* Neutron magnetic storage and neutron lifetime measuring

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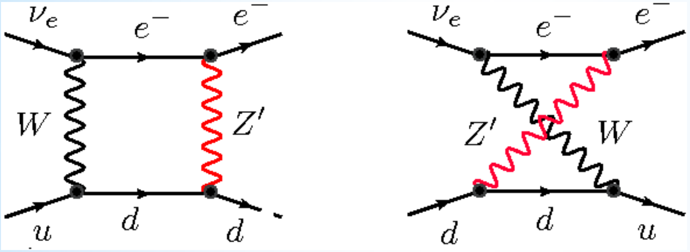
31.01.17

Test of Standard model

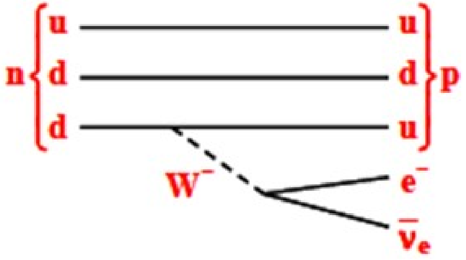
- The most precise determination of V_{ud} is obtained from superallowed nuclear-decays, combined with theoretical computations of the SM electroweak radiative corrections. Further reductions in the SM radiative correction uncertainties associated with the W box graphs will be essential.



- Theoretical nuclear structure uncertainties suggest that a 10^{-4} determination of $|V_{ud}|$ from superallowed decays will be challenging even with the advent of improved SM radiative correction calculations.
- Determination of $|V_{ud}|$ from neutron decay provides a promising alternative path to 10^{-4} precision. Achieving this goal will require a robust measurement of τ_n with 0.1 s uncertainty and an order-of-magnitude reduction in the uncertainty of g_V/g_A as obtained from neutron decay correlation studies.

Cirigliano V., et al. Prog. Part. Nucl. Phys. 71, 93-118 (2013).

Neutron β-decay and Standard Model



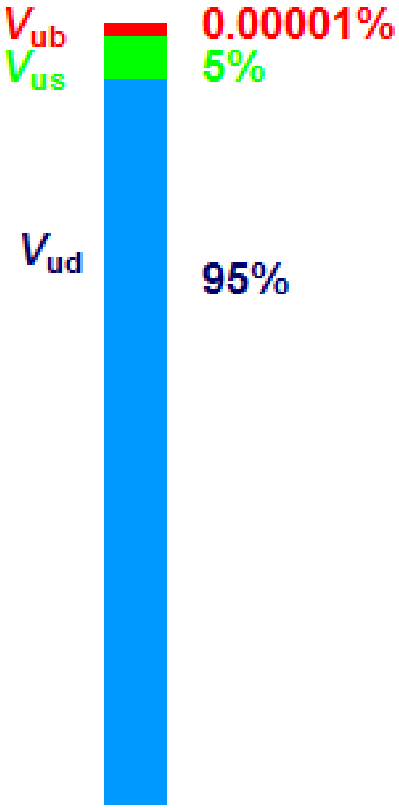
$$\lambda = \frac{G_A}{G_V} \qquad A_0 = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$

$$\boxed{|V_{ud}|^2 = \frac{4908.7 \pm 1.9\ \mathrm{s}}{\tau_n\left(1+3\lambda^2\right)}}$$

W.Marciano
A.Sirlin
PRL 96, 032002
(2006)

CKM mixing matrix:

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



$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$\Delta_{\mathrm{CKM}} \equiv \left(|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2\right)_{\mathrm{exp}} - 1 = -0.0001 \pm 0.0006,$$

Нуклеосинтез

$$p + e^{-} \longleftrightarrow n + \nu$$

$$n + e^{+} \longleftrightarrow p + \bar{\nu}$$

- До 1 секунды после Большого взрыва соотношение нейтроны/протоны находится в тепловом равновесии. Когда же температура становится немного ниже, чем энергетический эквивалент различия масс нейтрона и протона, эти реакции не успевают за скоростью расширения Вселенной, и соотношение нейтронов и протонов замораживается на величине около 1:6.

$$n \longrightarrow p + e^{-} + \bar{\nu}$$

- Через 1 секунду единственной реакцией остается бета-распад нейтронов. Период полураспада нейтрона составляет 880 секунд. Без дальнейших реакций, сохраняющих нейтроны внутри стабильных ядер, Вселенная состояла бы из одного водорода. Начинается нуклеосинтез.

Нуклеосинтез

$$p + n \longleftrightarrow d + \gamma$$

- **Реакцией, сохраняющей нейтроны, является образование дейтронов. Эта имеет энергетический порог в 2.2 МэВ, однако из-за того, что фотоны в миллиард раз более многочисленны, чем протоны, реакция не идет до тех пор, пока температура Вселенной не достигнет kT = 0.1 МэВ, т.е. через 100 секунд после Большого взрыва. К этому времени, отношение нейтронов к протонам составляет около 1:7**

