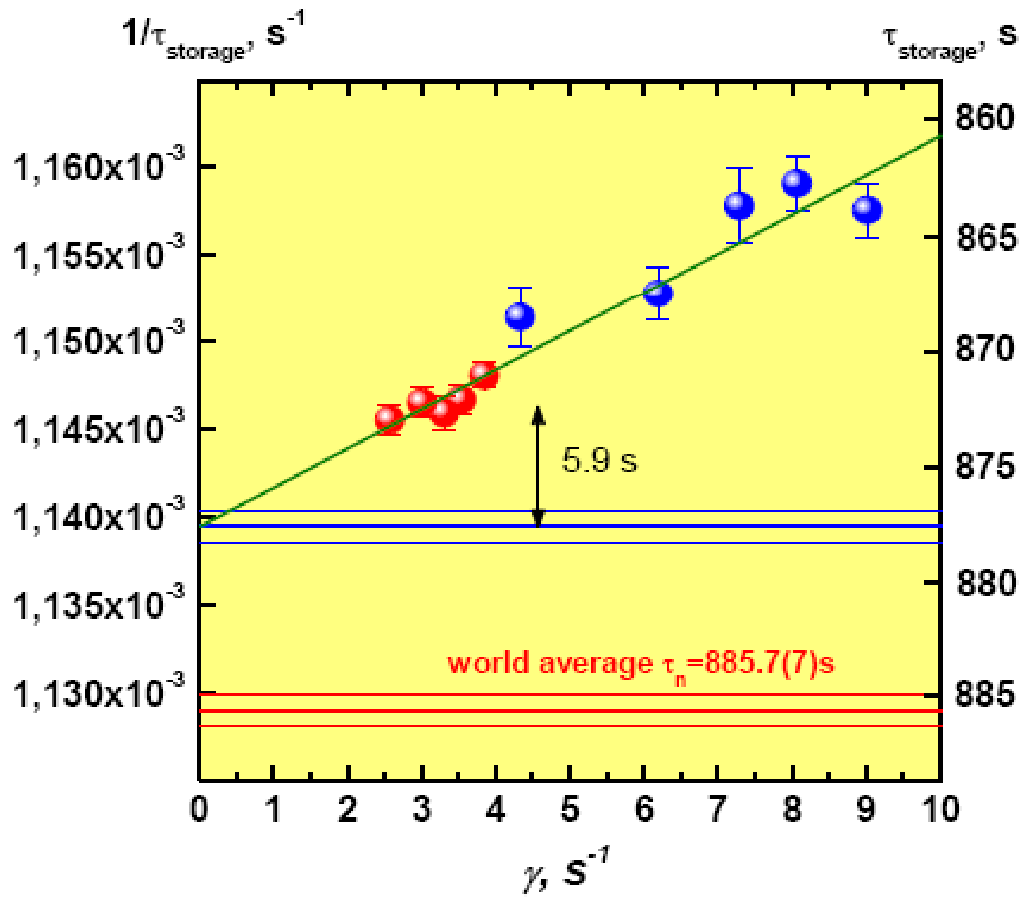
quasispherical trap

$\tau_{st} = 872.2 \pm 0.3\ s$

narrow trap

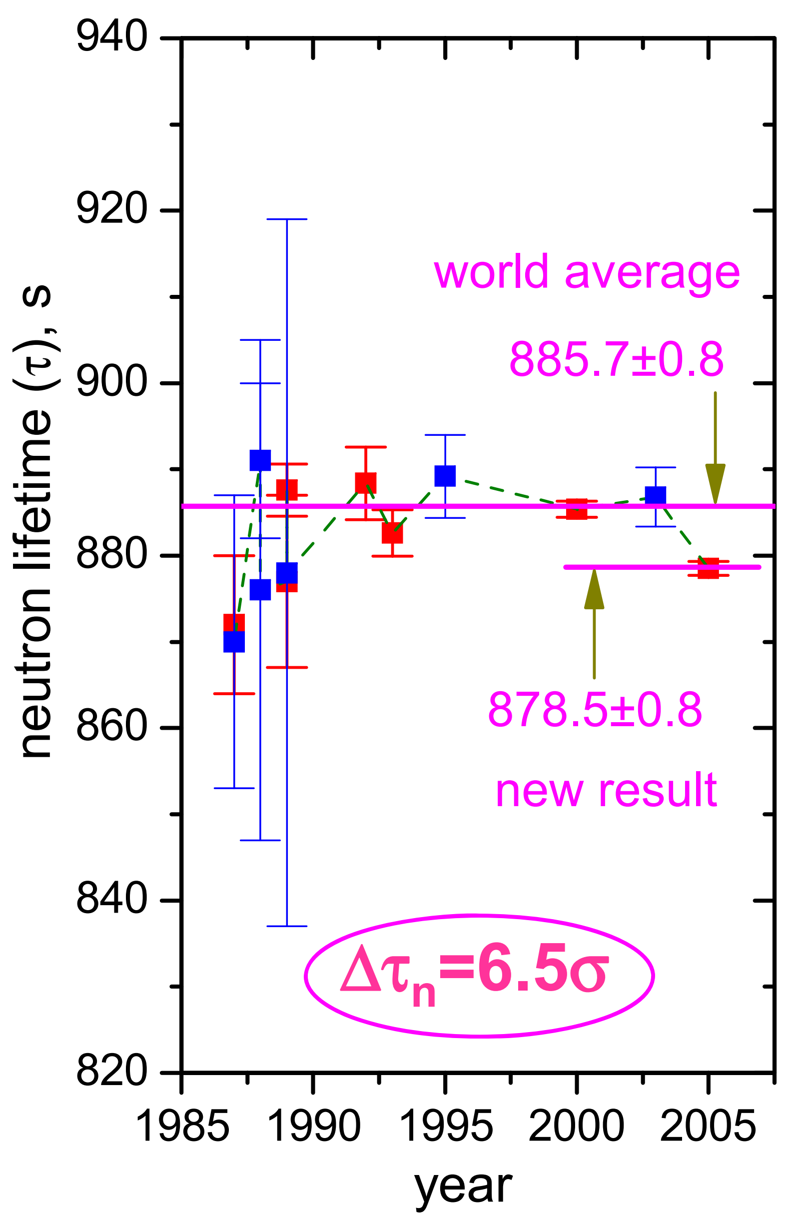
$\tau_{st} = 865.6 \pm 0.6\ s$

Extrapolation to n-lifetime



Neutron lifetime: world average and new result

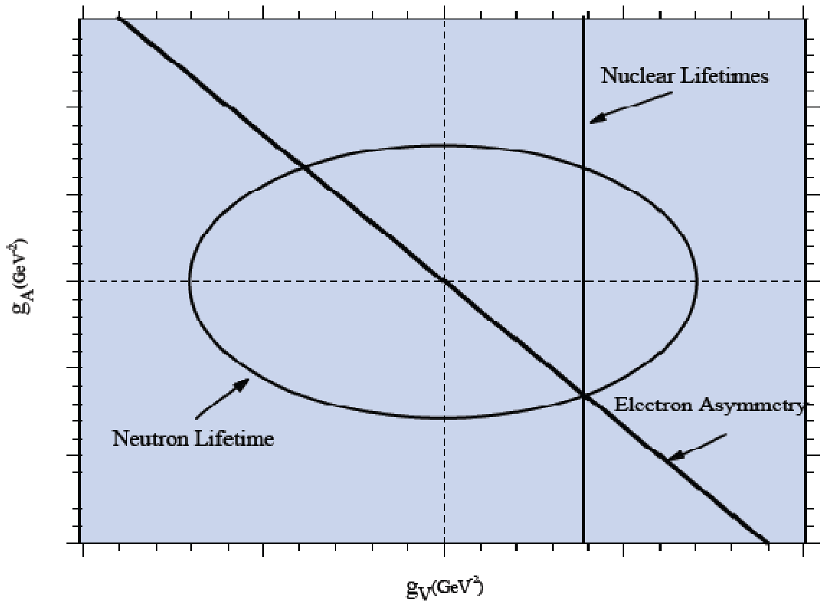
Lifetime τ[s]	Method	Ref./Year
878.5 ± 0.8 878.5 ± 0.7_{stat} ± 0.3_{sys}	Storage of ultra-cold neutrons	Serebrov et al. 2005 PLB 605(2005)72
886.8 ± 3.42	Neutron beam experiment	M.S. Dewey et al. 2003
885.4 ± 0.95 885.4 ± 0.9_{stat} ± 0.4_{sys}	Storage of ultra-cold neutrons	S. Arzumanov et al. 2000 PLB 483(2000)15
889.2 ± 4.8	Neutron beam experiment	J. Byrne et al. 1995
882.6 ± 2.7	Storage of ultra-cold neutrons	W. Mampe et al. 1993
888.4 ± 3.1 ± 1.1	Storage of ultra-cold neutrons	V. Nesvizhevski et al. 1992
878 ± 27 ± 14	Neutron beam experiment	R. Kosakowski 1989
887.6 ± 3.0	Storage of ultra-cold neutrons	W. Mampe et al. 1989
877 ± 10	Storage of ultra-cold neutrons	W. Paul et al. 1989
876 ± 10 ± 19	Neutron beam experiment	J. Last et al. 1988
891 ± 9	Neutron beam experiment	P. Spivac et al. 1988
872 ± 8	Storage of ultra-cold neutrons	A. Serebrov et al. 1987
870 ± 17	Neutron beam experiment	M. Arnold et al. 1987
903 ± 13	Storage of ultra-cold neutrons	Y.Y. Kosvintsev et al. 1986
875 ± 95	Storage of ultra-cold neutrons	Y.Y. Kosvintsev et al. 1980
937 ± 18	Neutron beam experiment	J. Byrne et al. 1980
881 ± 8	Neutron beam experiment	L. Bondarenko et al. 1978
918 ± 14	Neutron beam experiment	C.J. Christensen et al. 1972
885.7 ± 0.8	world average 2004	PDG 2004



Standard Model Test

$$dW \propto (g_V^2 + 3g_A^2)F(E_e)[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + \vec{\sigma_n}\cdot(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_e E_\nu})]$$

Jackson, Treiman, Wyld, *Nucl. Phys.* **4**, 206 (1957)



Lifetime

$$\tau = \frac{1}{f(1+\delta_R)}\frac{K/ln2}{(1+\Delta_R^V)(g_V^2+3g_A^2)} = (885.7 \pm 0.8)\,\mathrm{s}$$

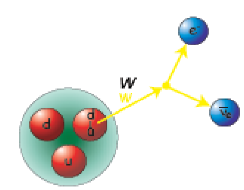
Spin-electron asymmetry

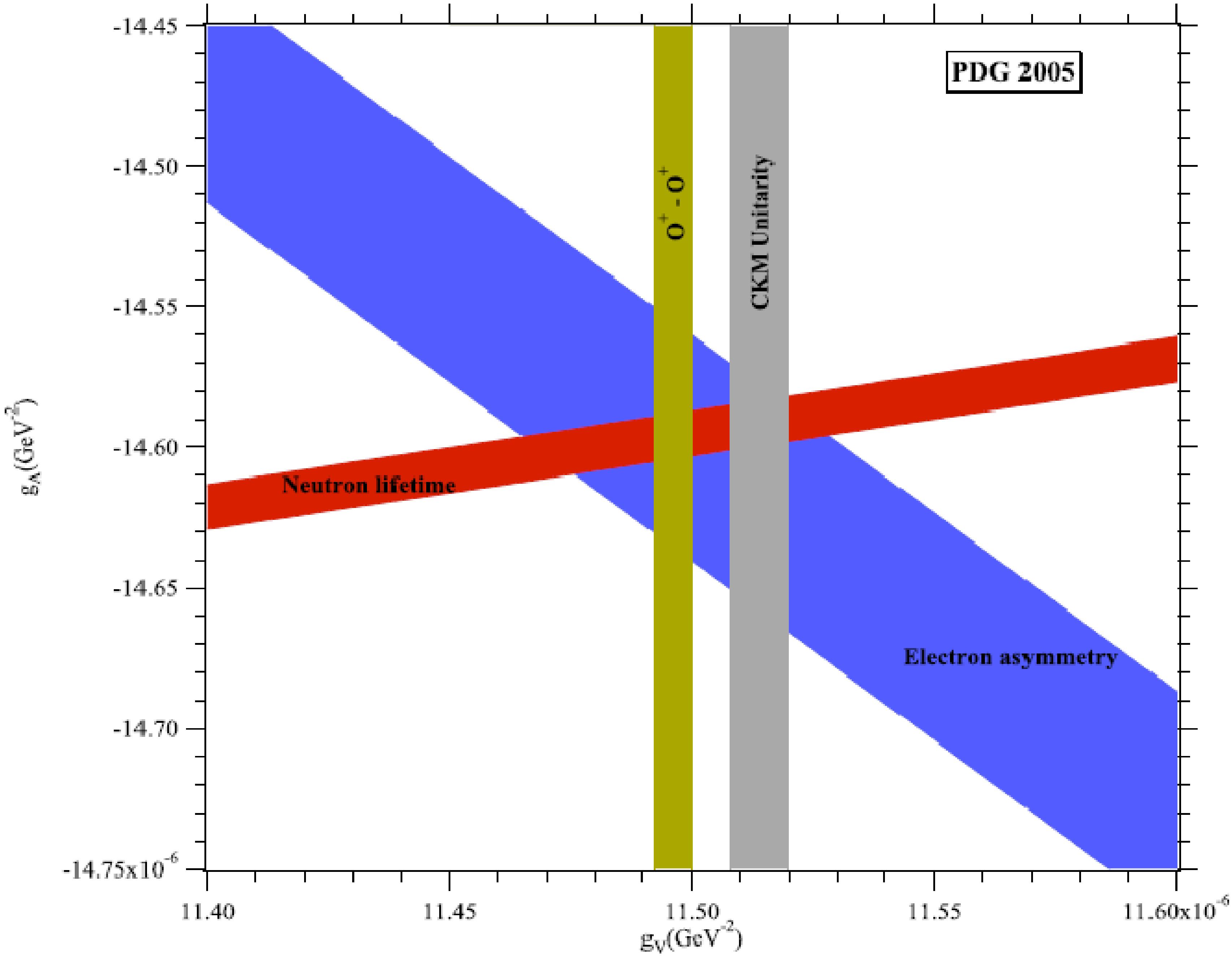
$$A = -2\frac{|\lambda|^2 + |\lambda|cos\phi}{1+3|\lambda|^2} = (-0.1173 \pm 0.0013)$$

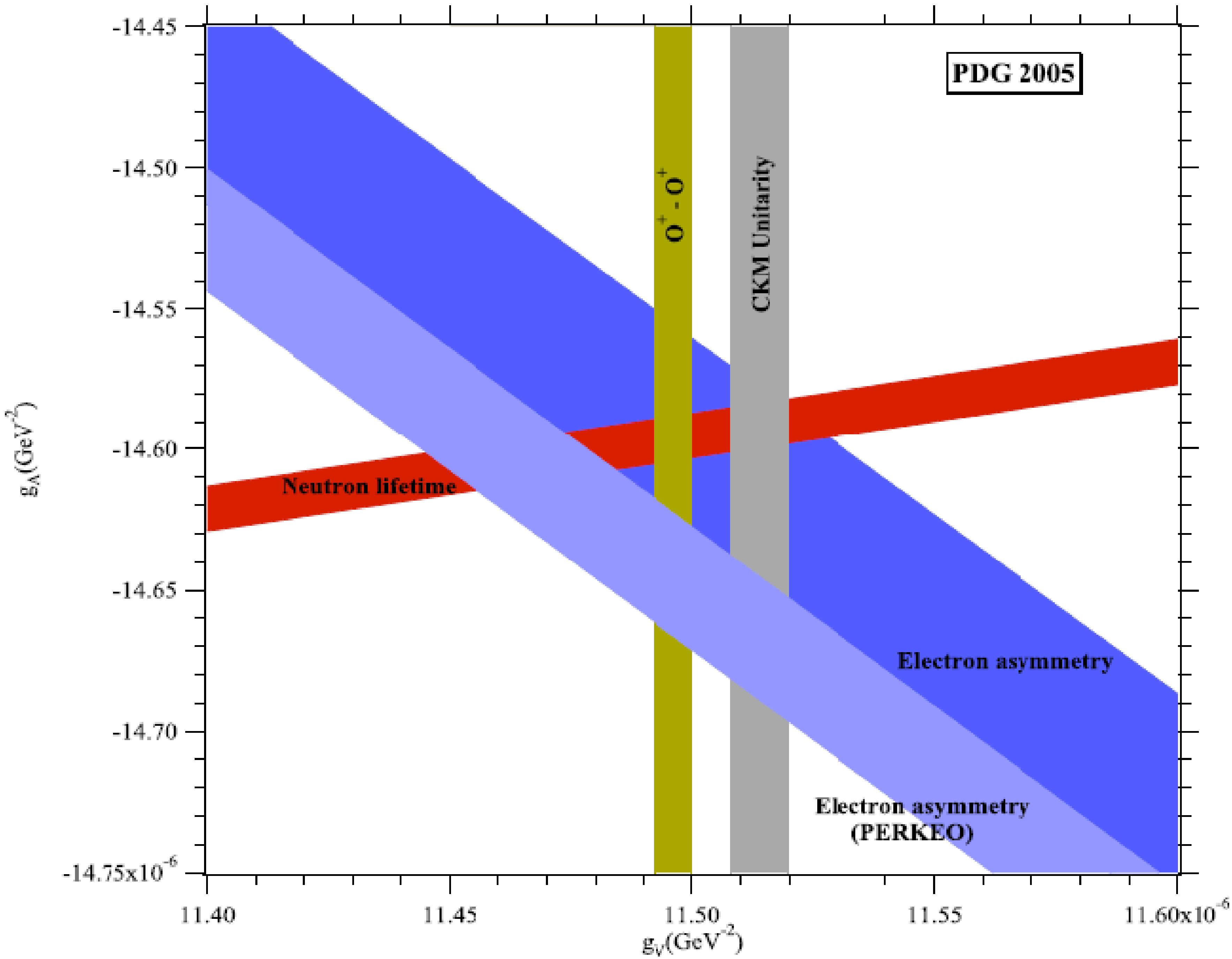
CKM matrix represents a rotation of the quark mass eigenstates to the weak eigenstates.

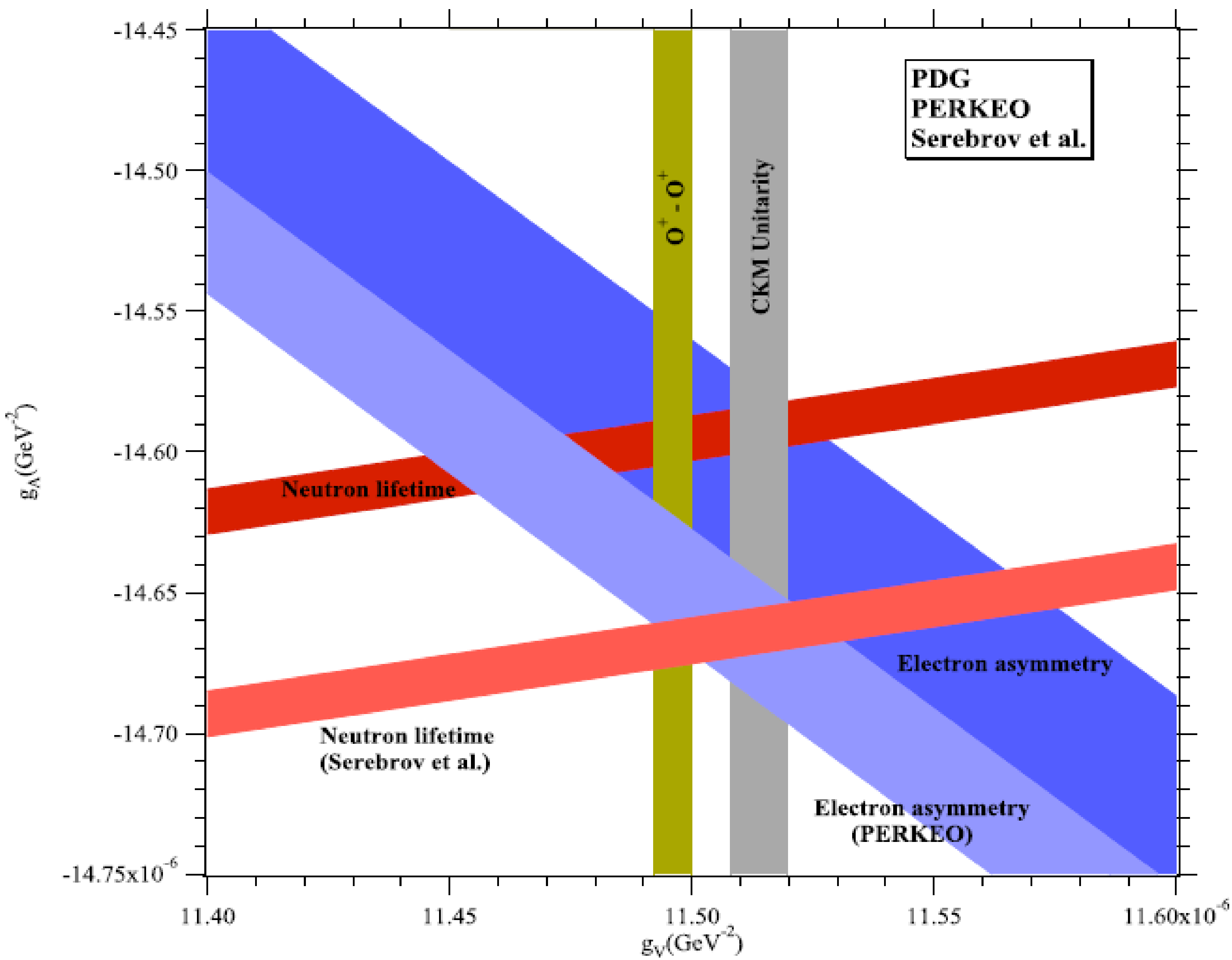
$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

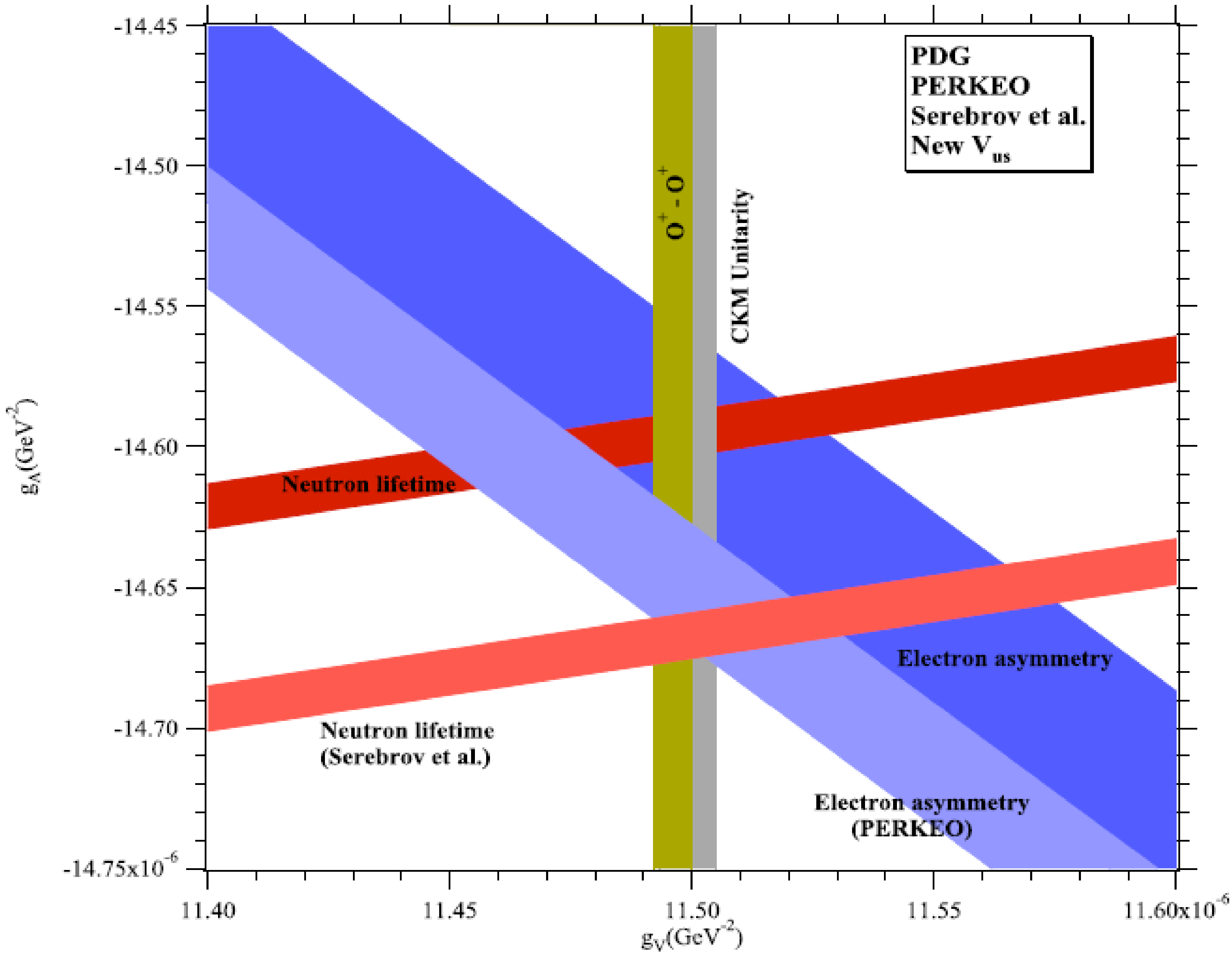
- Unitarity requires $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- $|V_{us}|$ and $|V_{ub}|$ are obtained from high-energy experiments; experimental and theoretical issues with $|V_{us}|$ from kaon decays.
- $|V_{ud}|$ obtained from
  1. nuclear lifetimes,
  2. pion beta decay, and
  3. neutron beta decay.




PDG 2005
$0^+ - 0^+$
CKM Unitarity
Neutron lifetime
Electron asymmetry
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10^-6
$g_A(\mathrm{GeV}^{-2})$
11.40
11.45
11.50
11.55
11.60x10^-6
$g_V(\mathrm{GeV}^{-2})$


PDG 2005
0^+ - 0^+
CKM Unitarity
Neutron lifetime
Electron asymmetry
Electron asymmetry (PERKEO)
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10^{-6}
g_A(GeV^{-2})
11.40
11.45
11.50
11.55
11.60x10^{-6}
g_V(GeV^{-2})


PDG
PERKEO
Serebrov et al.
0+ - 0+
CKM Unitarity
Neutron lifetime
Neutron lifetime
(Serebrov et al.)
Electron asymmetry
Electron asymmetry
(PERKEO)
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10-6
gA(GeV-2)
11.40
11.45
11.50
11.55
11.60x10-6
gV(GeV-2)


PDG
PERKEO
Serebrov et al.
New V_{us}
$0^+ - 0^+$
CKM Unitarity
Neutron lifetime
Electron asymmetry
Neutron lifetime (Serebrov et al.)
Electron asymmetry (PERKEO)
$g_A(GeV^{-2})$
$g_V(GeV^{-2})$
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
$-14.75x10^{-6}$
11.40
11.45
11.50
11.55
$11.60x10^{-6}$

n MEAN LIFE

We now compile only direct measurements of the lifetime, not those inferred from decay correlation measurements. For the average, we only use measurements with an error less than 10 s.

The most recent result, that of SEREBROV 05, is so far from other results that it makes no sense to include it in the average. It is up to workers in this field to resolve this issue. Until this major disagreement is understood our present average of 885.7 ± 0.8 s must be suspect.

For an early review, see EROZOLIMSKII 89 and papers that follow it in an issue of NIM devoted to the "Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons" (Grenoble 1989). For later reviews and/or commentary, see FREEDMAN 90, SCHRECKENBACH 92, and PENDLEBURY 93.

Limits on lifetimes for *bound* neutrons are given in the section "*p* PARTIAL MEAN LIVES."

VALUE (s)	*DOCUMENT ID*		*TECN*	*COMMENT*
885.7± 0.8 OUR AVERAGE				
886.3± 1.2± 3.2	NICO	05	CNTR	In-beam *n*, trapped *p*
885.4± 0.9± 0.4	ARZUMANOV	00	CNTR	UCN double bottle
889.2± 3.0± 3.8	BYRNE	96	CNTR	Penning trap
882.6± 2.7	[9] MAMPE	93	CNTR	Gravitational trap
888.4± 3.1± 1.1	NESVIZHEV...	92	CNTR	Gravitational trap
887.6± 3.0	MAMPE	89	CNTR	Gravitational trap
891 ± 9	SPIVAK	88	CNTR	Beam

• • • We do not use the following data for averages, fits, limits, etc. • • •

W.-M. Yao et al. (Particle Data Group),

J. Phys. G 33, 1 (2006) and 2007 partial update for edition 2008 (URL: http://pdg.lbl.gov)

The most recent result, that of SEREBROV 05, is so far from other results that it makes no sense to include it in the average.
It is up to workers in this field to resolve this issue.
Until this major disagreement is understood
our present average of 885.7 ± 0.8 s must be suspect.

Proton counting experiments at KI in Moscow

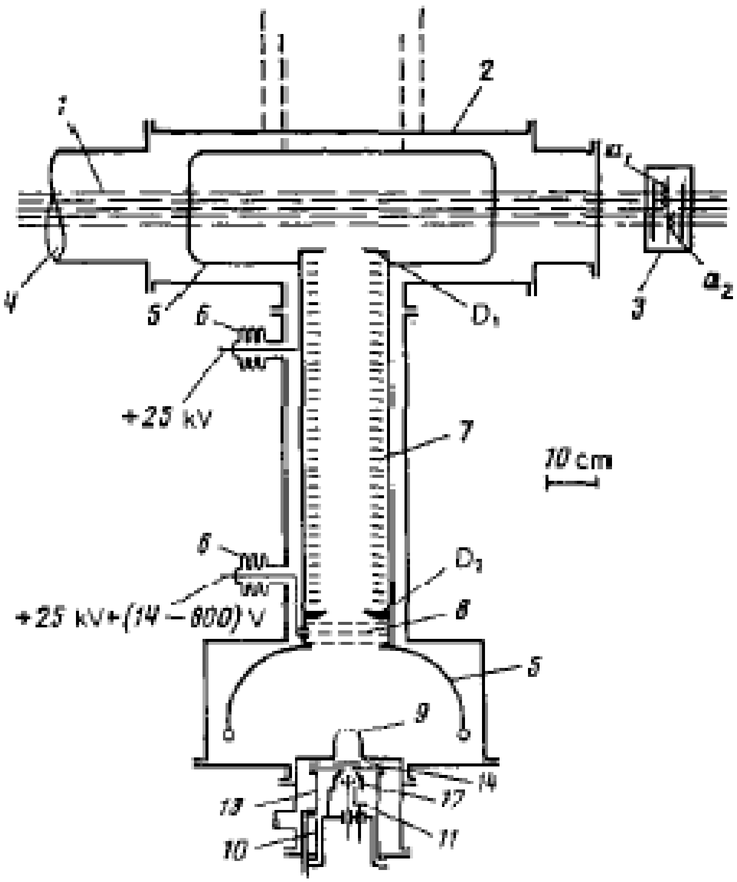


Figure 8. The IAE neutron lifetime experiment counting decay protons [13, 20]. 1, neutron beam; 2, vacuum chamber; 3, monitor chamber (a_1 and a_2 are ^{233}U layers); 4, channel for passage of extracted neutron beam to a trap and to a vacuum post; 5, electrodes; 6, ceramic insulators; D_1, D_2, diaphragms; 7, aluminium-foil rings; 8, electrostatic filter grids; 9, hemispherical grid; 10, detector vacuum chamber; 11, detector gas-filled volume; 12, detector comprising a proportional counter with a drift grid; 13, film-covered detector port; 14, valve separating the volumes of chambers 2 and 10.

First version in 1958: T_n = 1013 (26) s

1978 result: T_n = 877 (11) s

In 1988 slightly revised: T_n = 891 (9) s

In 1980 Byrne et al. found T_n = 937 (18) s [withdrawn in the meantime]. They concluded in a Letter to Nature 310, 212 (1984)
"… a third direct measurement has given the value T_n = 877 (11) s, which is totally at variance with all other evidence. We suggest here that …. exclude values of T_n outside the range 911 (10) …

Письма в ЖЭТФ, том 23, вып. 2, стр. 135 — 138 20 янв

ХРАНЕНИЕ УЛЬТРАХОЛОДНЫХ НЕЙТРОНОВ
В СОСУДЕ С МАГНИТНОЙ "СТЕНКОЙ"

"UCN storage in the vessel with magnetic wall."

JETP Letters 23(3), 1976

Y.Y.Kosvintsev, Y.A.Kushnir, V.I.Morozov

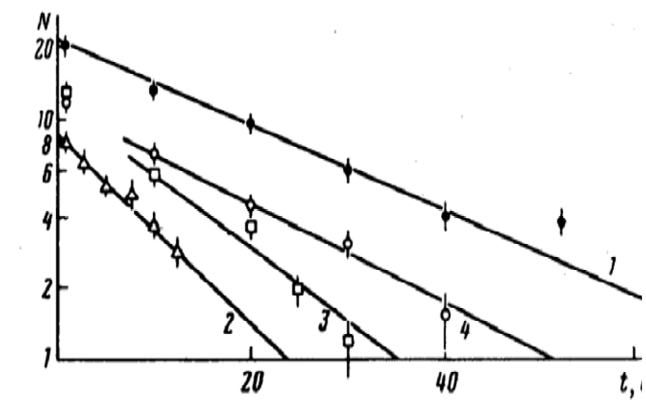


Рис. 2. Зависимость числа УХН, оставшихся в сосуде, от врем
нения: *1* – торец сердечника покрыт медной фольгой, электром
отключен, *2* – торец сердечника покрыт полиэтиленом, электро
отключен, *3* – торец покрыт полиэтиленом, электромагнит вкл
4 – торец покрыт полиэтиленом, электромагнит включен, солен
дущего поля включен

T=25±2 sec

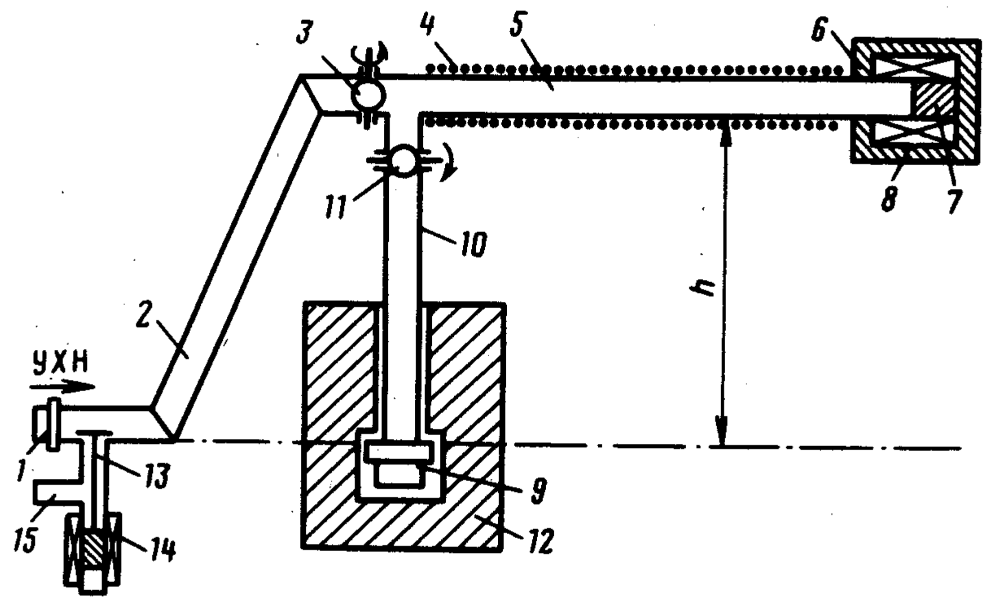
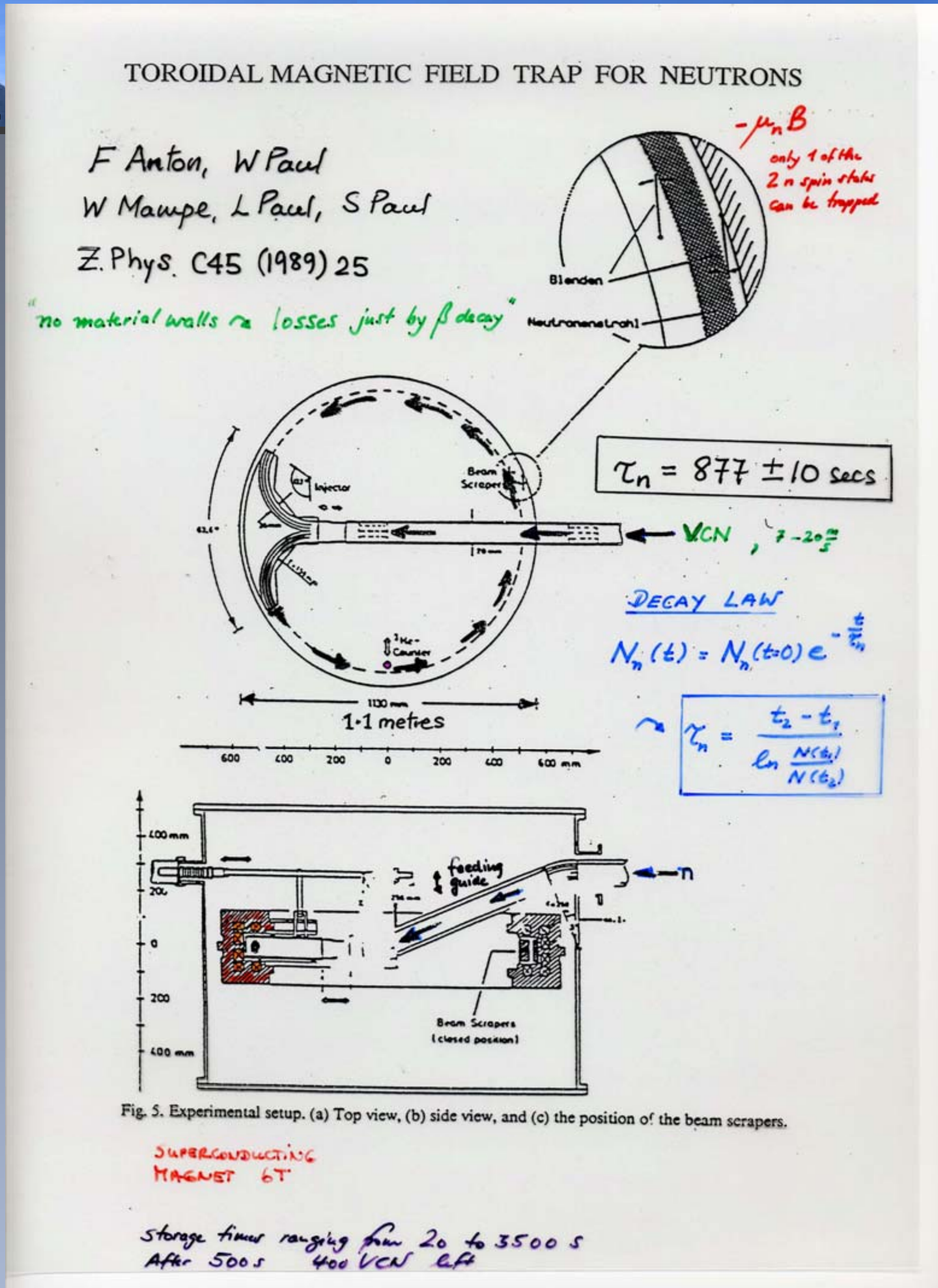
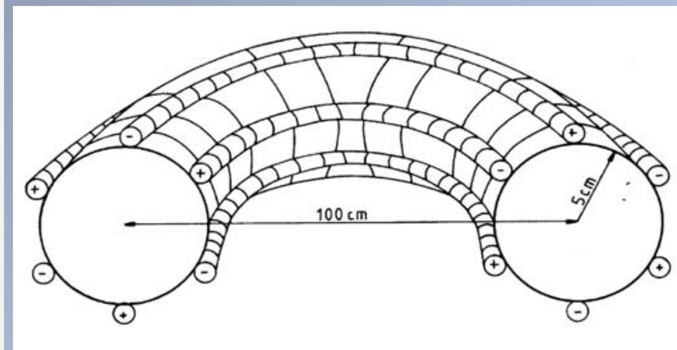
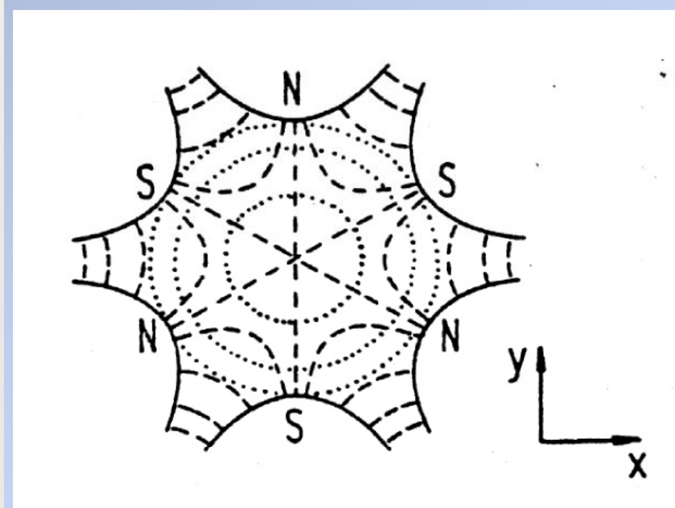


Рис. 1. Схема эксперимента по хранению УХН в сосуде с магнитной "ст. ко": *1* – выходной патрубок установки для извлечения УХН, *2* – наклонный нейтроновод, *3* – впускная заслонка, *4* – соленоид ведущего поля, *5* – сосуд для хранения УХН; *6* – панцирь электромагнита, *7* – сердечник электромагнита, *8* – соленоид, *9* – детектор УХН, *10* – вертикальный канал, *11* – заслонка детектора, *12* – защита детектора; *13* – клапан откачки, *14* – электромагнит клапана, *15* – патрубок откачки

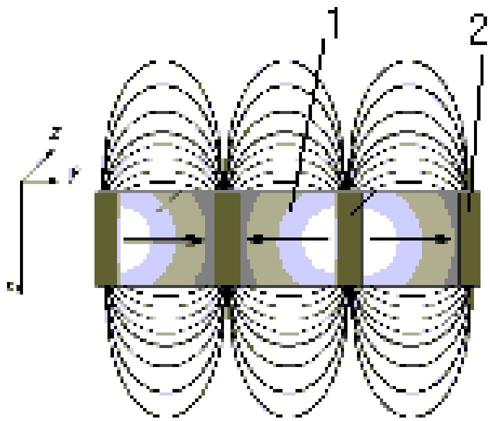

TOROIDAL MAGNETIC FIELD TRAP FOR NEUTRONS
F Anton, W Paul
W Mampe, L Paul, S Paul
Z. Phys. C45 (1989) 25
"no material walls ~ losses just by β decay"
$-\mu_n B$
only 1 of the 2 n spin states can be trapped
Blenden
Neutronenstrahl
$\tau_n = 877 \pm 10$ secs
Injector
Beam Scraper
VCN, 7 - 20 m/s
DECAY LAW
$N_n(t) = N_n(t{=}0)\, e^{-t/\tau_n}$
$\tau_n = \frac{t_2 - t_1}{\ln \frac{N(t_1)}{N(t_2)}}$
1100 mm
1·1 metres
600 400 200 0 200 400 600 mm
400 mm
200
0
200
400 mm
feeding guide
n
Beam Scrapers (closed position)
Fig. 5. Experimental setup. (a) Top view, (b) side view, and (c) the position of the beam scrapers.
SUPERCONDUCTING MAGNET 6T
Storage times ranging from 20 to 3500 s
After 500 s 400 VCN left


100 cm
5cm

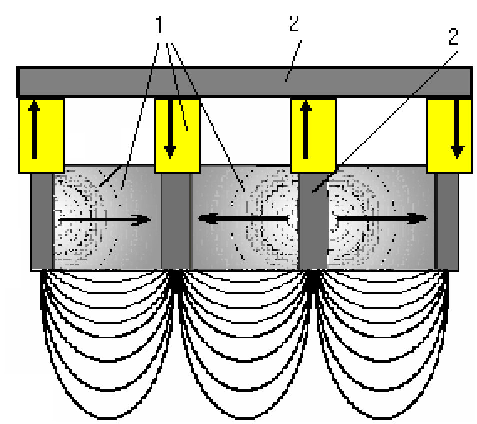

N
S
S
N
N
S
y
x

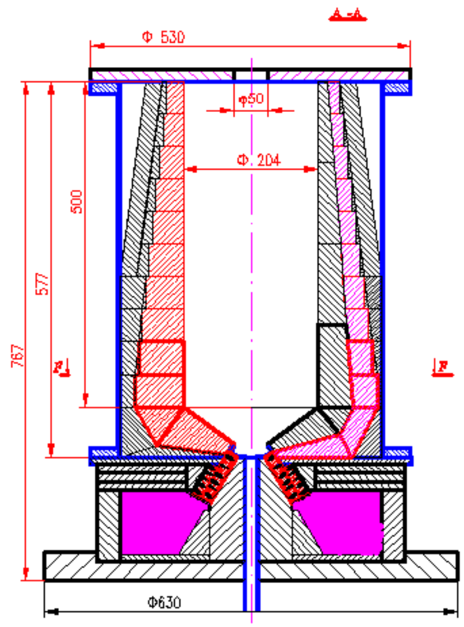
Neutron Storage Bottle

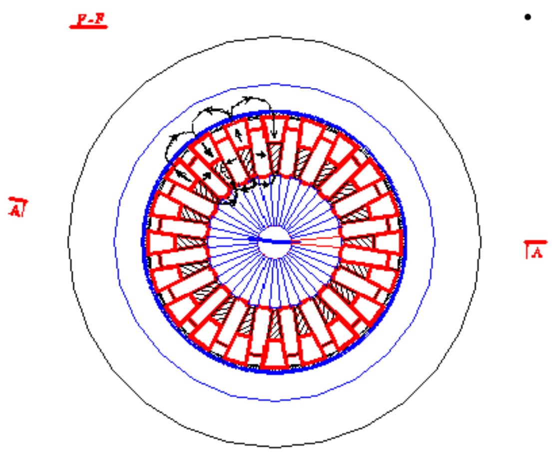
made of permanent magnets



1 – permanent magnet
2 – magnetic field guide







Reflection of UCN by magnetic barrier

W. Paul, in Proc. Int. Conf. on Nuclear Physics and Physics of Fundamental Particles, Chicago, 1951.

V.V. Vladimirskii, Sov.Phys. - JETP 12, 740, 1961

- Magnetic potential $U = -\vec{\mu} \cdot \vec{B}$
- For magnetic moment of neutron $U = 0.6 \cdot 10^{-7}\, eV \cdot T^{-1}$
- Nuclear potential of Be $2.5 \cdot 10^{-7}\, eV$
- Magnetic field 1 T reflects neutrons up to 3.4 m/s, as Al.
- $F = -\nabla U = \nabla(\vec{\mu} \cdot \vec{B}) = \pm \mu \nabla \left| \vec{B} \right|$
- + for $\vec{\mu} \uparrow\uparrow \vec{B}$ and
- – for $\vec{\mu} \uparrow\downarrow \vec{B}$

560 permanent magnets (made of Nd-Fe-Be) (~ 1 cm broad)

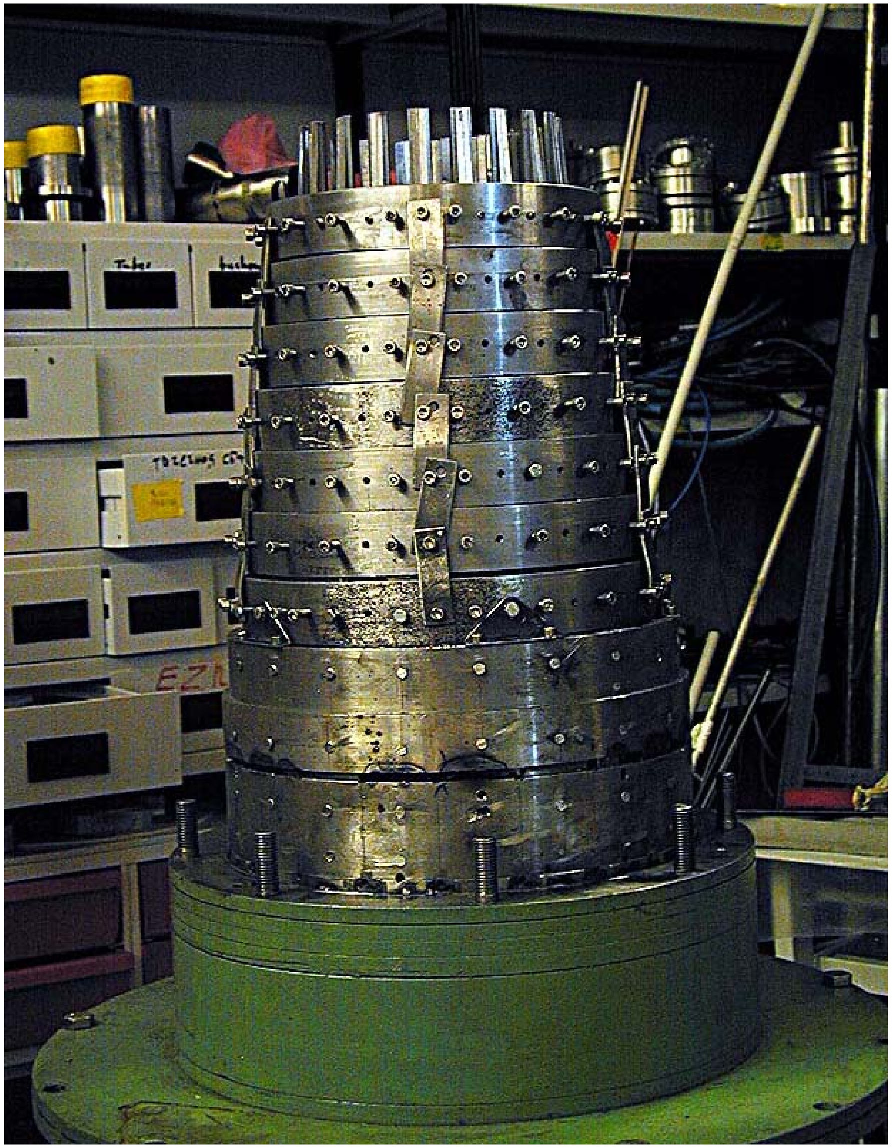
horizontal magnetization

$B_r \geq 1.2$ T ; gradient ~ 2T/cm

FeCo poles between the magnets

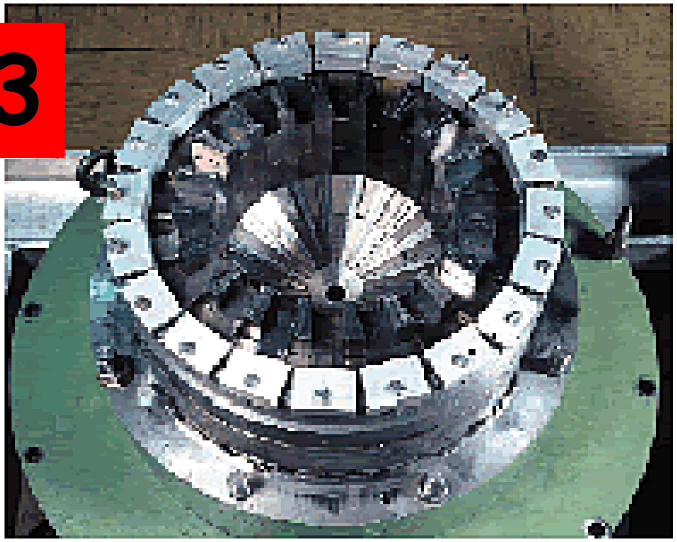
twenty-pole magnetic system

2004

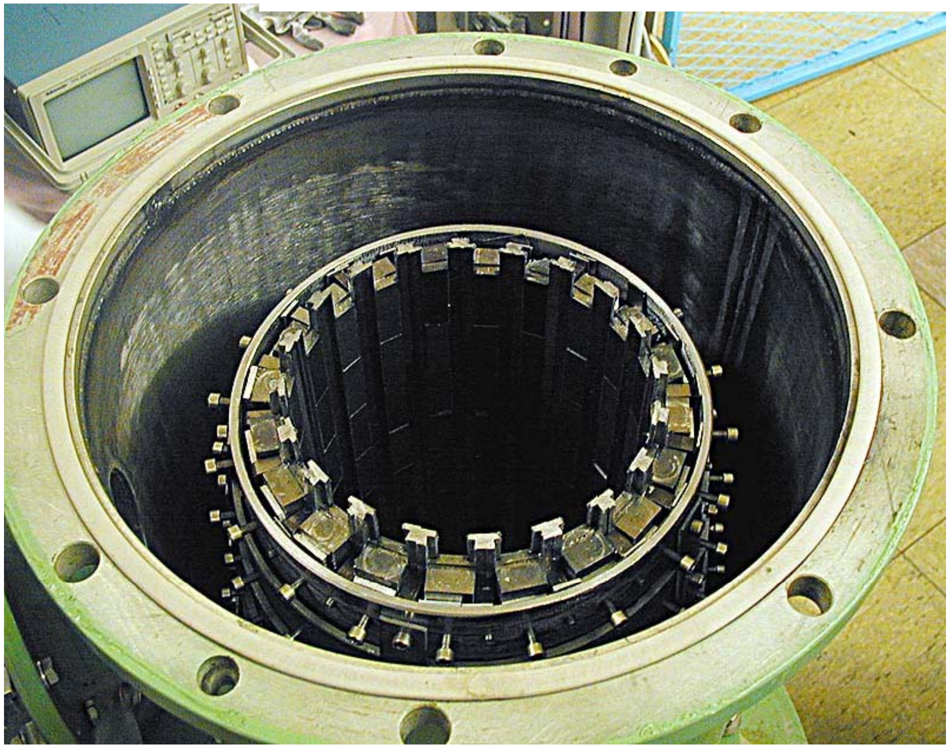


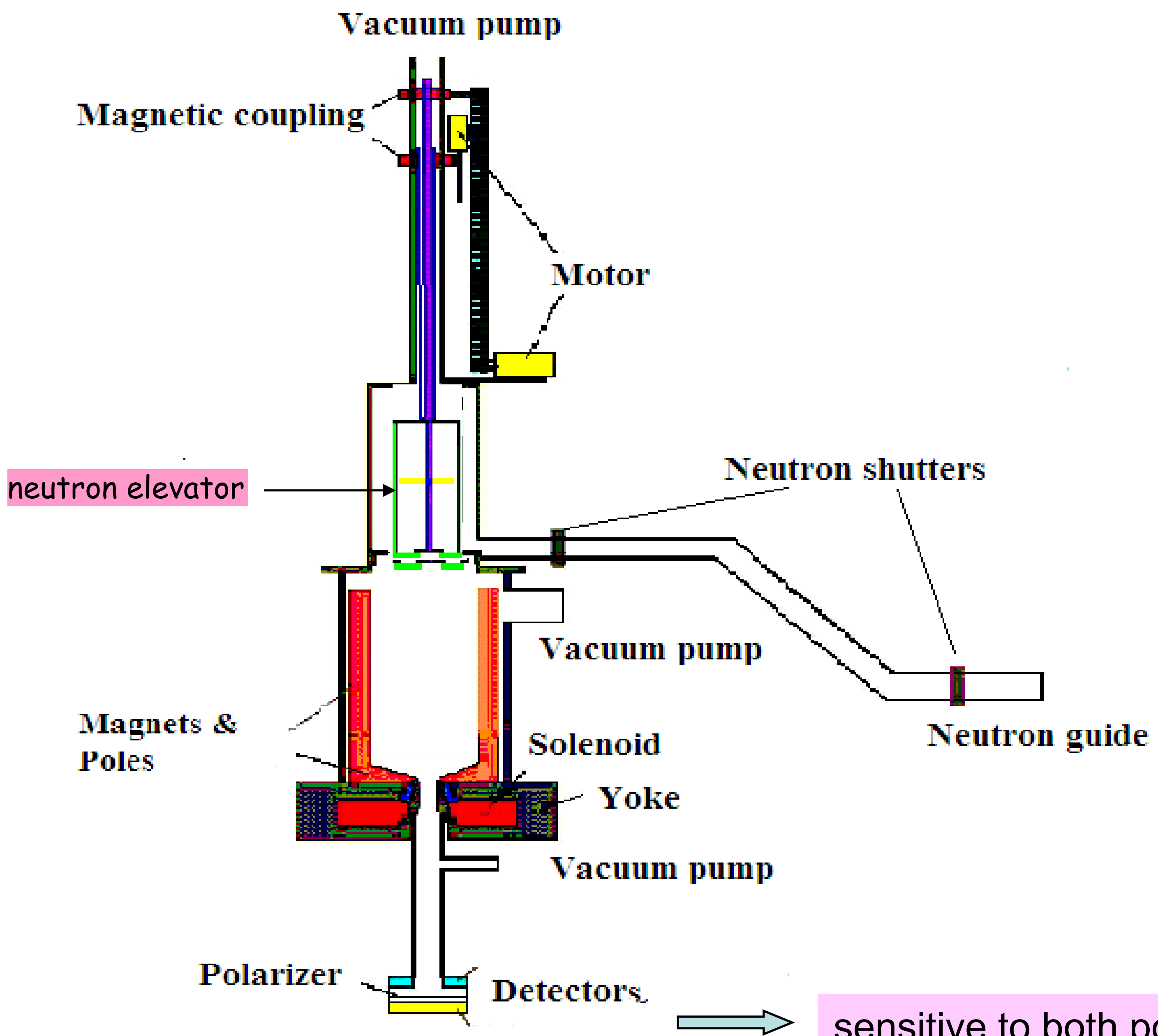
increase storage volume from 3.6 l to **15 l**

2003

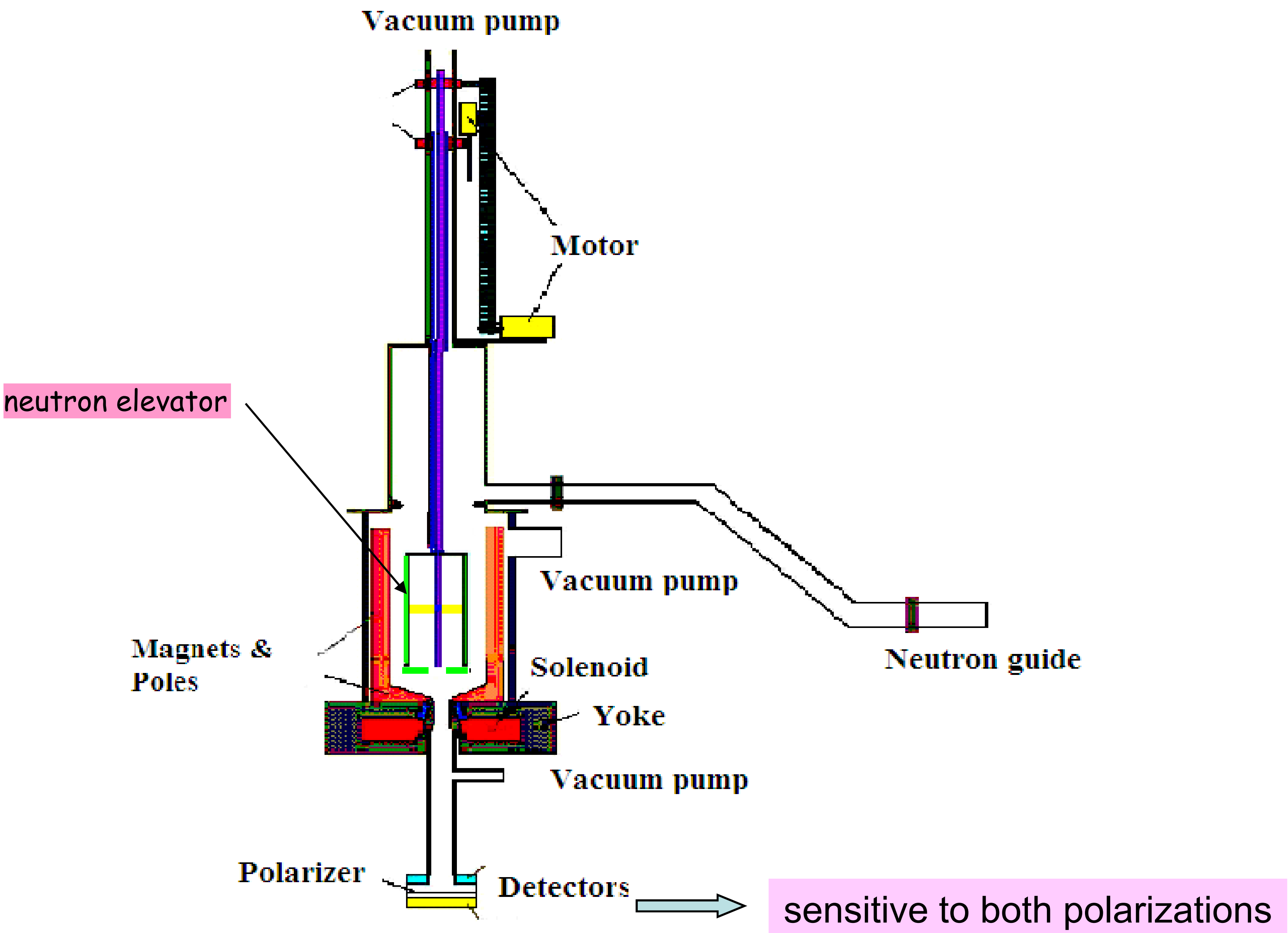


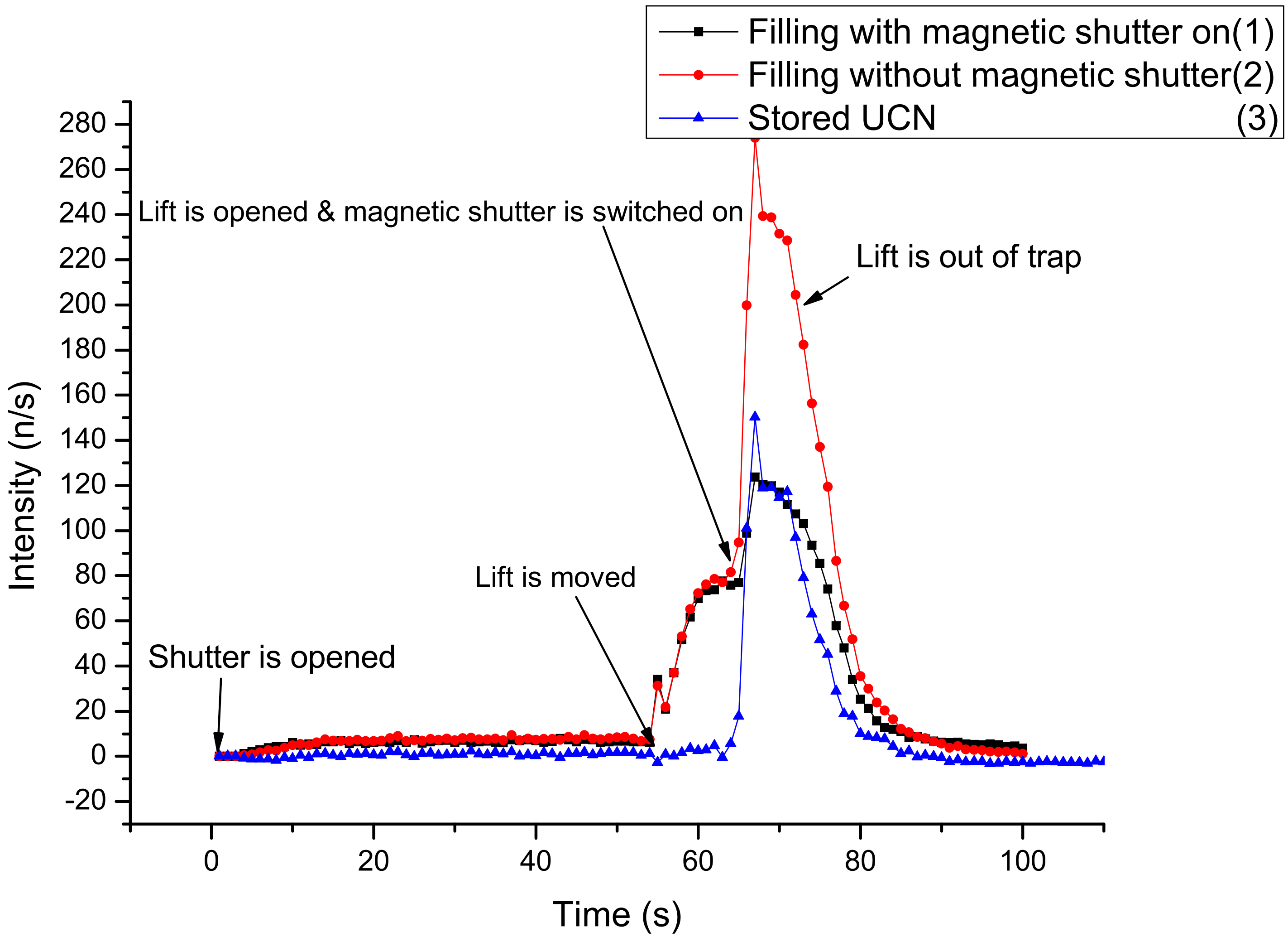
Top view of the storage bottle made of permanent magnets.





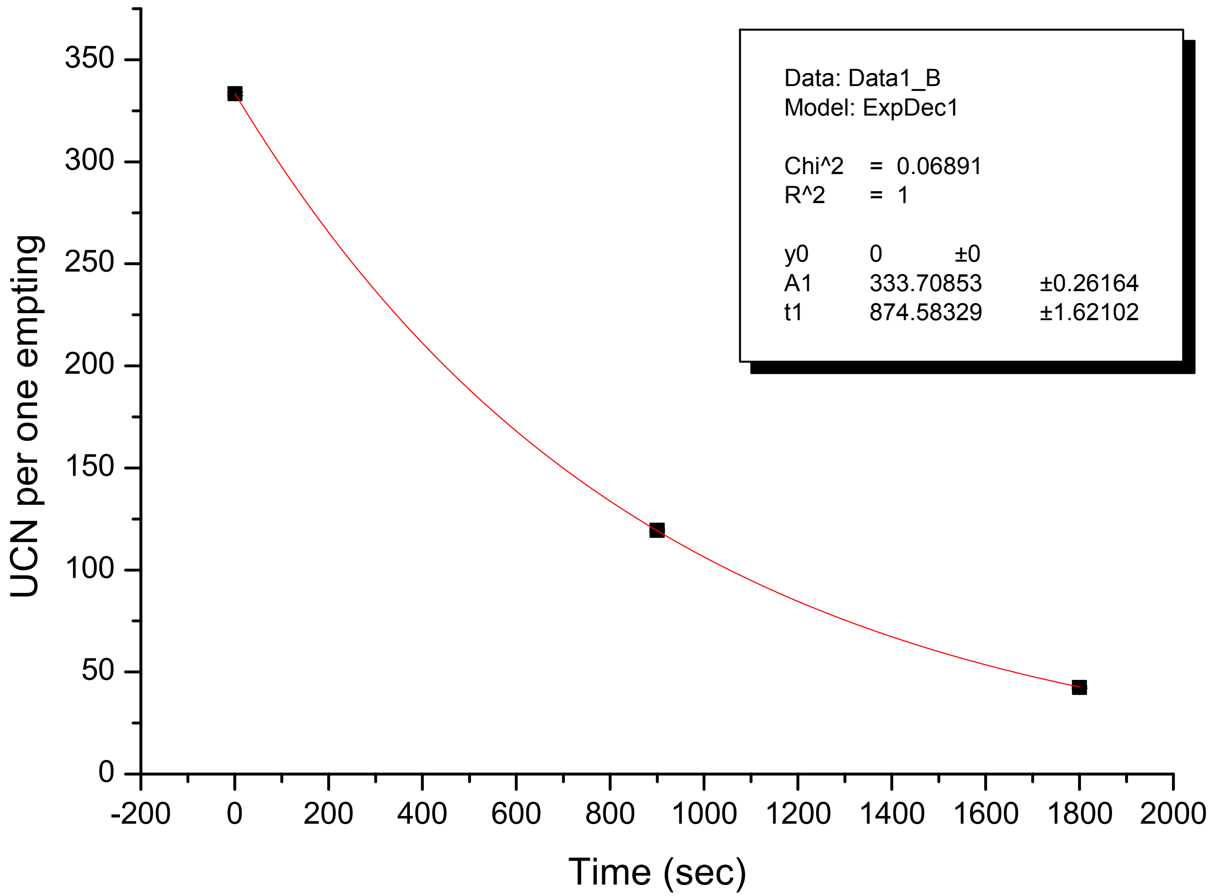
sensitive to both polarizations


Vacuum pump
Motor
neutron elevator
Vacuum pump
Magnets &
Poles
Solenoid
Neutron guide
Yoke
Vacuum pump
Polarizer
Detectors
sensitive to both polarizations



Filling with magnetic shutter on(1)
Filling without magnetic shutter(2)
Stored UCN (3)
Lift is opened & magnetic shutter is switched on
Lift is out of trap
Lift is moved
Shutter is opened
Intensity (n/s)
Time (s)
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
-20
0
20
40
60
80
100

Statistical treatment



Measuring Cycle:

filling elevator (I_S = 0): 50 s
elevator down (I_S = 0): 12 s
pre-cleaning (I_S = 95): 250 s
cleaning (I_S = 105): 100 s
storing (I_S = 105): 0 s, 900, or 1800 s
emptying (I_S = 0): 300 s
background (I_S = 0): 100 s
(I_S := solenoid current [A])

statistical error: 1.6 s

background: 0.004 s^{-1}

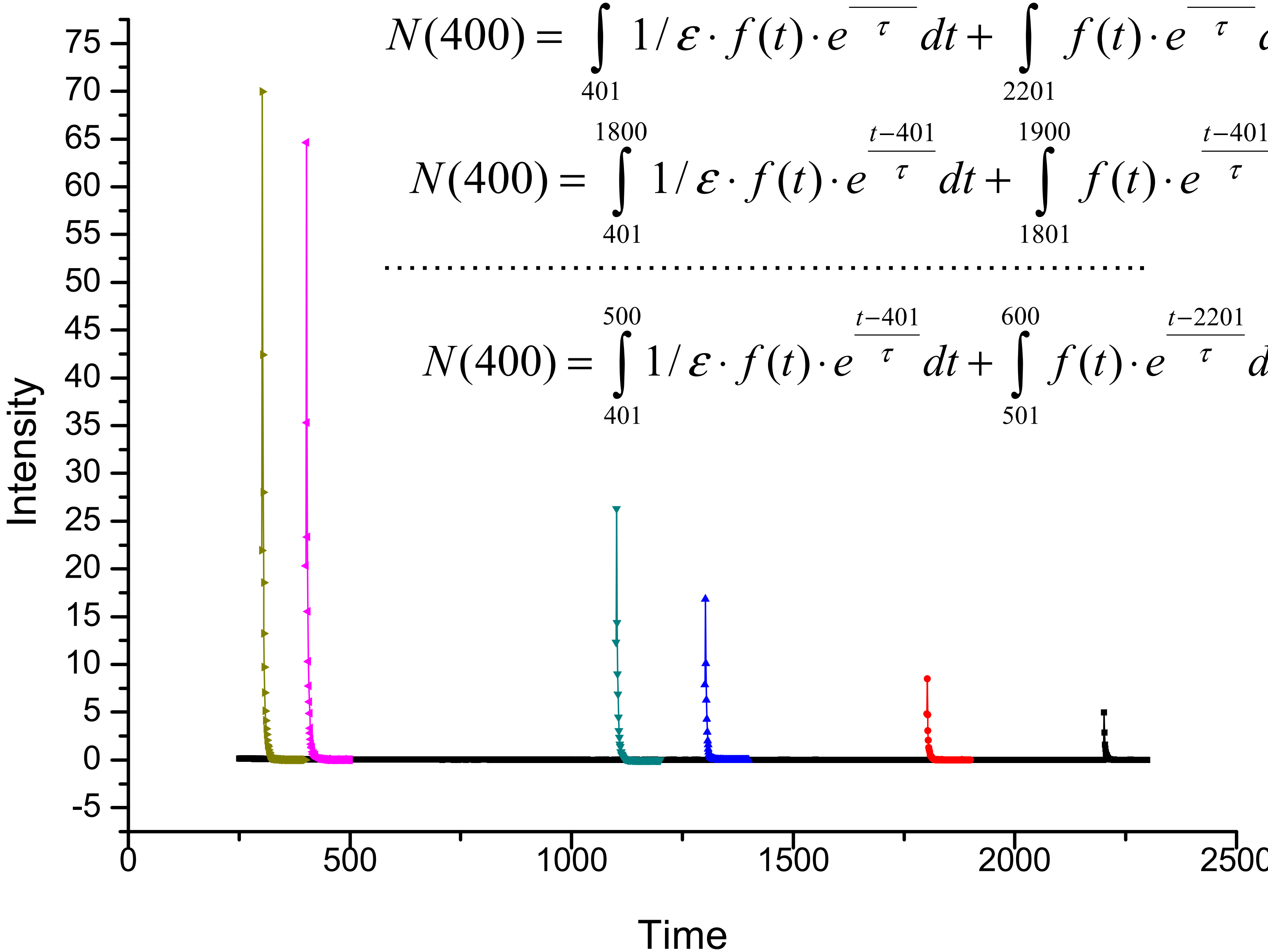
Main problem:
Detection efficiency of losses?

$$N(400)=\int_{401}^{2200} 1/\varepsilon\cdot f(t)\cdot e^{\frac{t-401}{\tau}}\,dt+\int_{2201}^{2300} f(t)\cdot e^{\frac{t-401}{\tau}}\,dt$$

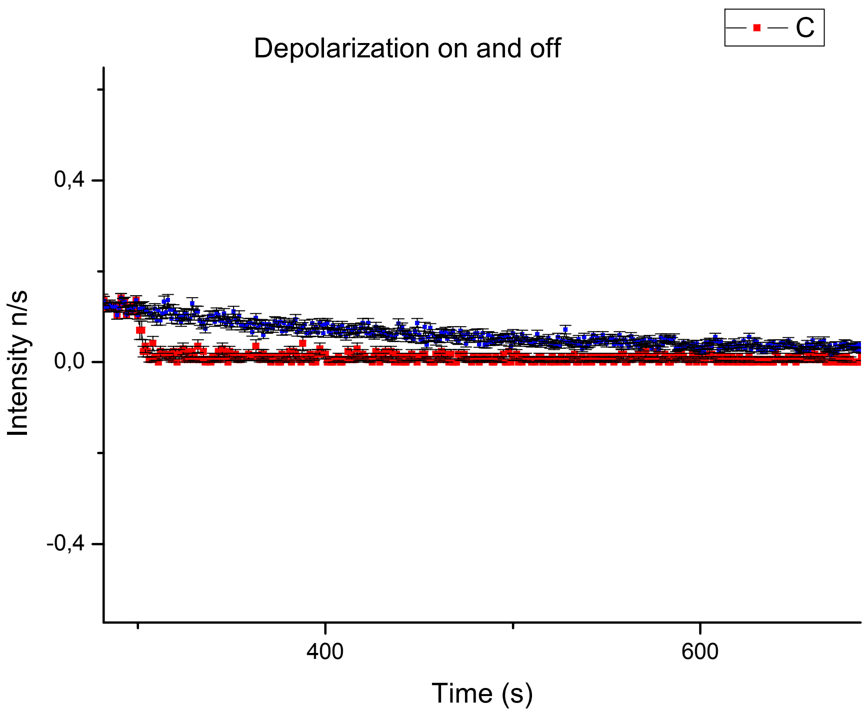
$$N(400)=\int_{401}^{1800} 1/\varepsilon\cdot f(t)\cdot e^{\frac{t-401}{\tau}}\,dt+\int_{1801}^{1900} f(t)\cdot e^{\frac{t-401}{\tau}}\,dt$$

. . . .

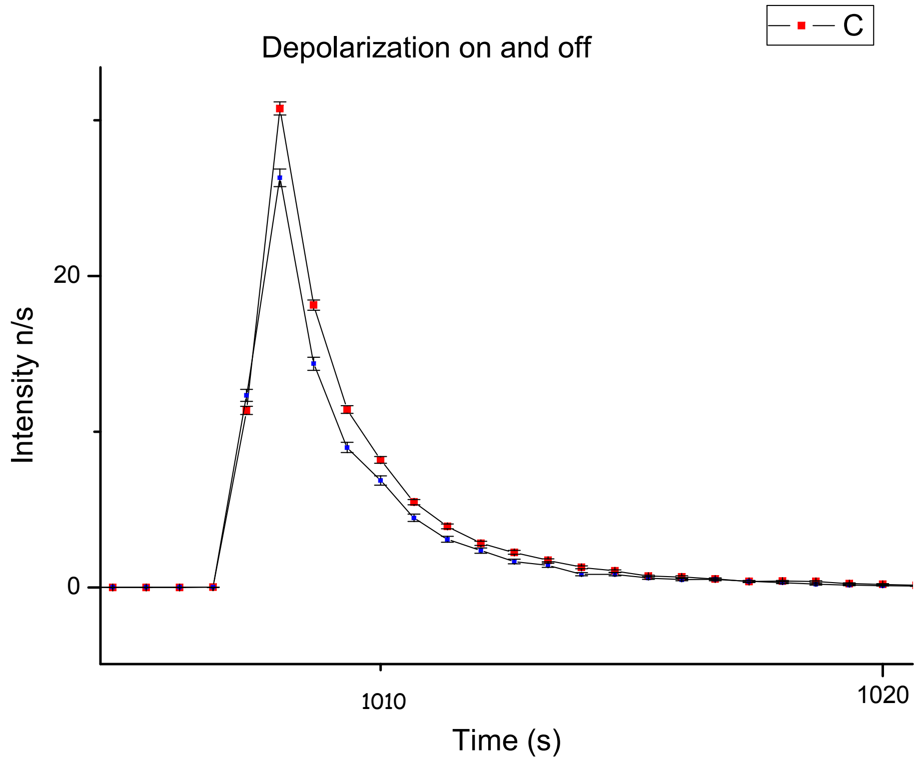
$$N(400)=\int_{401}^{500} 1/\varepsilon\cdot f(t)\cdot e^{\frac{t-401}{\tau}}\,dt+\int_{501}^{600} f(t)\cdot e^{\frac{t-2201}{\tau}}\,dt$$



$$\varepsilon = \frac{\int_{301}^{1000} (f_1(t) - f_2(t)) \cdot e^{\frac{t-301}{\tau}} \, dt}{\int_{1001}^{1100} (f_2(t) - f_1(t)) \cdot e^{\frac{t-301}{\tau}} \, dt}$$



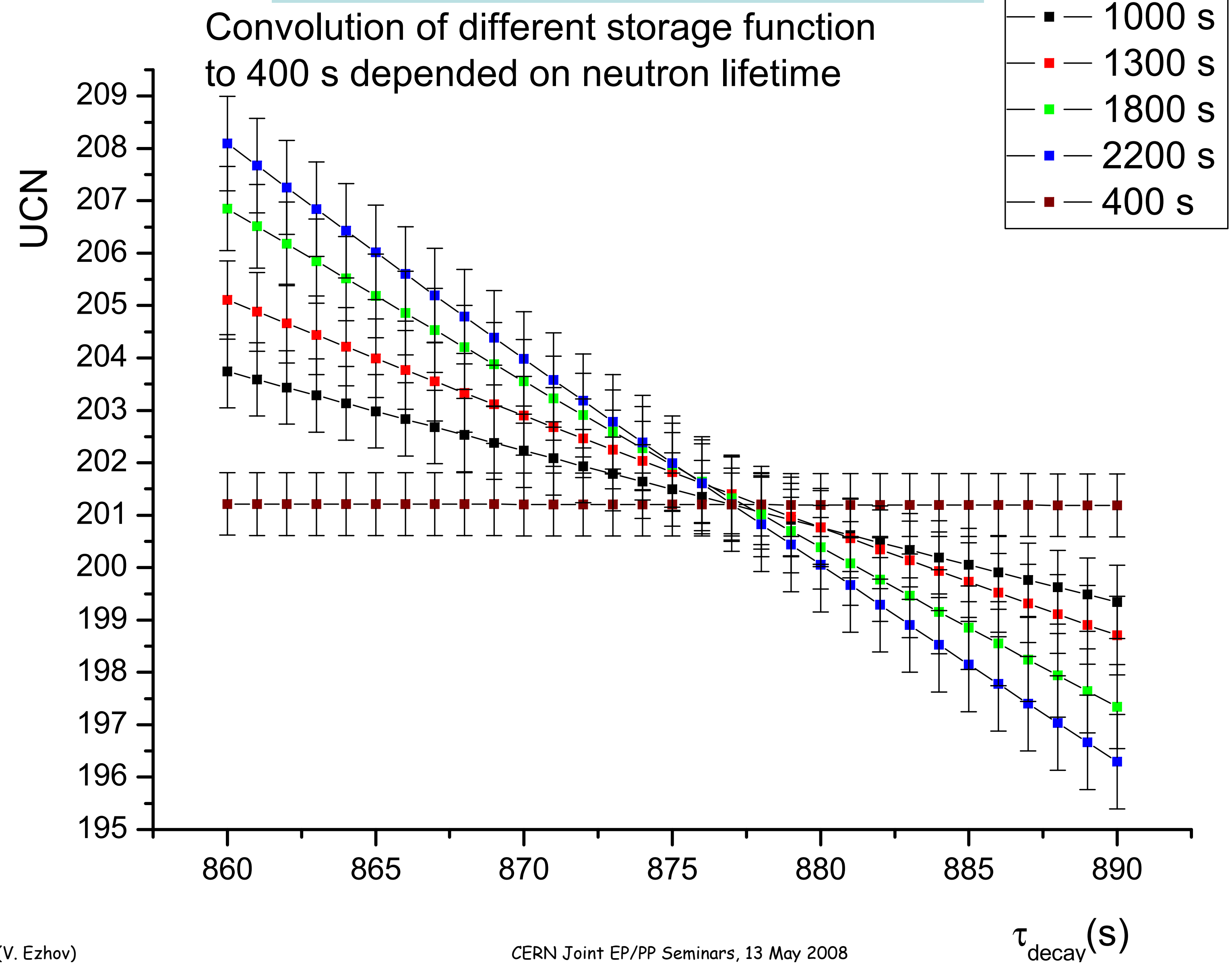
"Forced" depolarisation



! PRELIMINARY !

data treatment in progress

final result should be published soon



Storage of UCN in a trap made of permanent magnets
PNPI - ILL - TUM

2003
small trap 3.6 l
storage lifetime
(882 ± 16) s

2004
bigger trap 15 l
storage lifetime
(878 ± 6) s

2005
trap (as in 2004) 15l
+ neutron elevator
storage lifetime
(874.6 ± 1.6) s

on going

- larger neutron guide (cross section x 10)
  ⇒ precision about 1.8 s (to be published soon)

Outlook

- increase the trap volume (about 10 times)
  precision about 0.3 s

future neutron lifetime projects

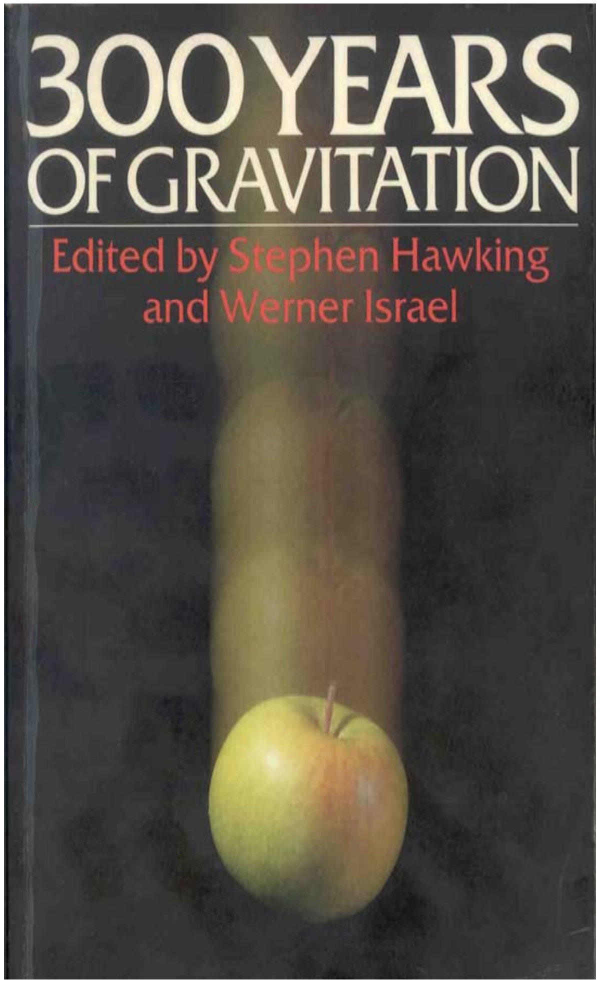
• S. Dewey, NIST	improvements in n flux measurement
• V. Ezhov, PNPI (ILL)	bottle made of permanent magnets
• A. Steyerl, URI (ILL)	LTF coated "accordion"
• V. Morozov, KI (ILL)	LTF coated teflon bottle
• A. Serebrov, PNPI (ILL)	big gravitational trap coated with LTF
• Y. Pokotilovski, FLNP (ILL)	"super" (even lower temperature) LTF
• P. Huffman, NSCU (NIST/SNS)	sc magnet and sLHe measure decay
• S. Paul, TUM (ILL,FRM-II)	bottle made of superconducting magnets measure storage and decay
• Y. Masuda, KEK (RCNP,J-PARC, TRIUMF)	bottle made of quadrupoles measure decay
• D. Bowman et others, LANL presented at PMSN, April '04	bottle made of quadrupoles now also with permanent magnets! measure decay
• PSI	bottle made of permanent magnets measure storage and decay

Quantum states of neutrons in the gravitational field

Nature 415, 297-299
(17 January 2002)

Valery V. Nesvizhevsky[*], Hans G. Börner[*],
Alexander K.Petoukhov[*‡], Hartmut Abele[†],
Stefan Baeßler[†], Frank J.Rueß[†], Thilo Stöferle[†],
Alexander Westphal[†], Alexei M. Gagarski[‡],
Guennady A. Petrov[‡] & Alexander V. Strelkov[§]

[*] *Institute Laue-Langevin, Grenoble, France;*
[†] *University of Heidelberg, Germany;*
[‡] *Petersburg Nuclear Physics Institute, Gatchina, Russia;*
[§] *Joint Institute for Nuclear Research, Dubna, Russia.*



Quantum states of matter in a potential well

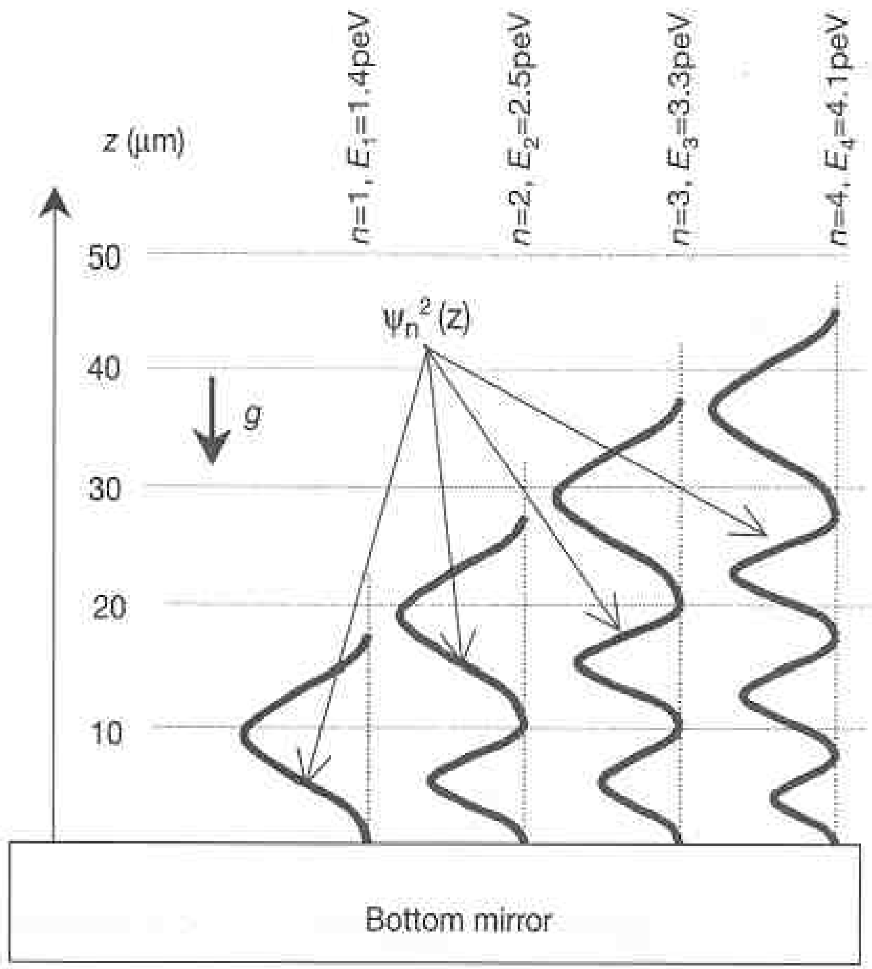
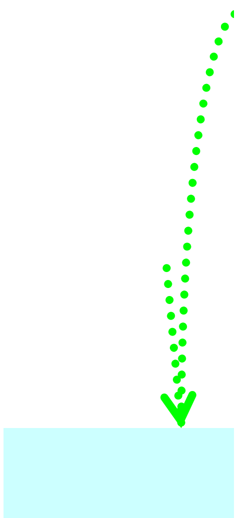


Figure 1 Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height *z*, corresponding to the *n*th quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$.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



gravitational
weaker than the

$$' \approx \frac{\hbar}{\Delta\tau})$$

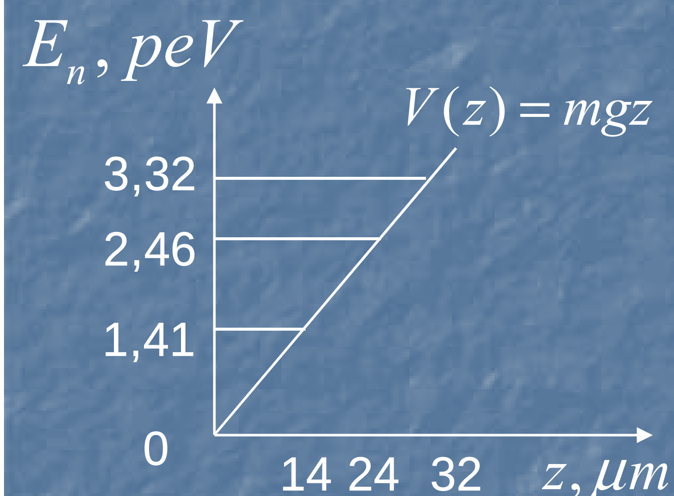
$$\Delta x \approx \frac{\hbar}{m})$$

e) of UCN
d it is not equal to
perature)

A neutron, w
in the Earth's
above a hori

Motivation

To find bound states of neutron in gravity field, predicted by Quantum Mecanics



$$z_0 = \sqrt[3]{\frac{\hbar^2}{2gm^2}} = 5{,}87\ \mu\text{m}$$

$V_{hor} \sim 4\text{-}15$ m/s

$V_{vert} \sim 2$ cm/s

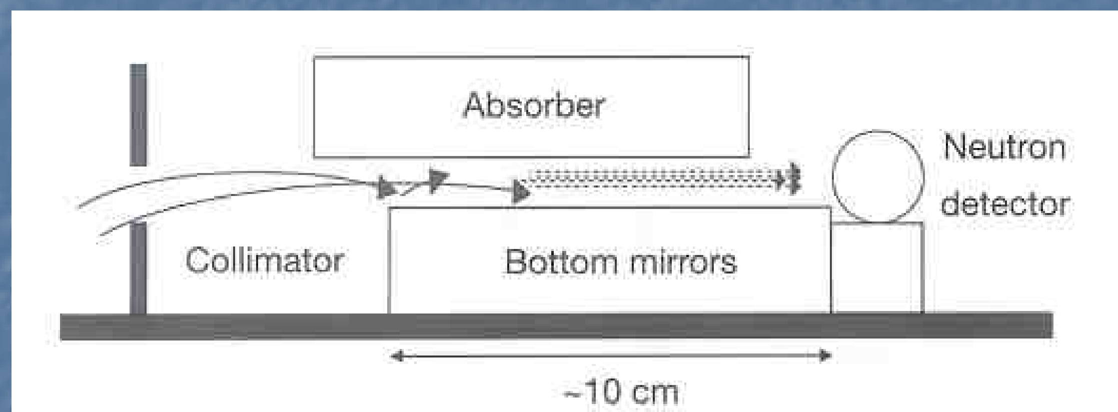


Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

Discovery of the ground state (1999)

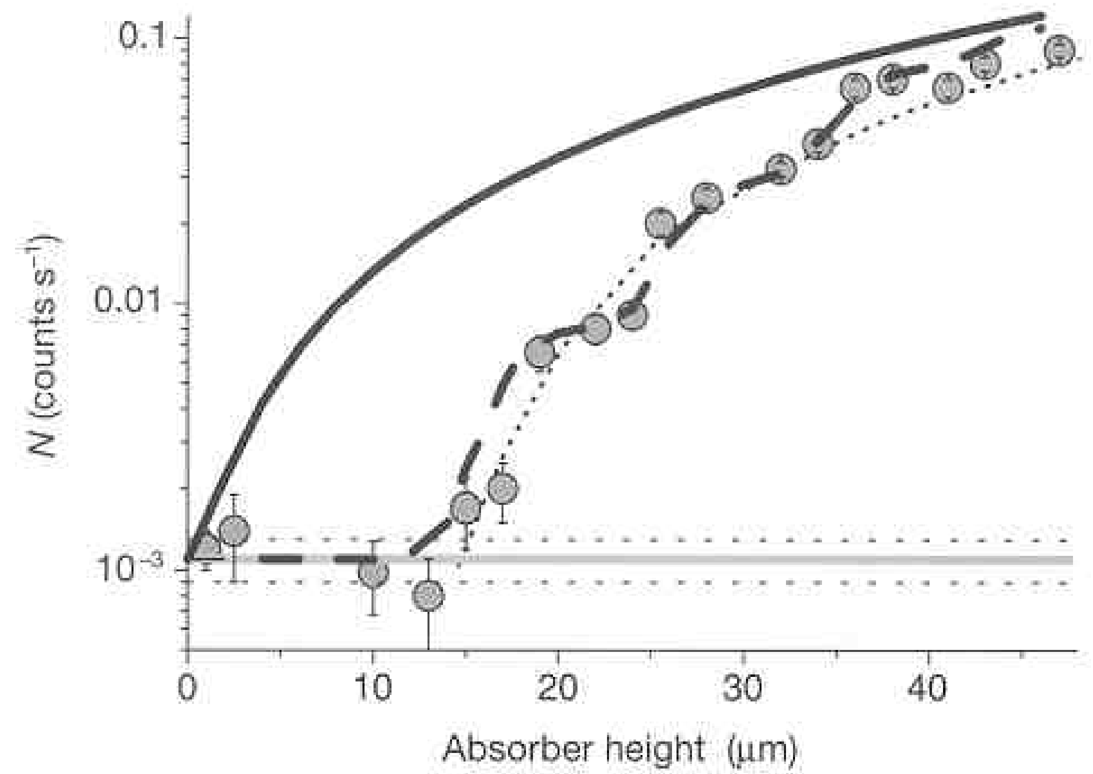


Figure 4 The neutron throughput versus the absorber height at low height values. The data points are summed up in intervals of 2 μm. The dashed curve corresponds to a fit using the quantum-mechanical calculation, in which all level populations and the height resolution are fitted from the experimental 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.

V.V. Nesvizhevsky et al.,

Nature **415** (2002) 297;

Phys Rev **D87** (2003) 102002

classic

QM

GRANIT (GRavitational Neutron Induceed Transitions)

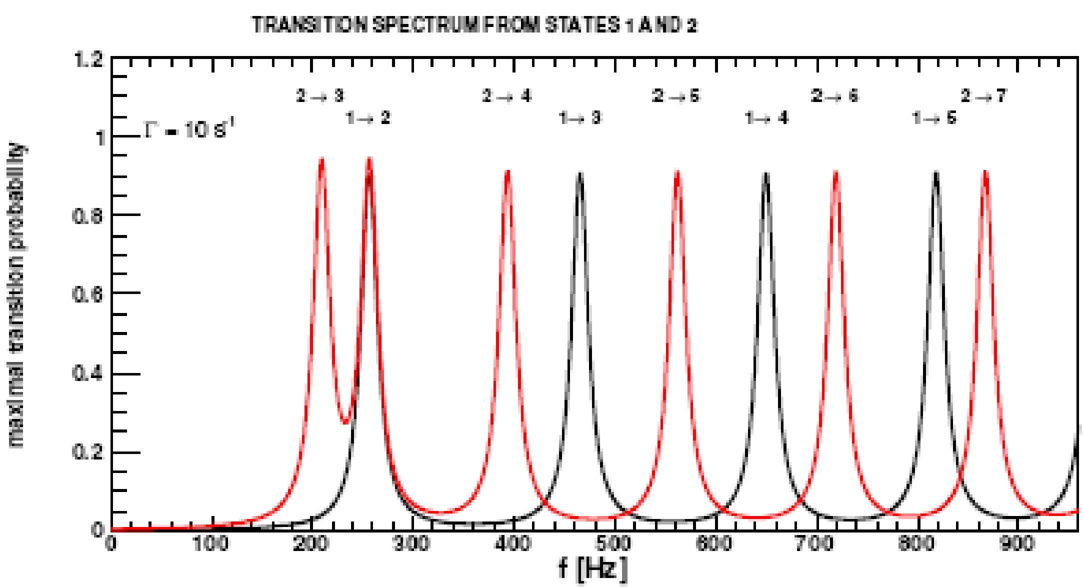
a trap for gravitational quantum states of UCN

Resonant transitions between quantum states

Transition probability for a periodic perturbation $Re\left[\ V(z)e^{i\omega t}\ \right]$

$$P_{N\to n}(t) = \frac{1}{1+\left(\frac{\omega-\omega_{Nn}}{\Omega_{Nn}}\right)^2}\sin^2\left(\sqrt{(\omega-\omega_{Nn})^2+\Omega_{Nn}^2}\ \frac{t}{2}\right)$$

Rabi pulsation $\Omega_{Nn} = \frac{2}{\hbar} < n|V(z)|N >$ defines $N \to n$ perturbation strength



For storage time T:

- need $\Omega_{Nn} = \frac{2\pi}{T}$ for 100% transition.
- get resolution $\Delta E = \frac{h}{T}$

Resonant transitions using magnetic gradient

Easiest way to induce transitions:

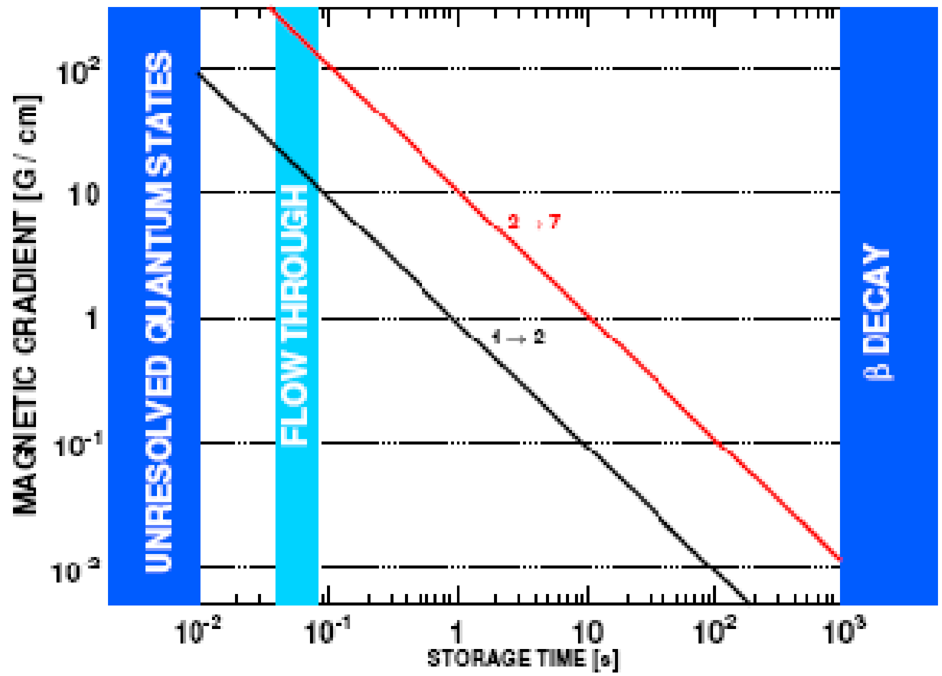
$\mathbf{B} = (\beta_z \mathbf{e}_z + \beta_x \mathbf{e}_x)\, z \cos(\omega t)$.

- Perturbation without spin-flip:

$$\hat{V}(t) = -\hat{\mu}_z \beta_z\, \hat{z}\;\cos(\omega t)$$

- Perturbation with spin-flip:

$$\hat{V}_{\text{flip}}(t) = -\hat{\mu}_x \beta_x\, \hat{z}\;\cos(\omega t)$$

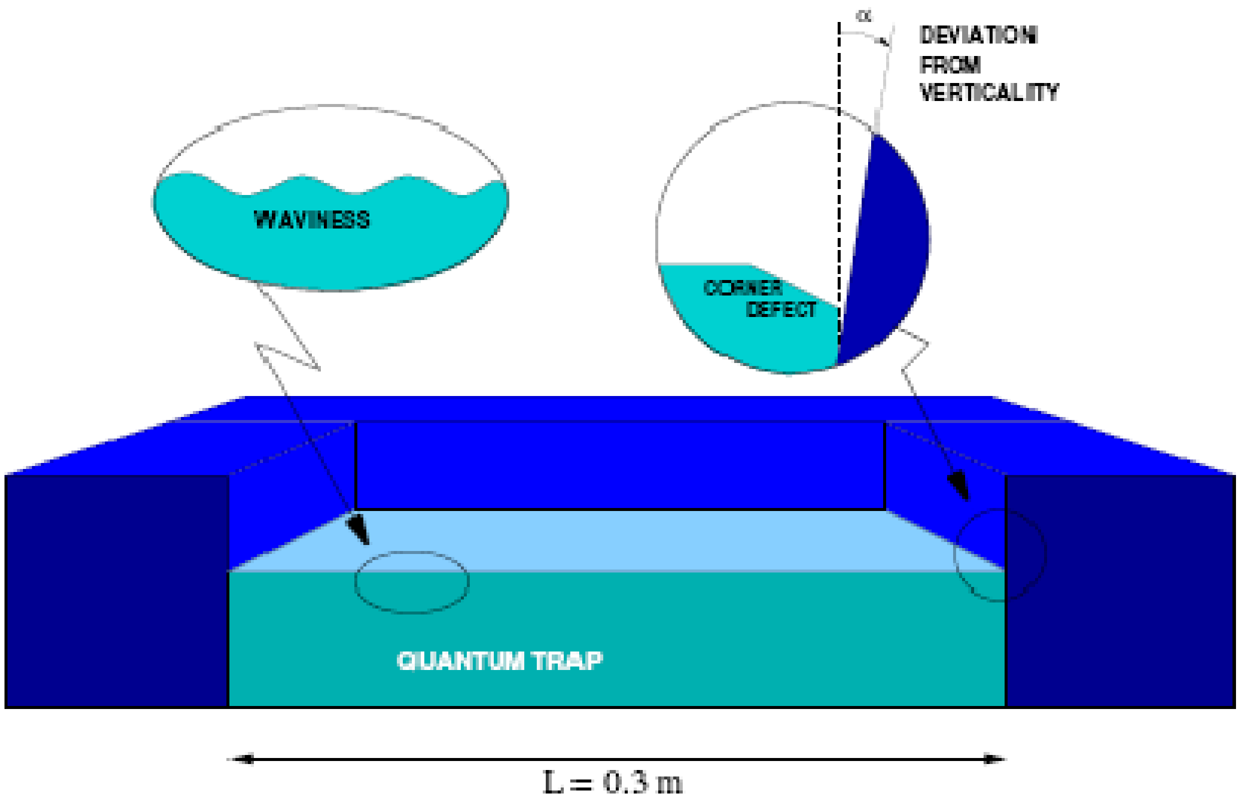


Future experiments (needs longer storage time):

- Perturbation using oscillating mirror
- Gravitational perturbation: oscillating (rotating?) mass.

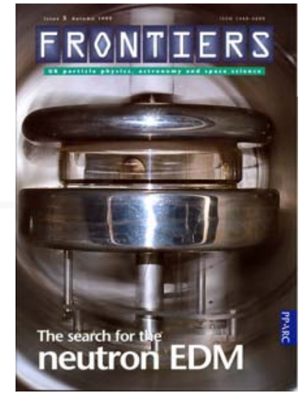
Geometrical constraints

- How do we fill the trap? How do we extract neutrons? Detect transitions?
- HOW LONG CAN NEUTRONS BE TRAPPED?



Horizontal velocity of trapped neutrons $v \approx 5$ m/s.

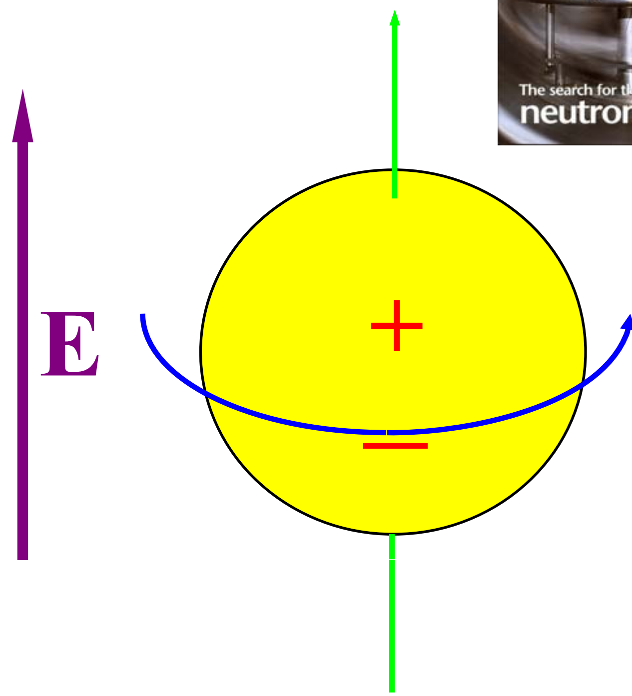
What's an EDM?



- Separation between +,- charge centres

- EDMs are
  - P odd
  - T odd

- Complementary approach to study of CPv

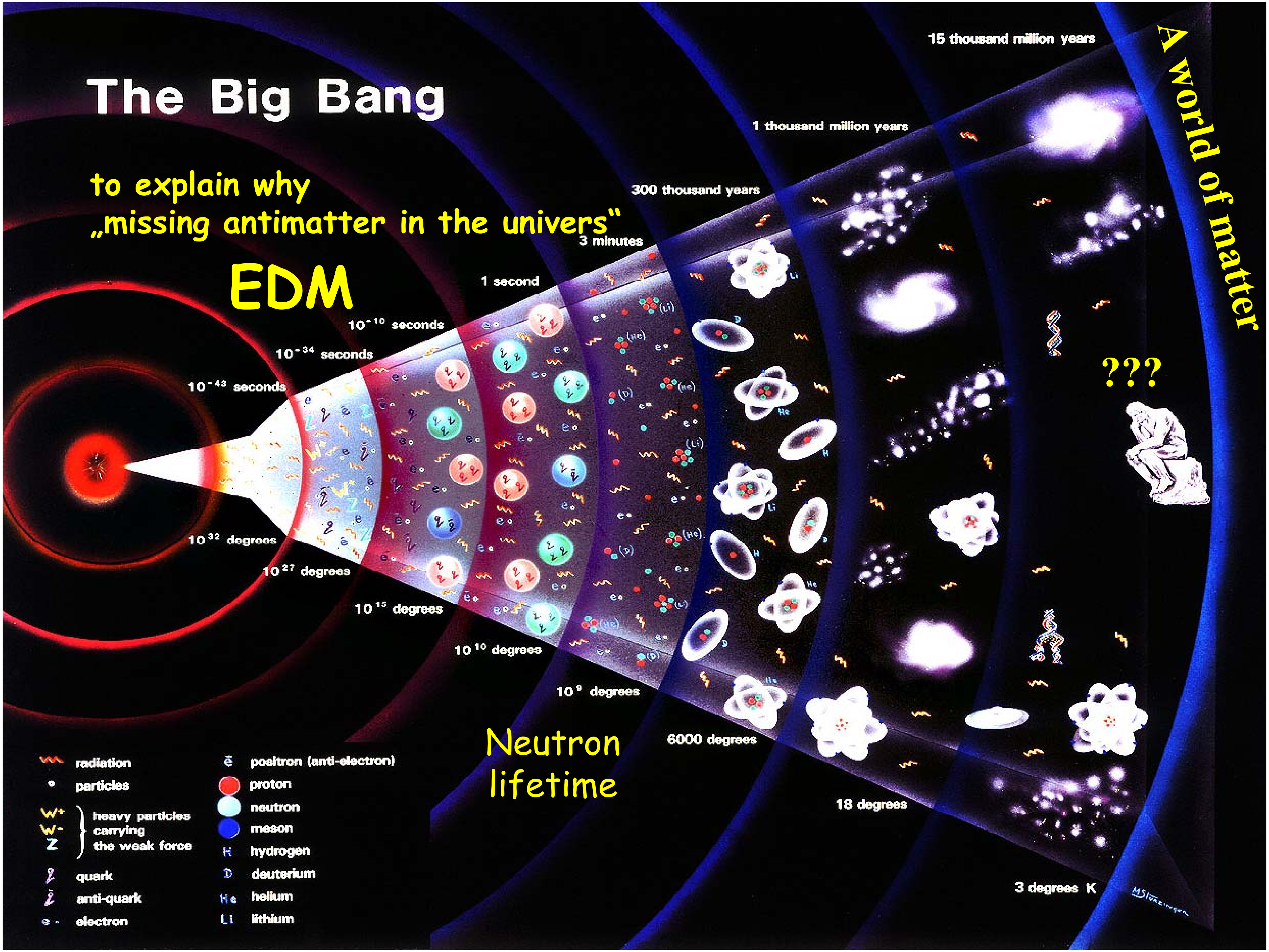


$$\vec{\mathbf{d}}_n = d_n \hat{\mathbf{s}}$$

[expressed in e·cm]

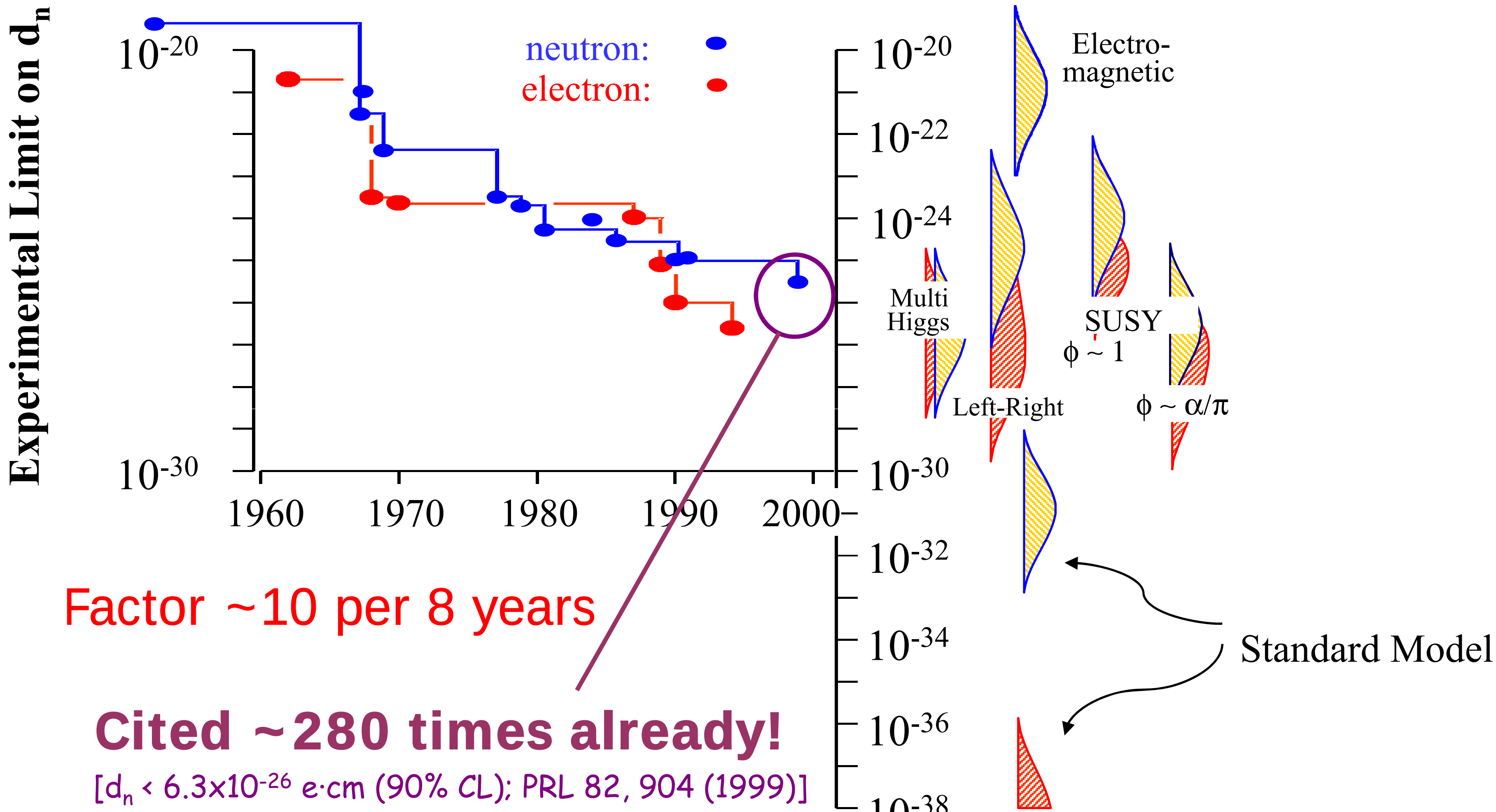
CP violation & the neutron EDM

- SM EDM predictions very small…
  - … so no SM background to worry about
- Beyond SM predictions typ. 10^6 greater
  - … so EDMs are excellent probe of BSM CPv
- SM parameterisation of CPv inadequate to explain baryon asymmetry
- “Strong CP Problem ” : why does QCD not violate CP? Nobody knows.



The Big Bang
to explain why
„missing antimatter in the univers"
EDM
Neutron
lifetime
A world of matter
???
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+
W-
Z
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

EDM limits: the first 50 years



Factor ~10 per 8 years

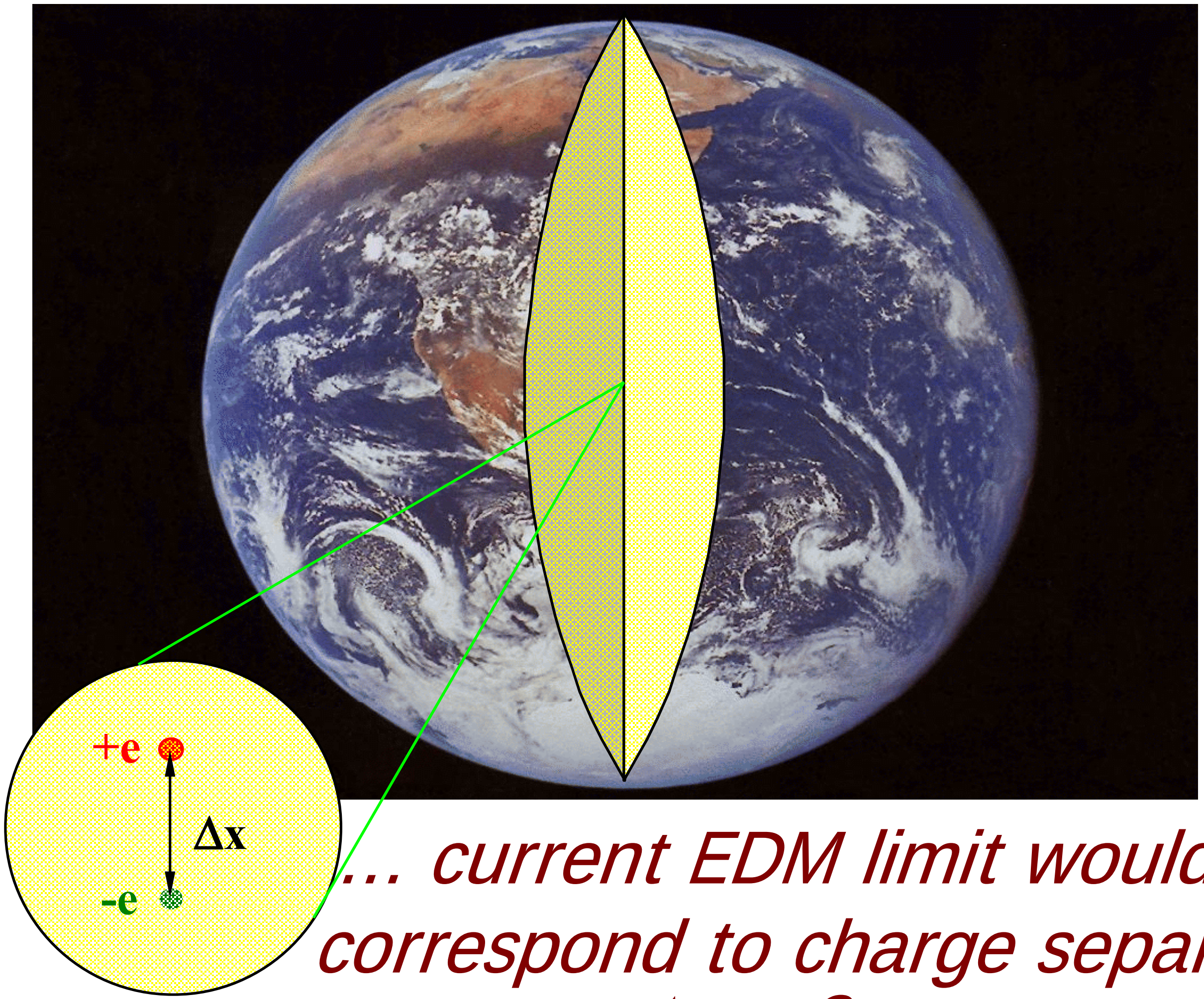
Cited ~280 times already!

[d_n < 6.3×10^{-26} e·cm (90% CL); PRL 82, 904 (1999)]

"It is fair to say that the neutron EDM has ruled out more theories (put forward to explain K_0 decay) than any experiment in the history of physics" R. Golub

Reality check

If neutron were the size of the Earth...



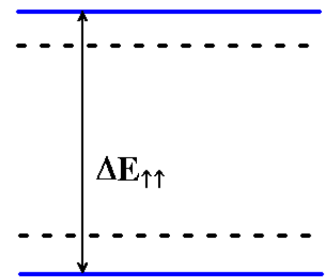
... current EDM limit would correspond to charge separation of

$\Delta x \approx 3\mu$

Experiments:

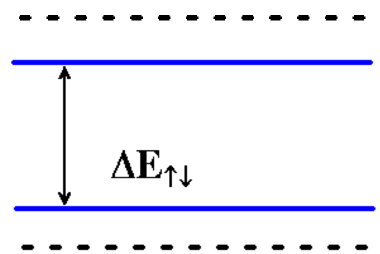
Measurement of Larmor precession frequency of polarised neutrons in a magnetic & electric field

Compare the precession frequency for parallel fields:



$\nu_{\uparrow\uparrow} = \Delta E_{\uparrow\uparrow}/h = [-2B_0\mu_n - 2Ed_n]/h$

to the precession frequency for anti-parallel fields



$\nu_{\uparrow\downarrow} = \Delta E_{\uparrow\downarrow}/h = [-2B_0\mu_n + 2Ed_n]/h$

The difference is proportional to d_n and E:

$$\mathbf{h(\nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow}) = 4E\, d_n}$$

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

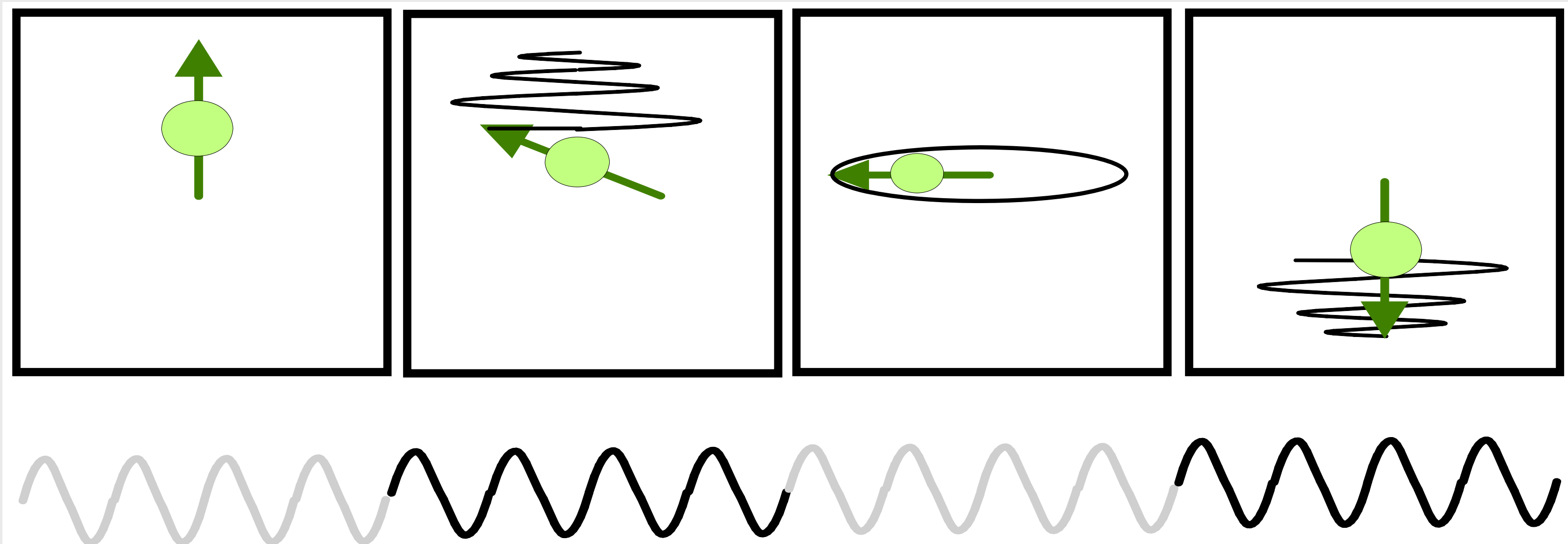
α: polarisation product

E: electric field

T: observation time

N: number of neutrons

Measuring the precession frequency of the neutron



RF generator

RF gated OFF	RF gated ON	RF gated OFF	RF gated ON
UCN spin parallel to holding field	**1st $\pi/2$ pulse applied: spin perpendicular to holding field**	**UCN precessing during storage time**	**2^{nd} UCN $\pi/2$ pulse applied: spin anti-parallel to holding field**

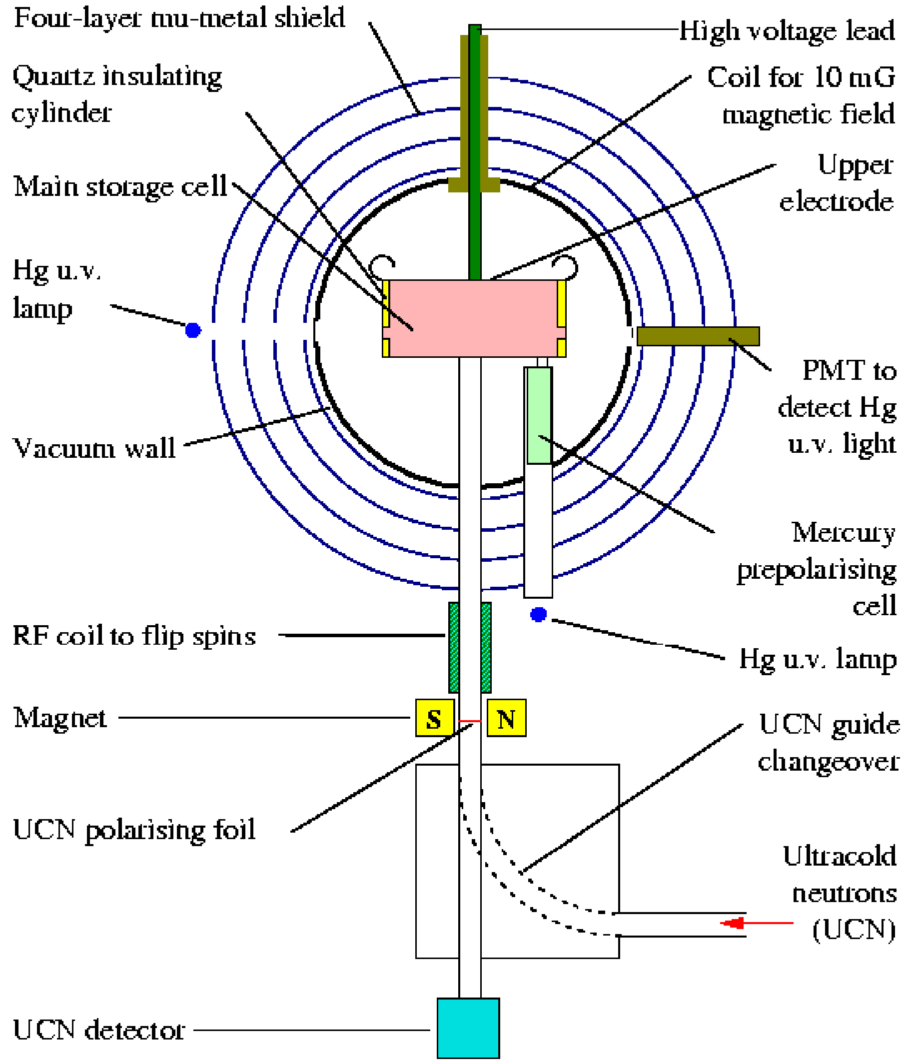
	1999	end of running
α	0.5	0.7
E	4.5 kV/cm	11 kV/cm
N	13000	18000
T	130 s	130 s
σ_{EDM}	6×10^{-25} e·cm	1.5×10^{-25} e·cm

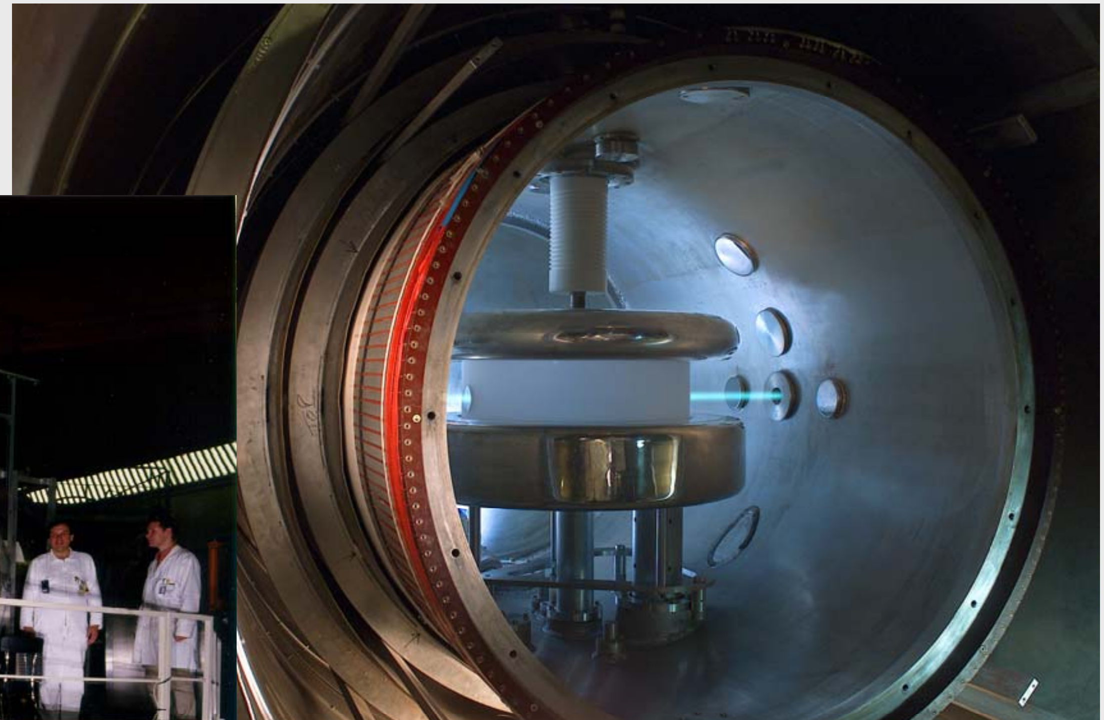
α : Si polariser

E : DLC, bottle configuration, discharge cleaning,

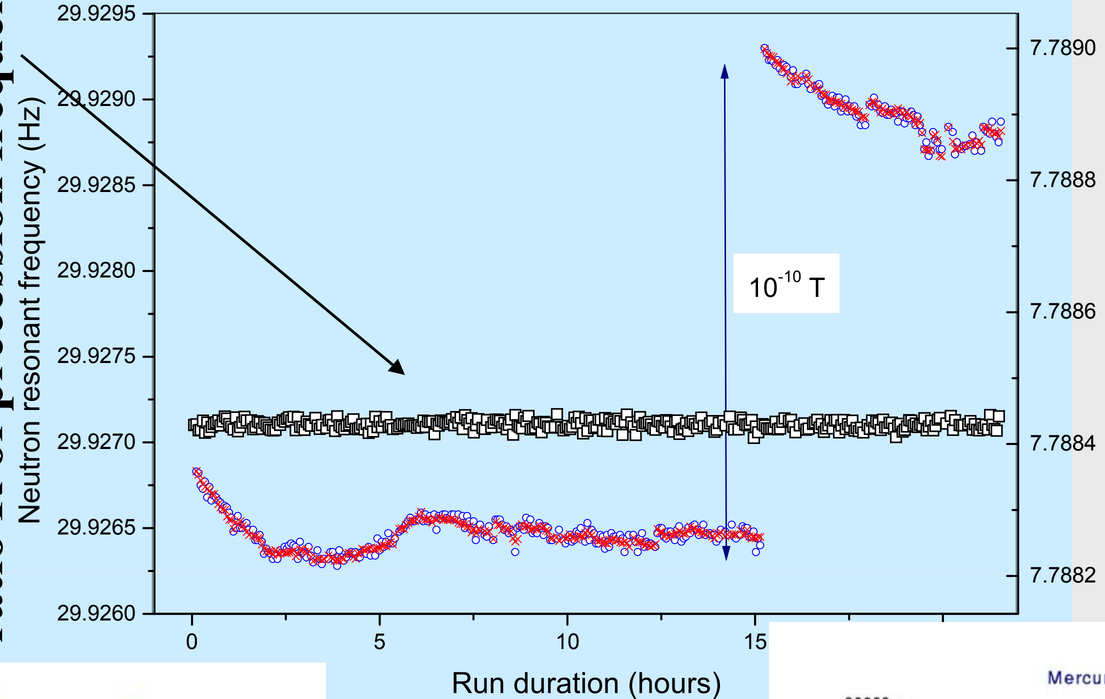
N : DLC, Si polariser, UCN-guides

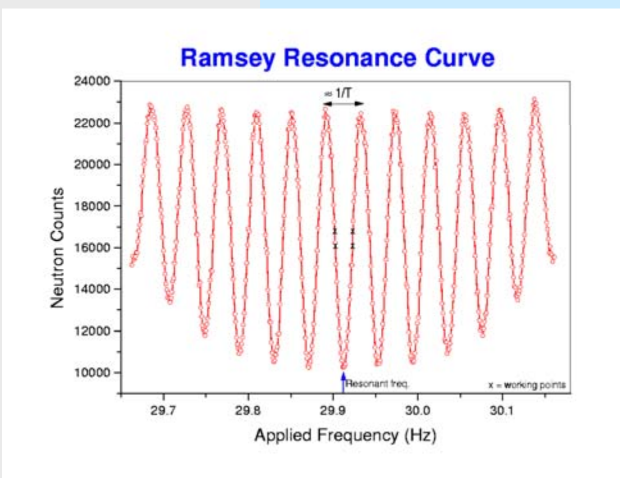
Neutron EDM Experimental Apparatus

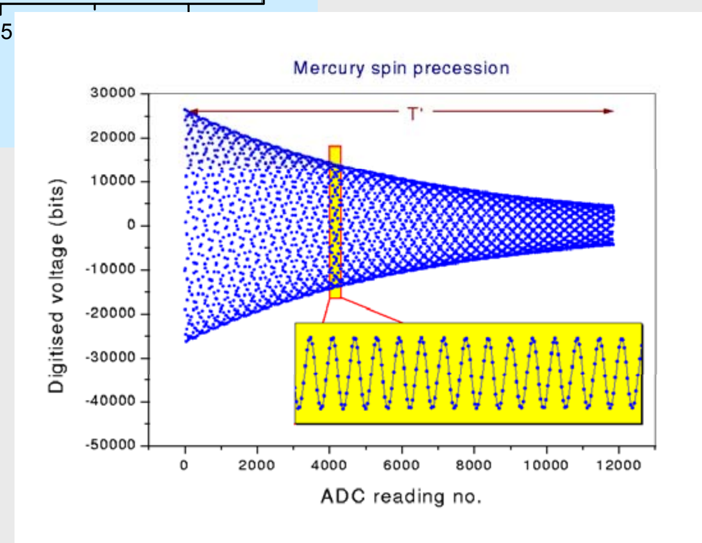




ratio R of precession frequencies







statistical precision

$$\sigma(d_n) = 1.53 \times 10^{-26}\ e\,cm$$

what about systematics ?

Geometric Phase Effect:

rotating magnetic field in the x-y plane
will affect precession of the neutron spin

ω_L shifts away from ω_0
(Ramsey-Bloch-Siegert shift)

$$\Delta\omega = \omega_L - \omega_0$$

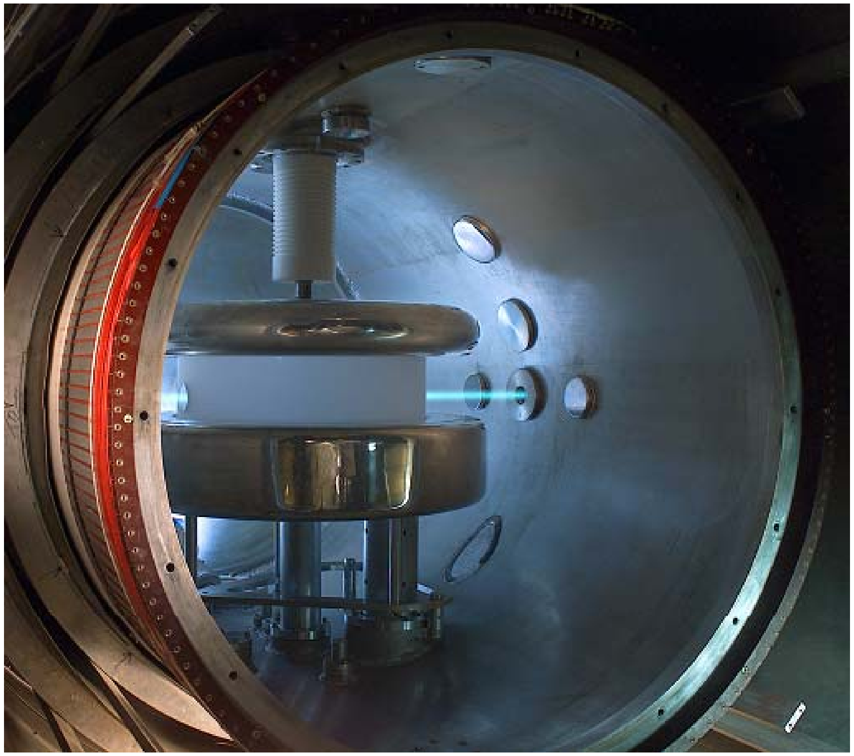
$$\Delta\omega = \frac{\gamma^2 B_{xy}^2}{2(\omega_0 - \omega_r)}$$

field B_{xy} rotating at angular speed ω_r,

Error budget (10^{-27} e·cm)

Effect	**Shift**	**Uncertainty**
Statistical	0	15.1
Door cavity dipole	-11.0	4.5
Other GP dipole shifts	0	6.0
$(\mathbf{E} \times \mathbf{v})/c^2$ from translation	0	0.5
$(\mathbf{E} \times \mathbf{v})/c^2$ from rotation	0	1.0
Light shift: direct & GP	3.5	0.8
B fluctuations	0	2.4
E forces – distortion of bottle	0	0.4
Tangential leakage currents	0	0.1
AC B fields from HV ripple	0	0.01
Hg atom EDM	0	0.5
2^{nd} order $\mathbf{E} \times \mathbf{v}$	0	0.02
Total	–7.5	15.1 stat, 8.0 sys

Room Temperature Results



Room temperature neutron EDM result:

C.A. Baker et al., Phys. Rev. Lett. **97,** 131801 (2006) or hep-ex/0602020

$$|d_n| < 2.9\times10^{-26}\ \mathrm{e.cm}\ (90\%\ \mathrm{C.L.})$$

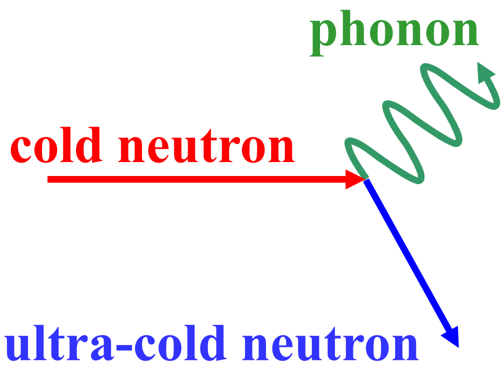
CryoEDM – the new generation

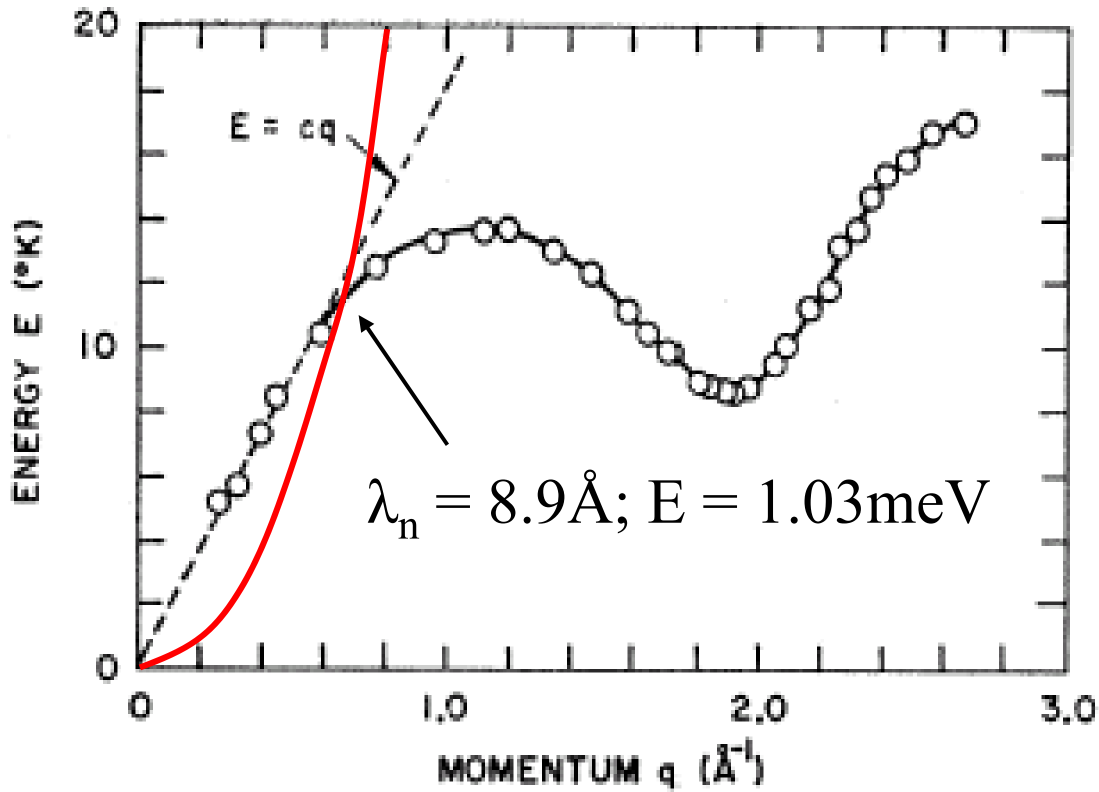
New technology:

- More neutrons
- Higher E field
- Better polarisation
- Longer NMR coherence time

100-fold improvement in sensitivity

Ultra-cold Neutron Production

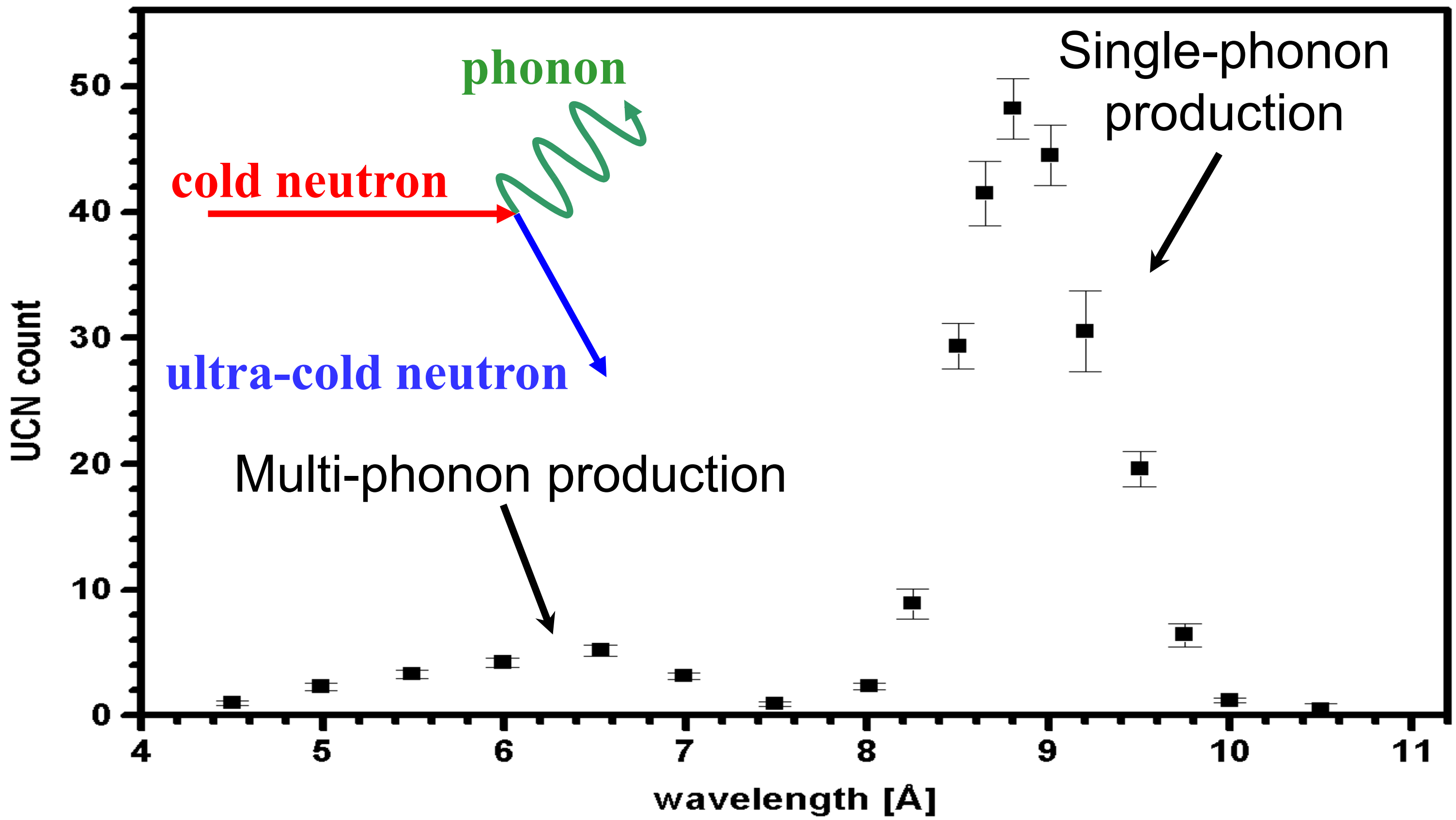




1.03 meV (11K) neutrons down-scatter by emission of phonons in superfluid helium at 0.5K

Up-scattering suppressed: hardly any 11K phonons

Ultra-cold Neutron Production



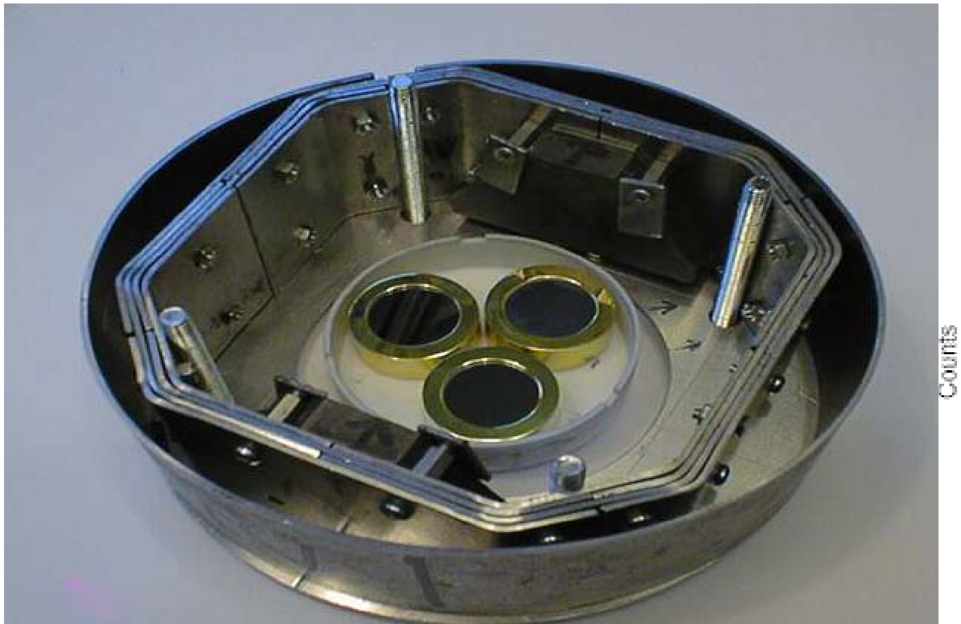
1.19 ± 0.18 UCN $cm^{-3}\ s^{-1}$ expected

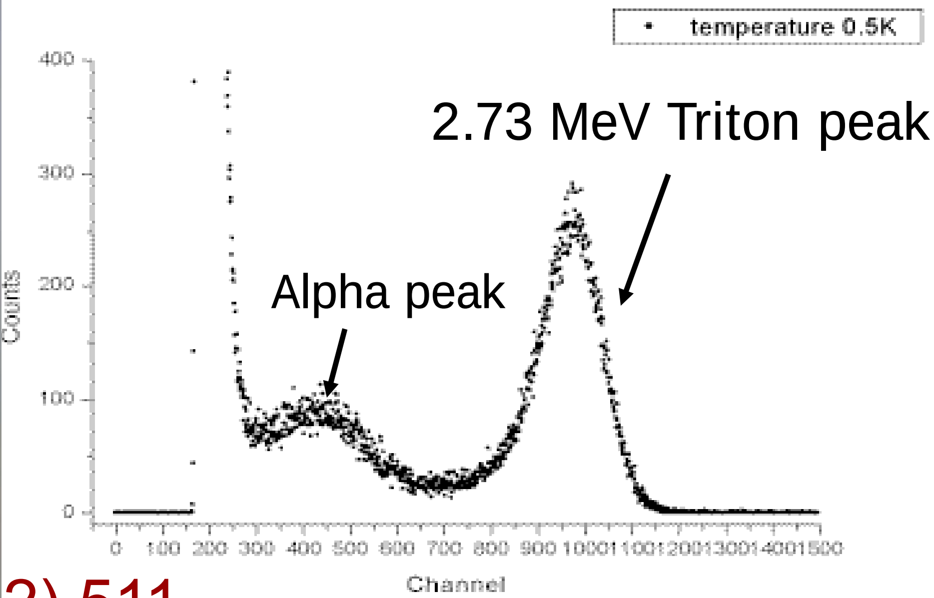
0.91 ± 0.13 UCN $cm^{-3}\ s^{-1}$ observed

C A Baker et al., Phys. Lett. **A 308** (2002) 67

Ultra-cold Neutron Detection

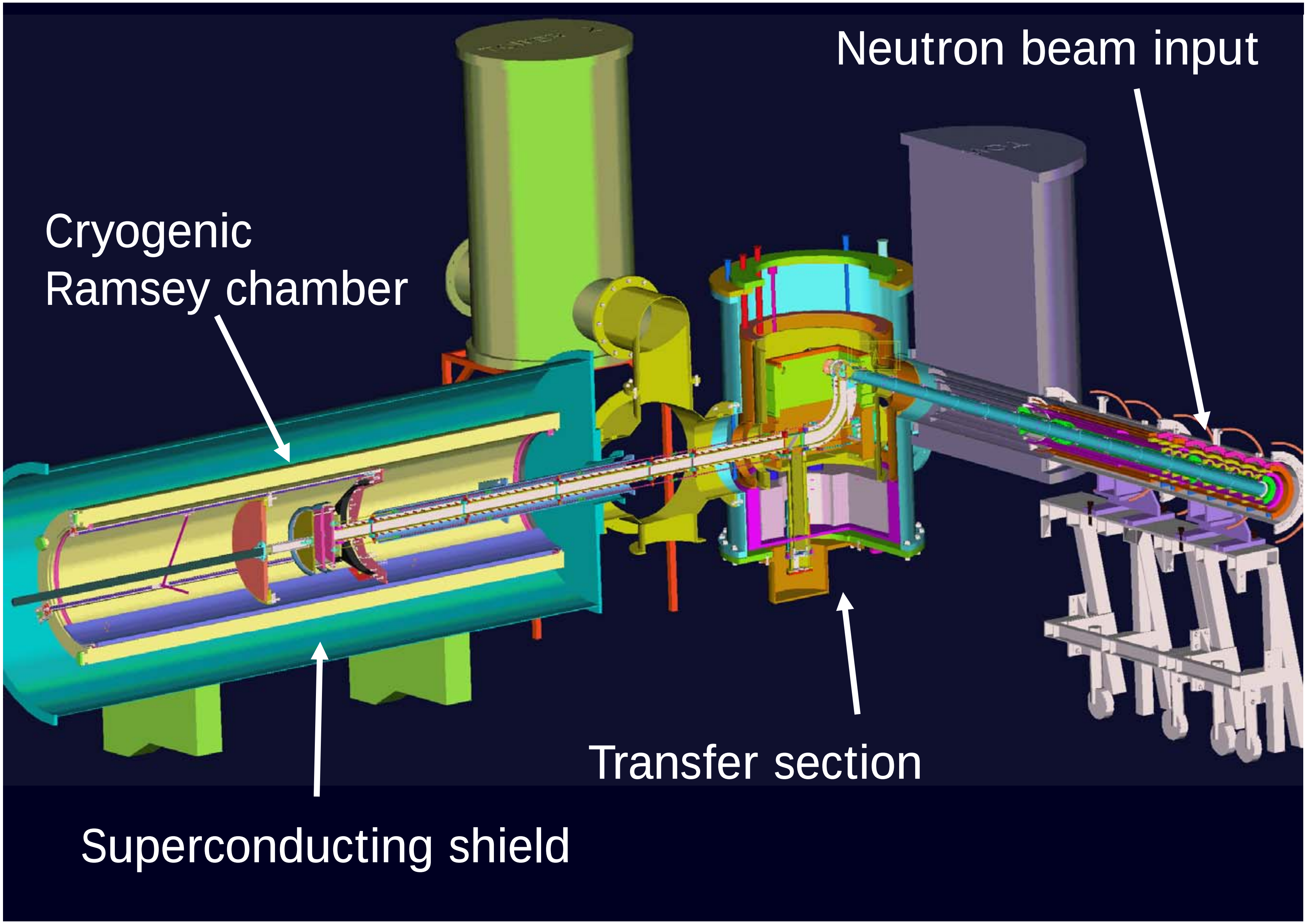
- ORTEC ULTRA at 430mK temperature.
- Equipped with thin surface layer of ^{6}Li.
- Using: $n + {}^{6}Li \rightarrow \alpha + {}^{3}H$





C.A.Baker *et al.*, NIM **A487** (2002) 511

The Cryogenic Setup



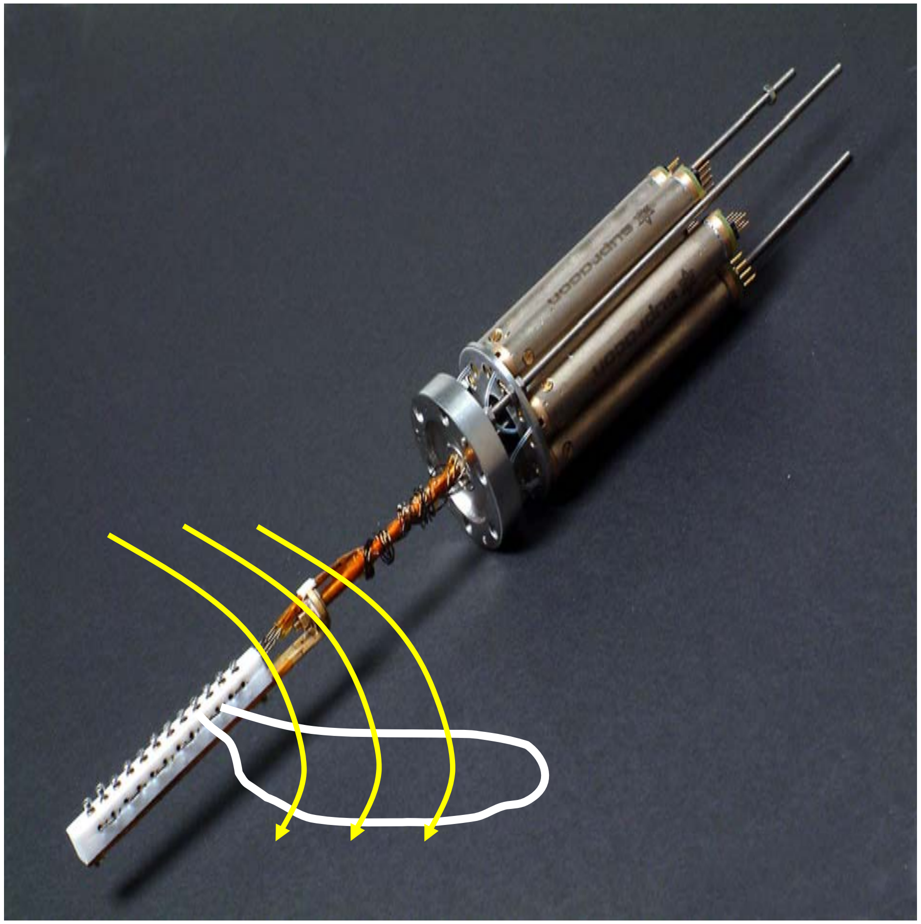
Improvements on Statistics

$$\sigma_D = \frac{\hbar/2}{\alpha E T \sqrt{N}}$$

Parameter	RT Expt	Sensitivity
• Polarisation+detection	α = 0.75	x 1.2
• Electric field:	E = 10^6 V/m	x 4
• Precession period:	T = 130 s	x 2
• Neutrons counted:	N = 6 x 10^6 /day	x 4.5
(with new beamline)		x 2.6

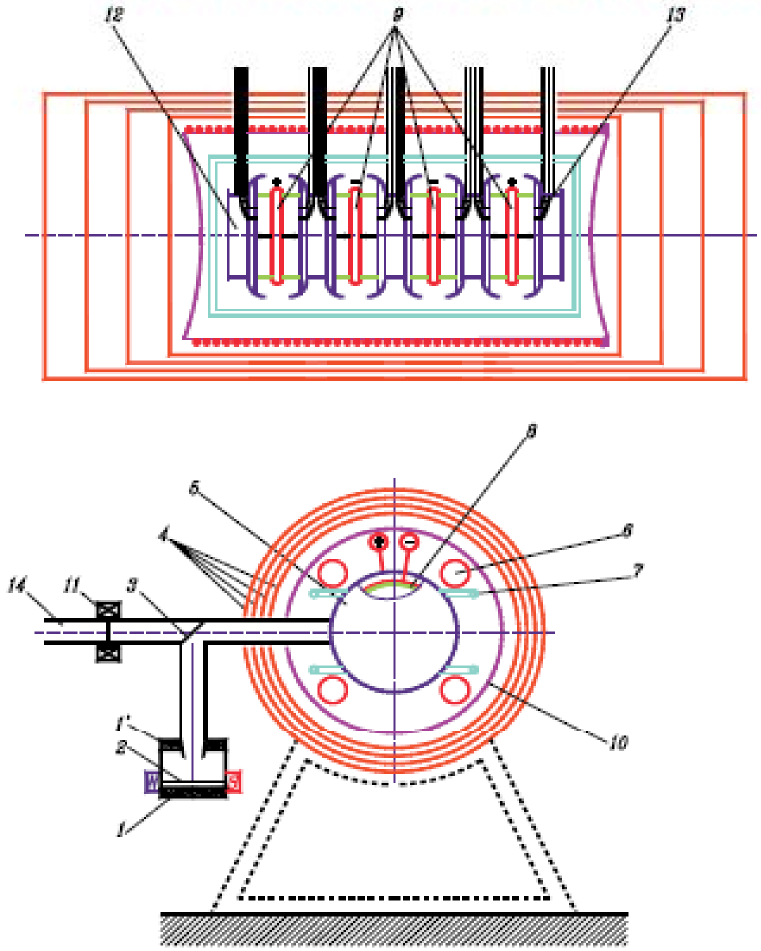
Total improvement: appr. x 100

SQUIDS from CRESST



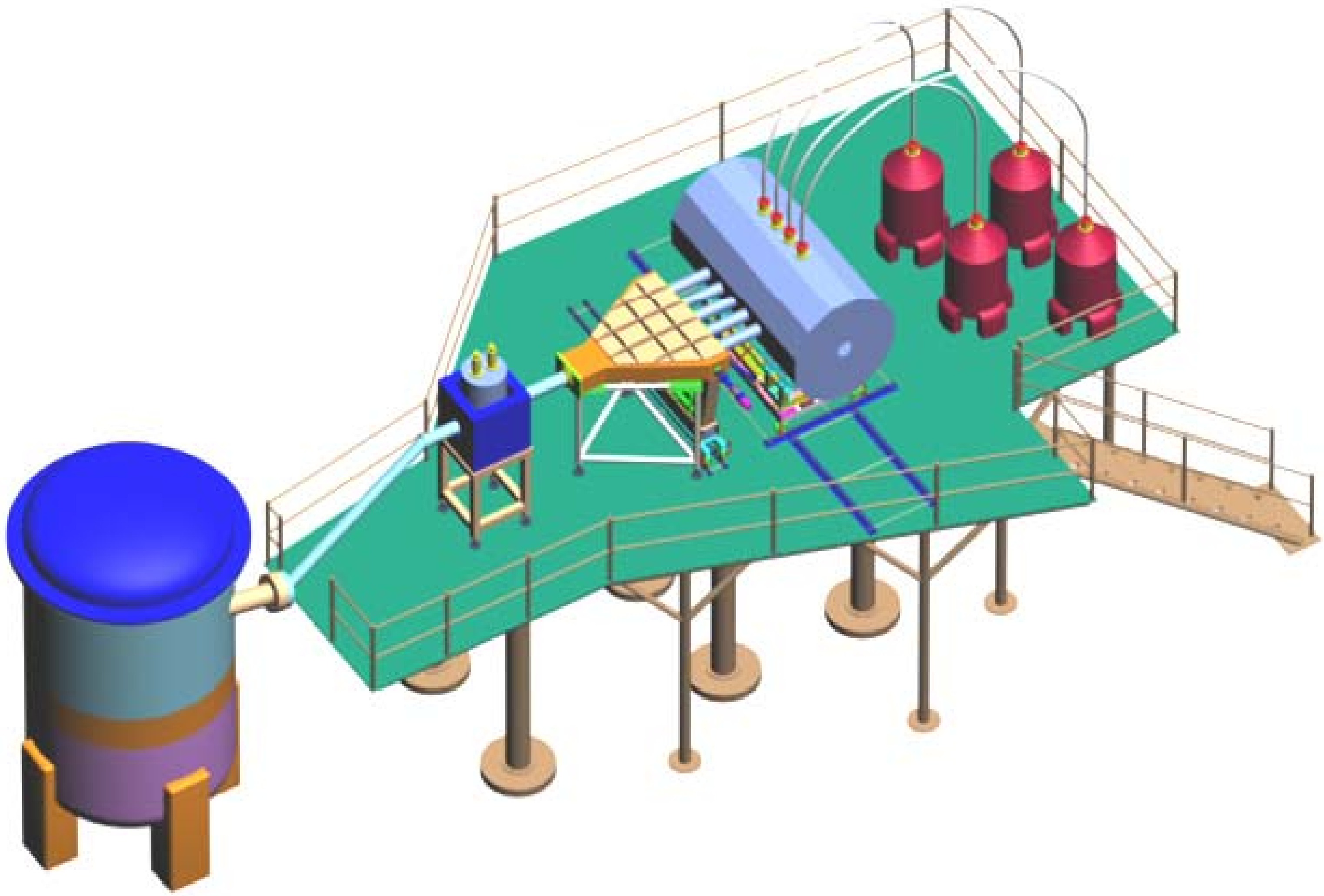
SQUIDs for Magnetometry

The scheme of the multichamber nEDM spectrometer



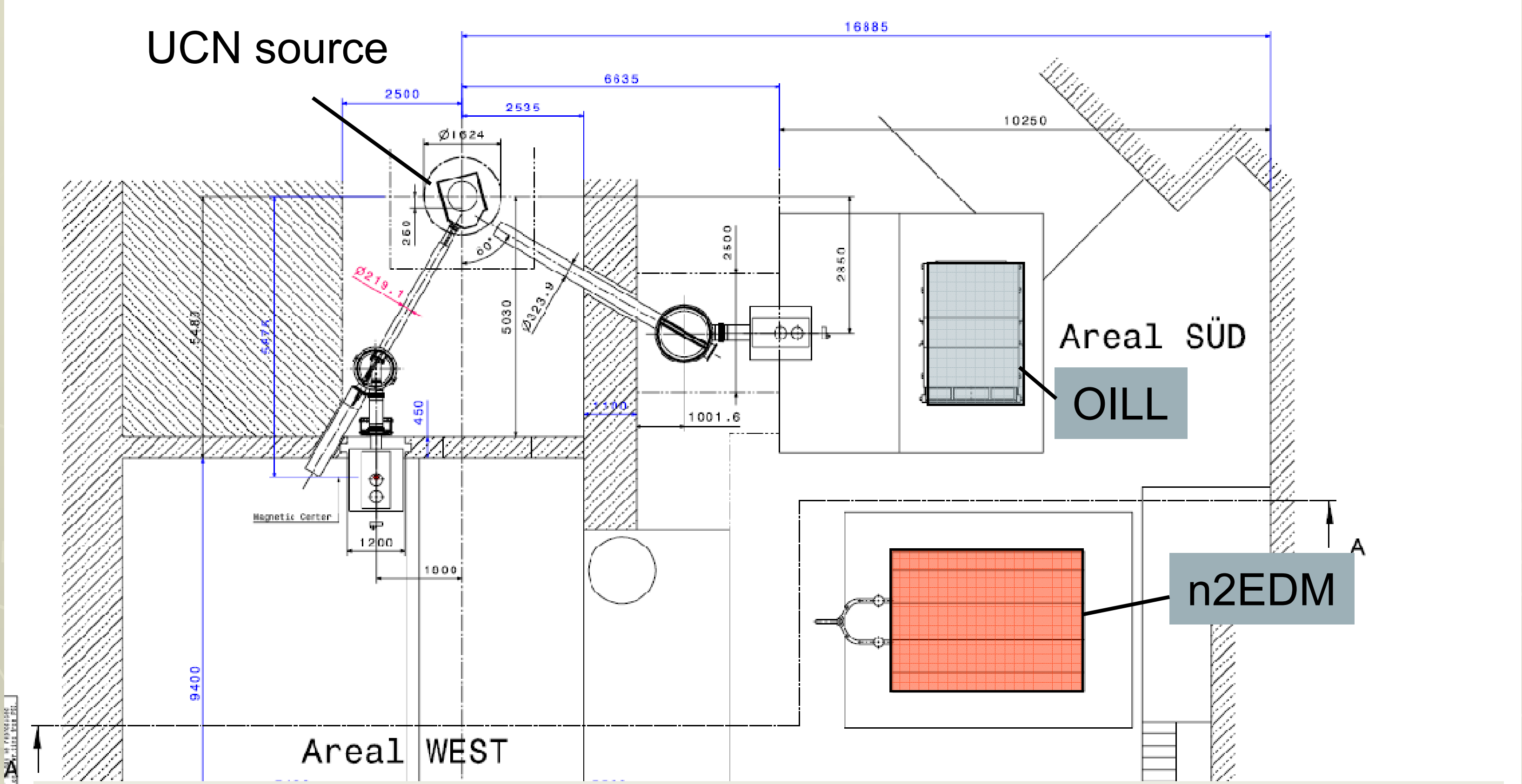
1. 1' - UCN detectors
2. - polarization analyzer foil
3. - UCN switch
4. - four-layer magnetic shield
5. - electrode with zero potential
6. - channel for Cs magnetometers
7. - oscillating field coils
8. - BeO-coated insulator
9. - HV electrodes
10. - vacuum chamber with magnetic field coil
11. - superconducting polarizer with a membrane to separate the vacuum of the UCN source from the vacuum of the EDM spectrometer
12. - UCN storage chamber (1 out of 13)
13. - UCN shutter
14. - UCN guide

PNPI multi-chamber EDM spectrometer at the UCN facility PF2 of the ILL



Phase II: OILL@PSI

KU Leuven is a collaborator



- MC simulation predicts x25 statistics
- B-field control better than 100fT/100s

→Sensitivity goal: **$5x10^{-27}$ecm**

Search for Neutron – Mirror Neutron Oscillations using storage of Ultracold Neutrons

PNPI/IPTI/ILL collaboration: A. Serebrov et al., E. Alexandrov et al., P. Geltenbort, O. Zimmer

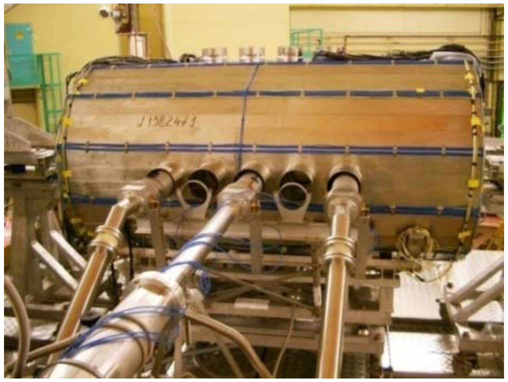
Hypothesis: There is a "mirror world" of partners of the known particles with

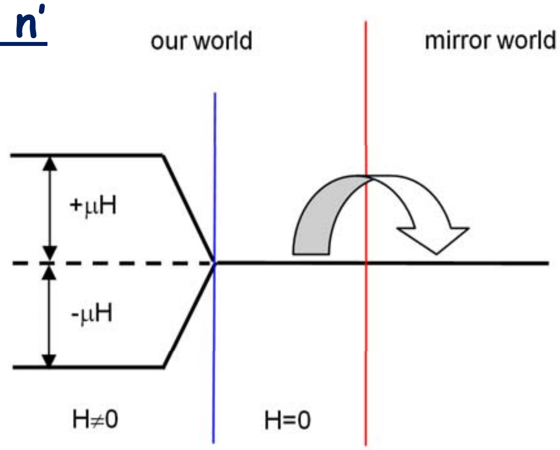
- same fundamental interactions with opposite handedness
  → natural explanation of parity violation
- no interactions with our world, apart gravity and mixing of neutral particles
  → mirror matter is a viable dark-matter candidate

Z. Berezhiani, A.D. Dolgov and R.N. Mohapatra, Phys. Lett. B **375**, 26 (1996)

Test: Search transition of neutron n to mirror neutron n'

- Situation 2006: $\tau_{osc} \geq 1$ s
- A magnetic field suppresses nn' mixing
  → Look for difference of UCN storage time without (<20 nT) and with field (2 μT)



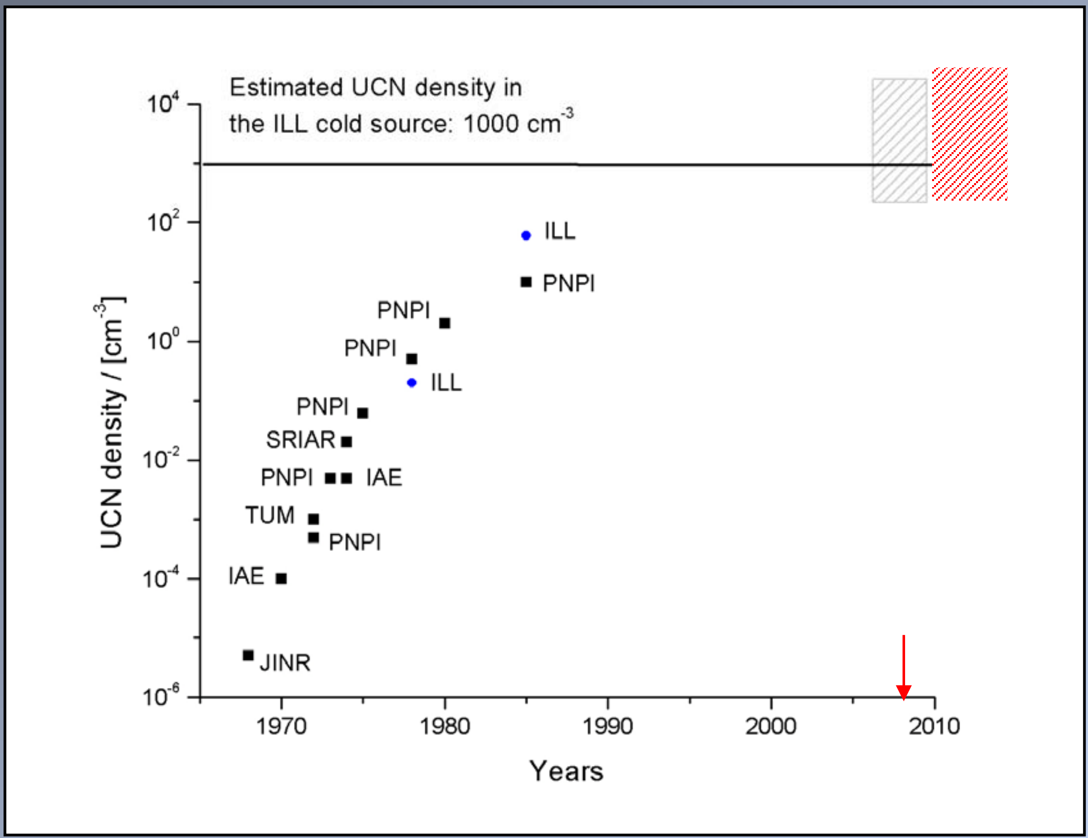


Result with PNPI EDM-setup at PF2:

τ_{osc} (90% C.L.) ≥ 414 s

A. Serebrov et al., arXiv:0706.3600; submitted to PLB

UCN facilities – Status and Future

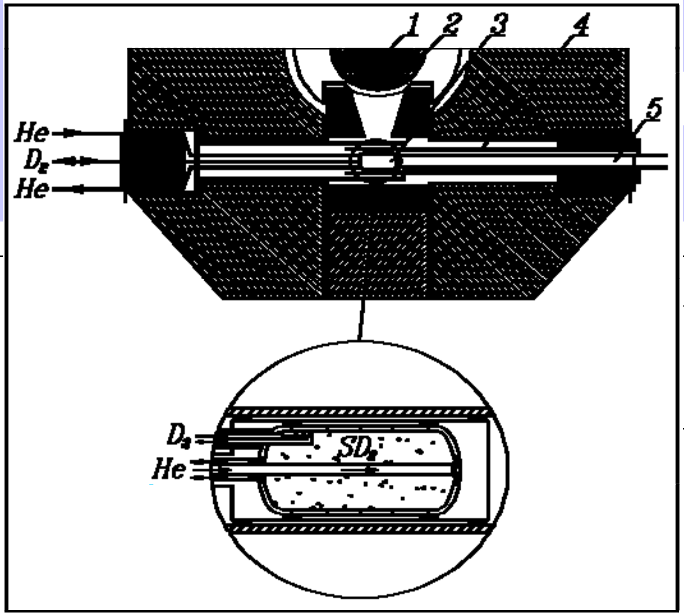


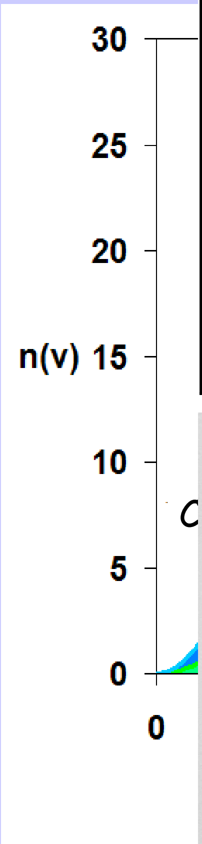
More and stronger UCN facilities in the future worldwide

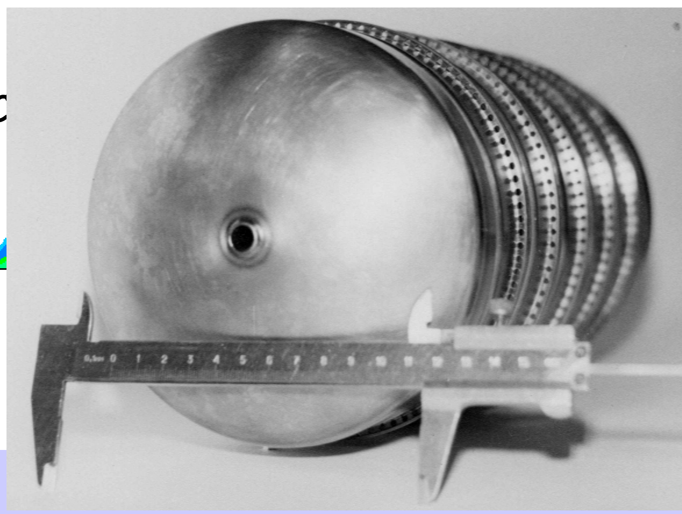
- **PSI (CH)**
- **Mainz / Munich (D)**
- **ILL (F)**
- **LANL / NIST / SNS / NCSU / LENS (USA)**
- **RCNP (J)** then (?) TRIUMF (Canada) then (?) JPARC (J)
- **PNPI (?) (RUS)**

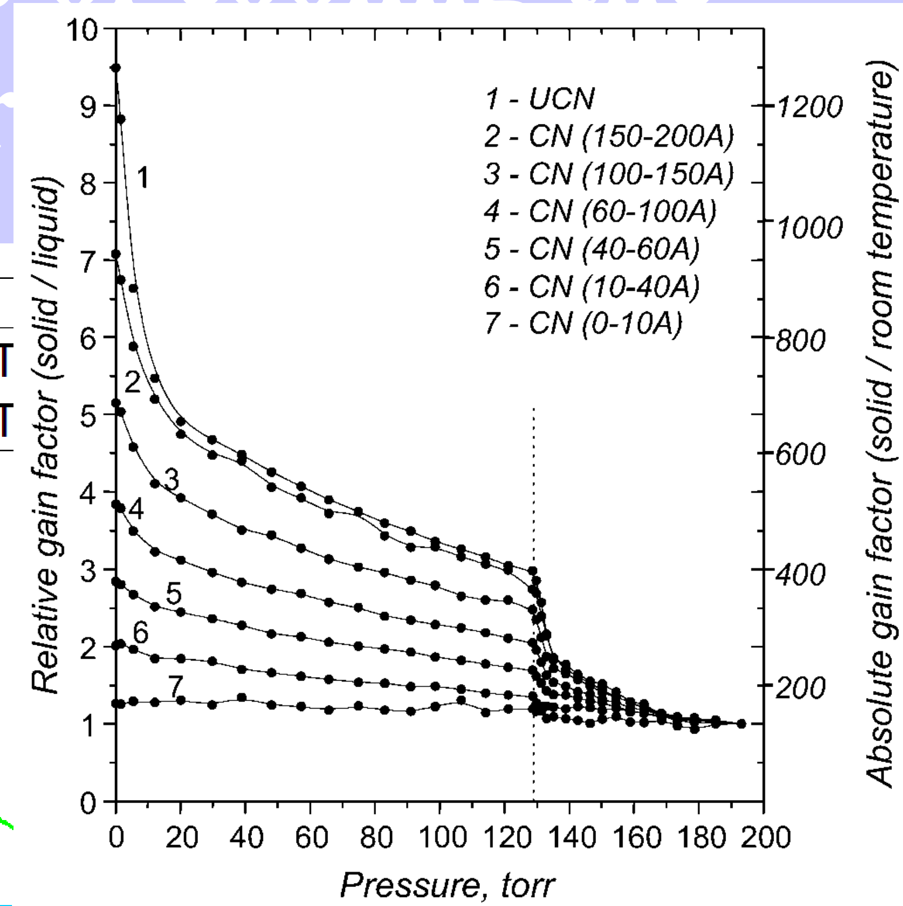
T nce of cooling the tr

Solid deuterium neutron source
for UCN production at PNPI









The relative and absolute gain factor for neutrons with different wavelengths as a function of the pressure in the system

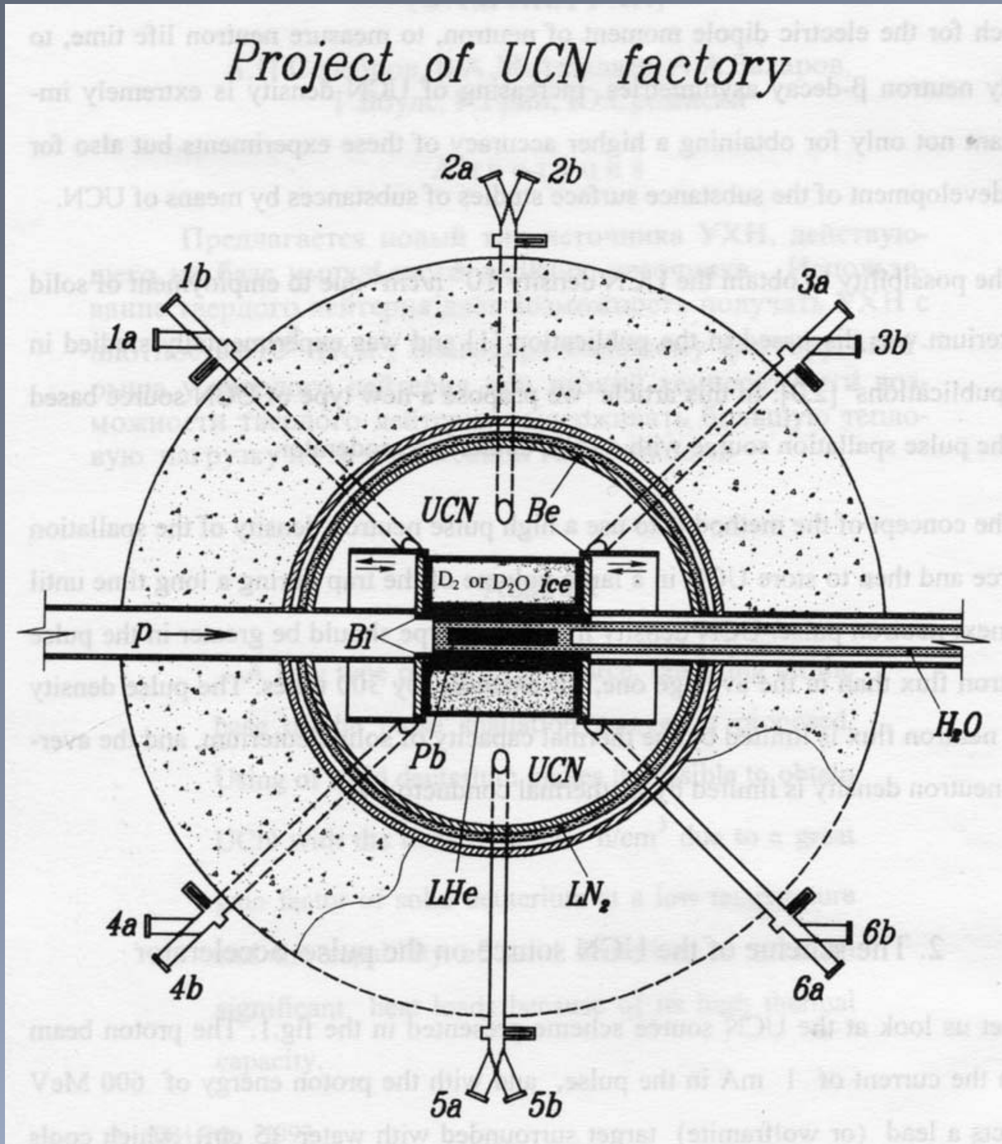
Yu. N. Pokotilovski, NIMA 356 (1995) 412

pulsed source, separation of production and storage volume

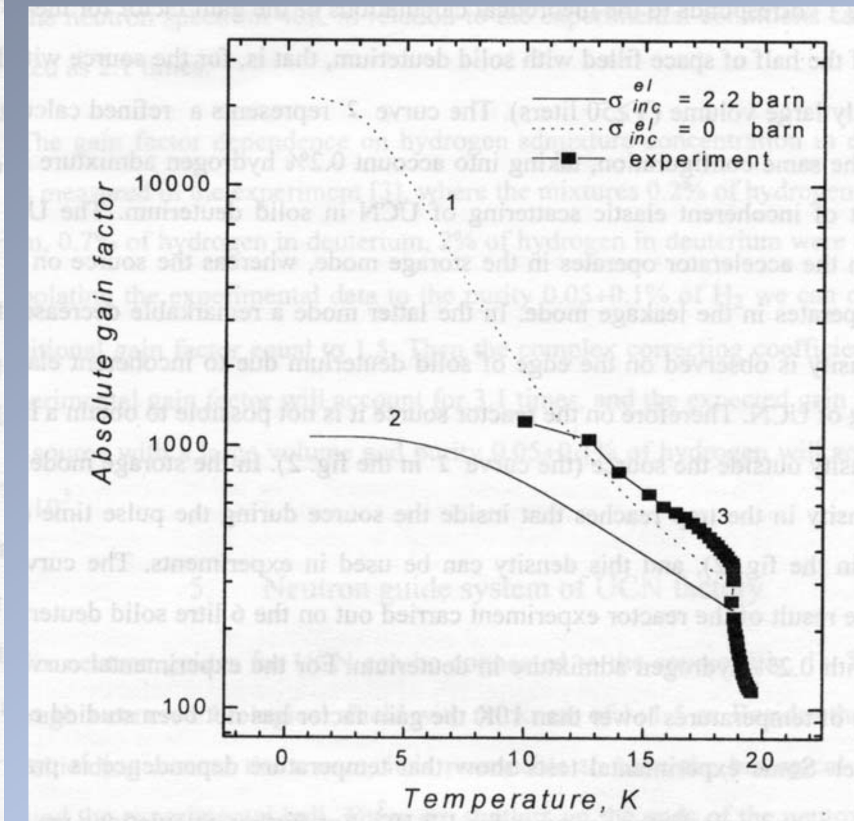
A. Serebrov et al.:

first test in 1980, then in 1995 again

Project of UCN factory



A.P. Serebrov et al, NP-63-1997-2206



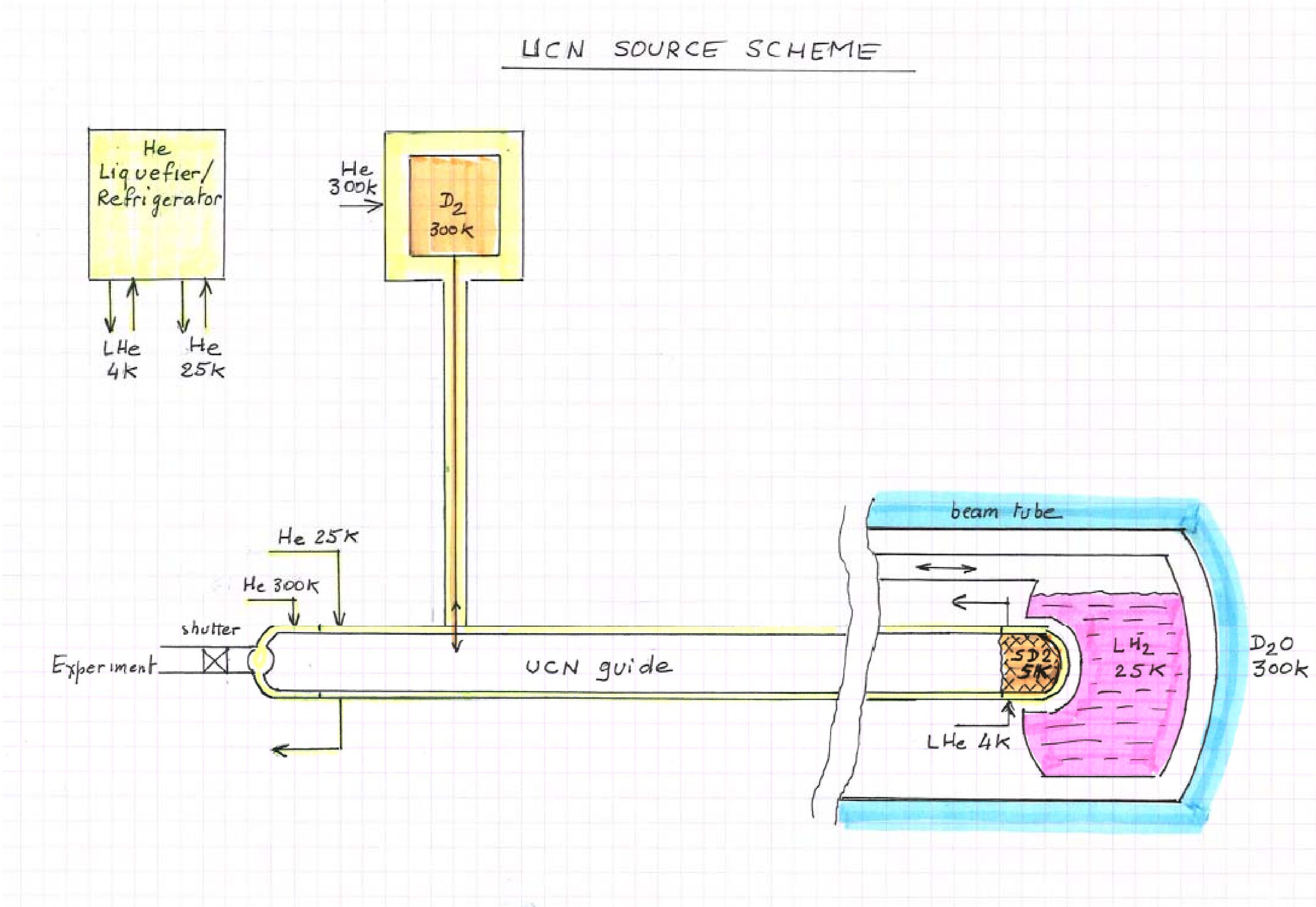
UCN Gain factor as a function of sD_2 temperature
Normalized to UCN yield at room temperature

followed up at

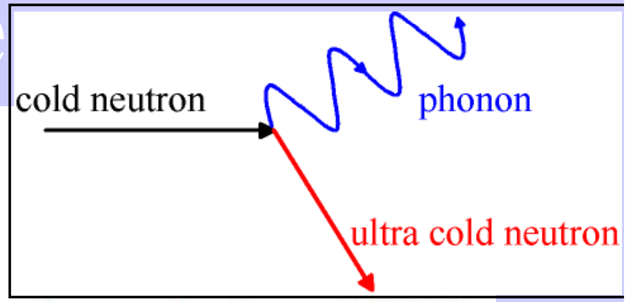
PSI
TRIGA Mainz
TUM
LANL
NCSU

ULTRA COLD SOURCE

integrated in a possible 3rd cold neutron source at the ILL



8.9 A neutrons are needed to create UCN in ^{4}He



2.1 A new method for UCN production

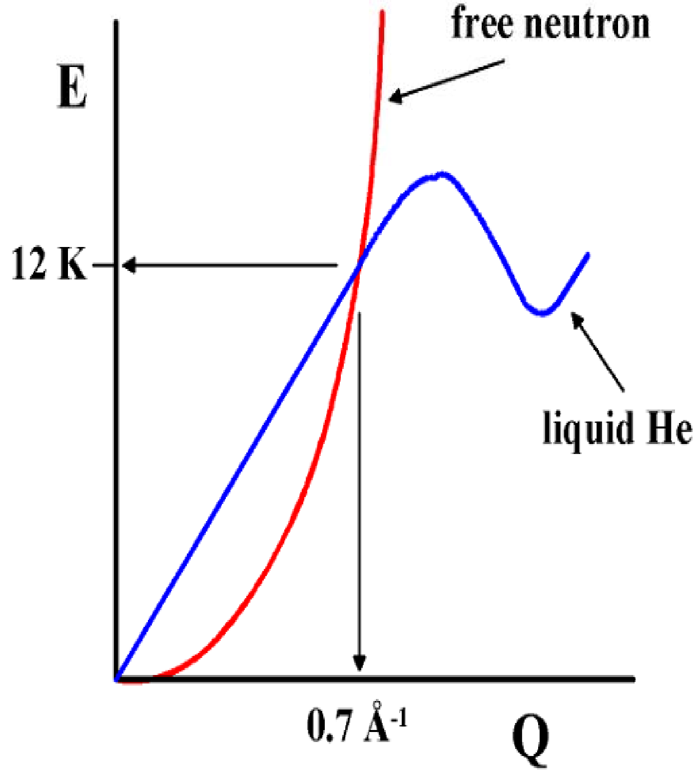


Figure 4 – Dispersion curves, see text.

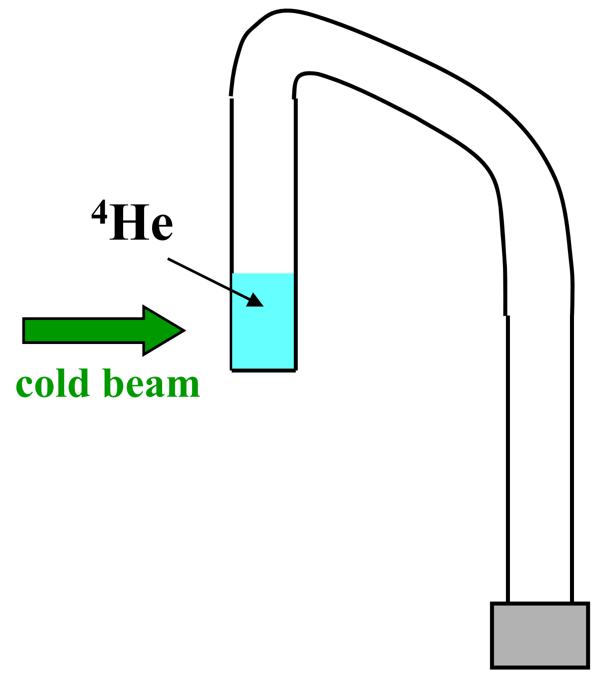
A new method for the production of UCN with the potential to reach far higher densities than available from the ILL neutron turbine was first proposed in 1977 by Bob Golub and one of us (JMP). This method relies on the properties of superfluid liquid helium (sLHe), specifically, on the dispersion curve as shown in Figure 4. This plots the energy vs. the momentum for a free neutron (the red curve), which is of course just a parabola, and the energy vs. momentum for phonon excitations in the LHe (the blue curve). The properties of superfluid LHe are such that these two curves cross at a momentum corresponding to a UCN wavelength of 8.9Å. A

UCN extraction?

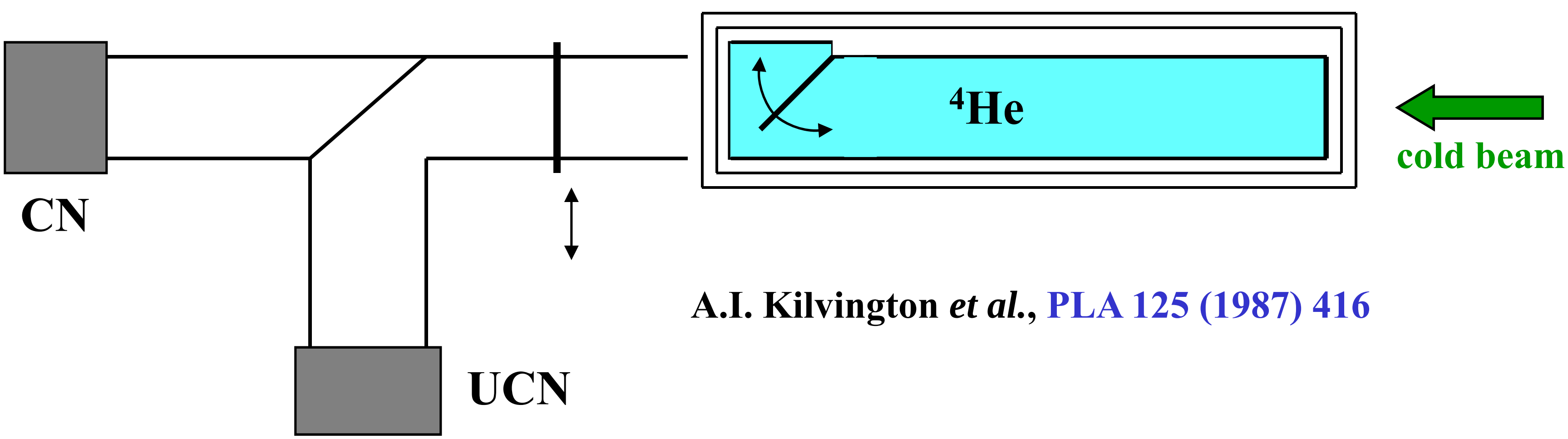
- **Extraction efficiency as expected for <u>open</u> UCN converter**

P. Ageron *et al.*, PL 66A (1978) 469

Y. Masuda *et al.*, PRL (2002) 284801-1



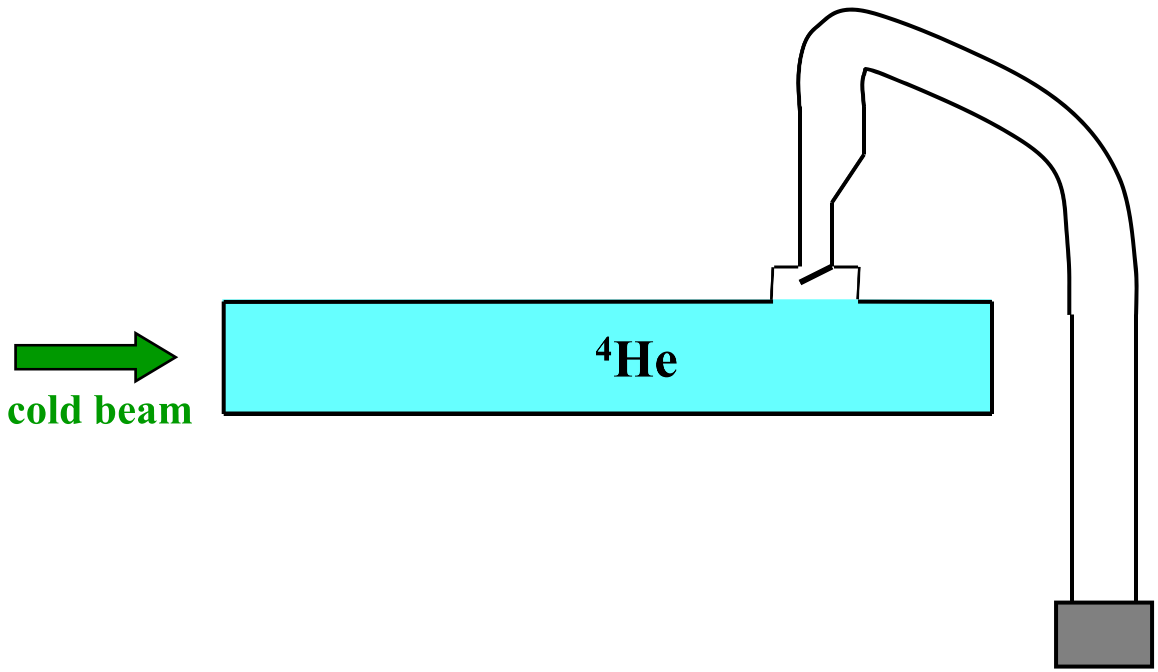
- **Extraction efficiency <u>with UCN accumulation</u> in converter so far not satisfactory (factor 50 missing)**



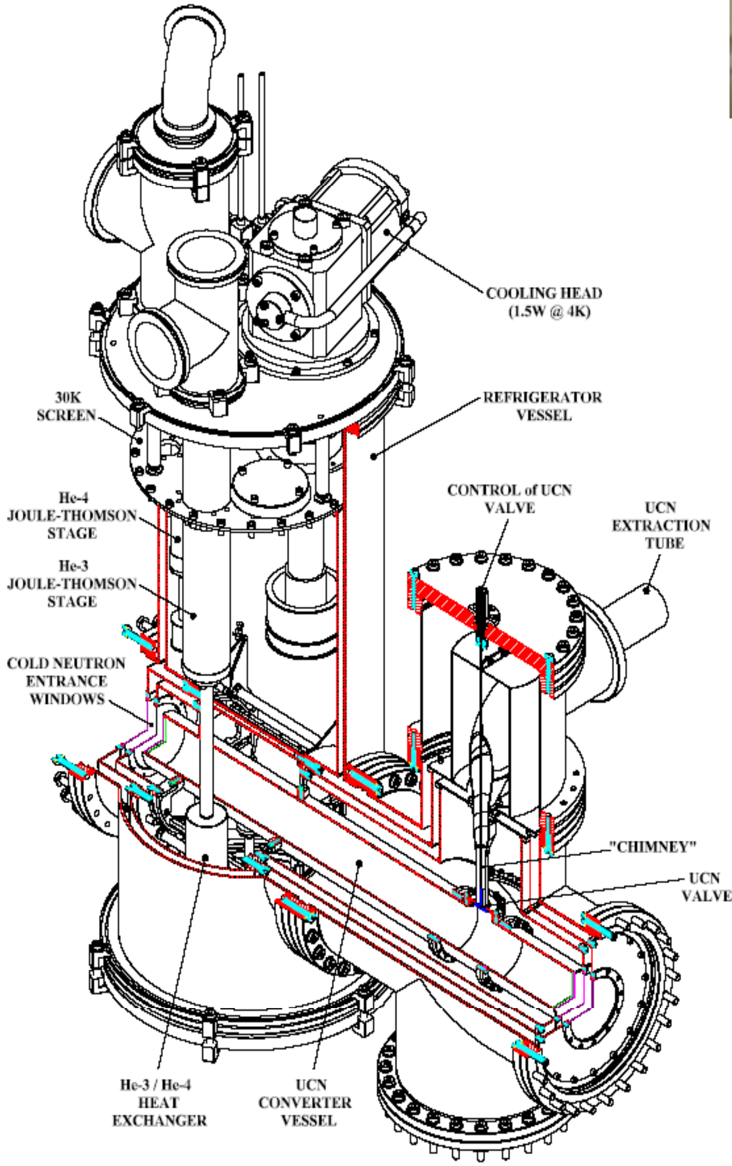
A.I. Kilvington *et al.*, PLA 125 (1987) 416

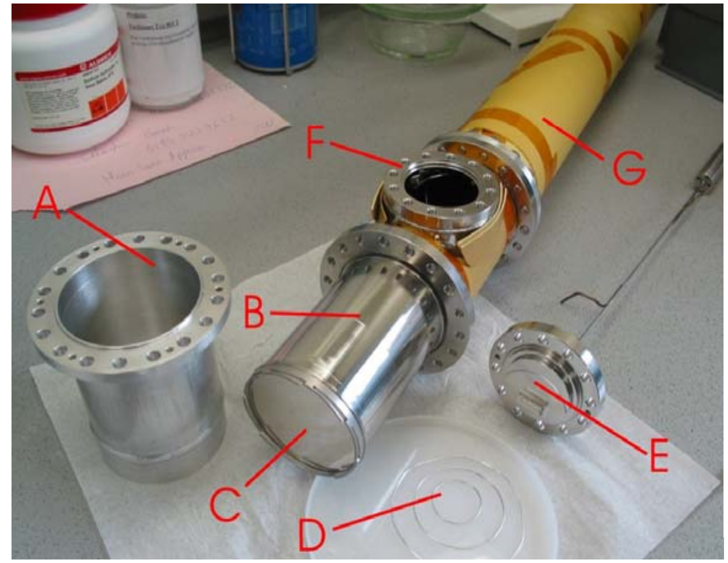
Principle

Accumulation and windowless vertical UCN extraction via a cold flap valve



Apparatus





- **stainless steel vessel**
- ***L* = 696 mm, *V* = 2.4 l**
- **Ni entrance/exit windows**

Helium liquefaction with GM-cooler

P. Schmidt-Wellenburg & O. Zimmer

Cryogenics 46 (2006) 799

^{4}He and ^{3}He evaporation stages

Superleak for removal of ^{3}He

I hope I could convince you
that ultracold neutrons are
– due to the fact that they are storable –
a fancy and powerful tool in fundamental physics!!

Info on http://www.ill.fr or http://www.ill.eu

Internat. Workshop "**Particle Physics with Slow Neutrons**"
at the ILL, Thursday 29th May – Saturday 31st May 2008

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

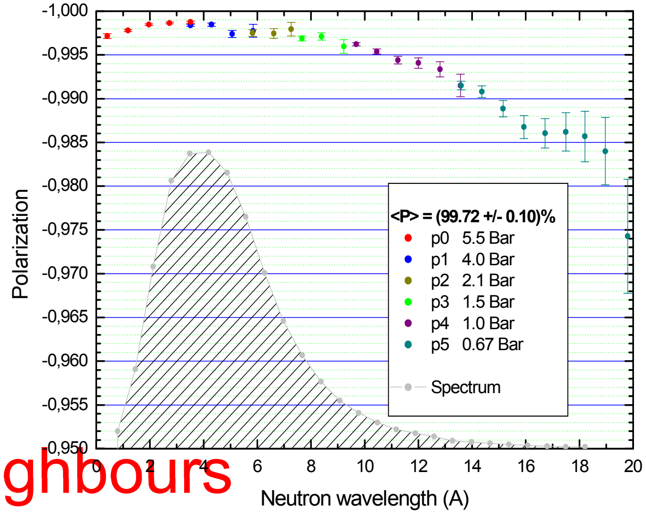
level C

level D

Spare viewgraphs

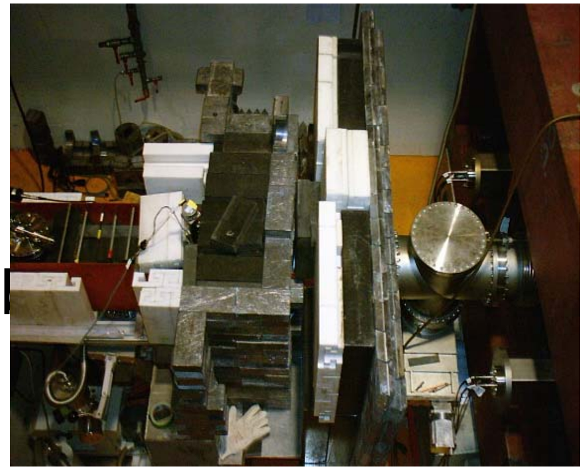
Strengths of PF1B

- Polarisation: up to 99.7%
- Polarisation measurement: ±0.1%
- Flux: $1.8 \cdot 10^{10}$ n/cm^2/s
- No upstream instruments
- Clean cold beam (out of direct view)
- TU experiments up tu 20 MBq ^{239}Pu



- But changing background due to neighbours
- But limited space

- Equipment:
  - polarisers, flippers
  - neutron detectors, other detectors in colla
  - shielding
  - electronics (NIM, motor control, etc.)



From proposal to experiment...

- Call for proposals:
  twice per year for the four scheduled instruments PN1, PN3, PF1, PF2

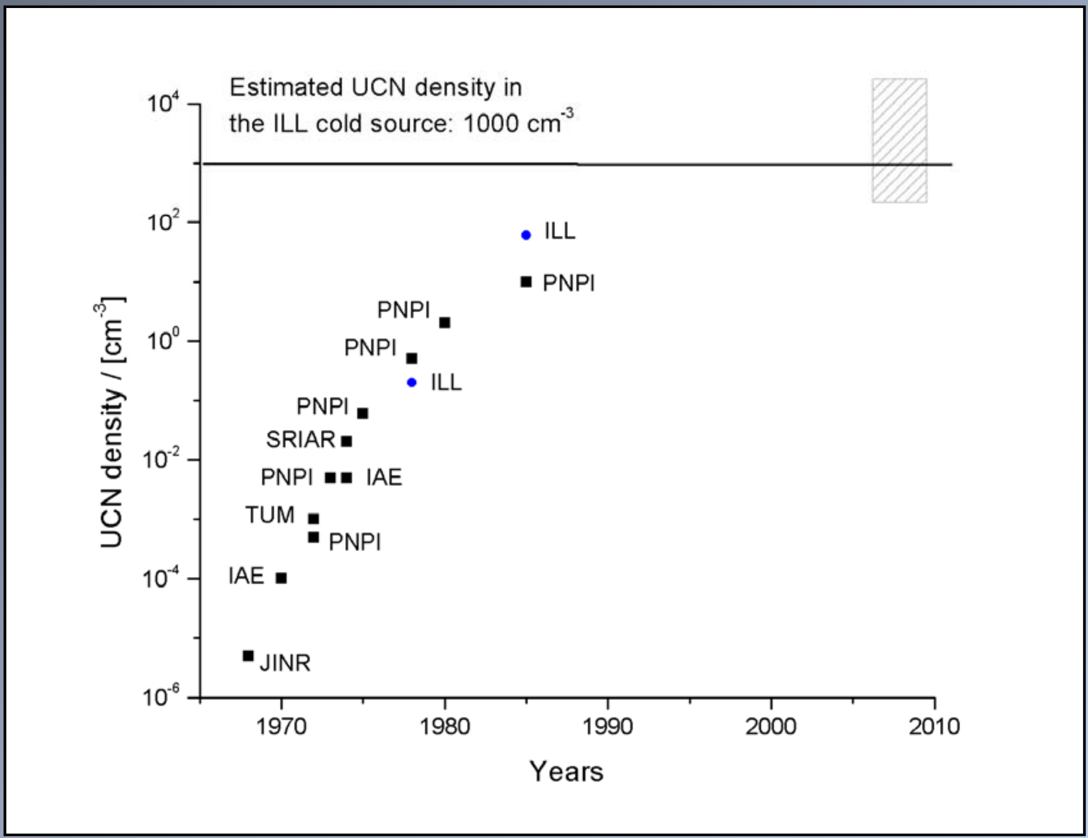
- Expert committee (College 3 subcommittee) judges proposals for their scientific merit,
  Directors usually follow suggestions (apart from national balance fine-tuning)

- Delay between proposal acceptance and execution of experiment:
  - on average about six months

Contributions of user groups to instrumentation have a long tradition and are very important for progress in nuclear and particle physics with slow neutrons:

- double flat crystal gamma ray spectrometer GAMS IV (NIST Washington)
- focussing magnet for Lohengrin (Univ. Tuebingen)
- ballistic neutron guide H113 for PF1B (Univ. Heidelberg)
- UCN turbine (TU Munich)

UCN facilities – Status and Future



More UCN facilities in the future worldwide

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- **Mainz / Munich (D)**
- **ILL (F)**
- **LANL / NIST / SNS/ NCSU / (LENS) (USA)**
- **RCNP / JPARC (J)**

A SD_2 UCN source at ILL is feasible

- Based on the CN flux of ILL cold sources, a solid-D2 source should provide a UCN density of several 10^4 UCN/cm^3.
- Considering a 100 cm^3 solid-D2 source & an heating level of ~0.3 W/g, cooling of the source appears feasible.
- ILL has experience with CN liquid-D2 sources,
- If solid-D2 can survive to ILL HFR radiation during a few hours (June 2007 tests) -->

a UCN solid-D2 source is feasible at ILL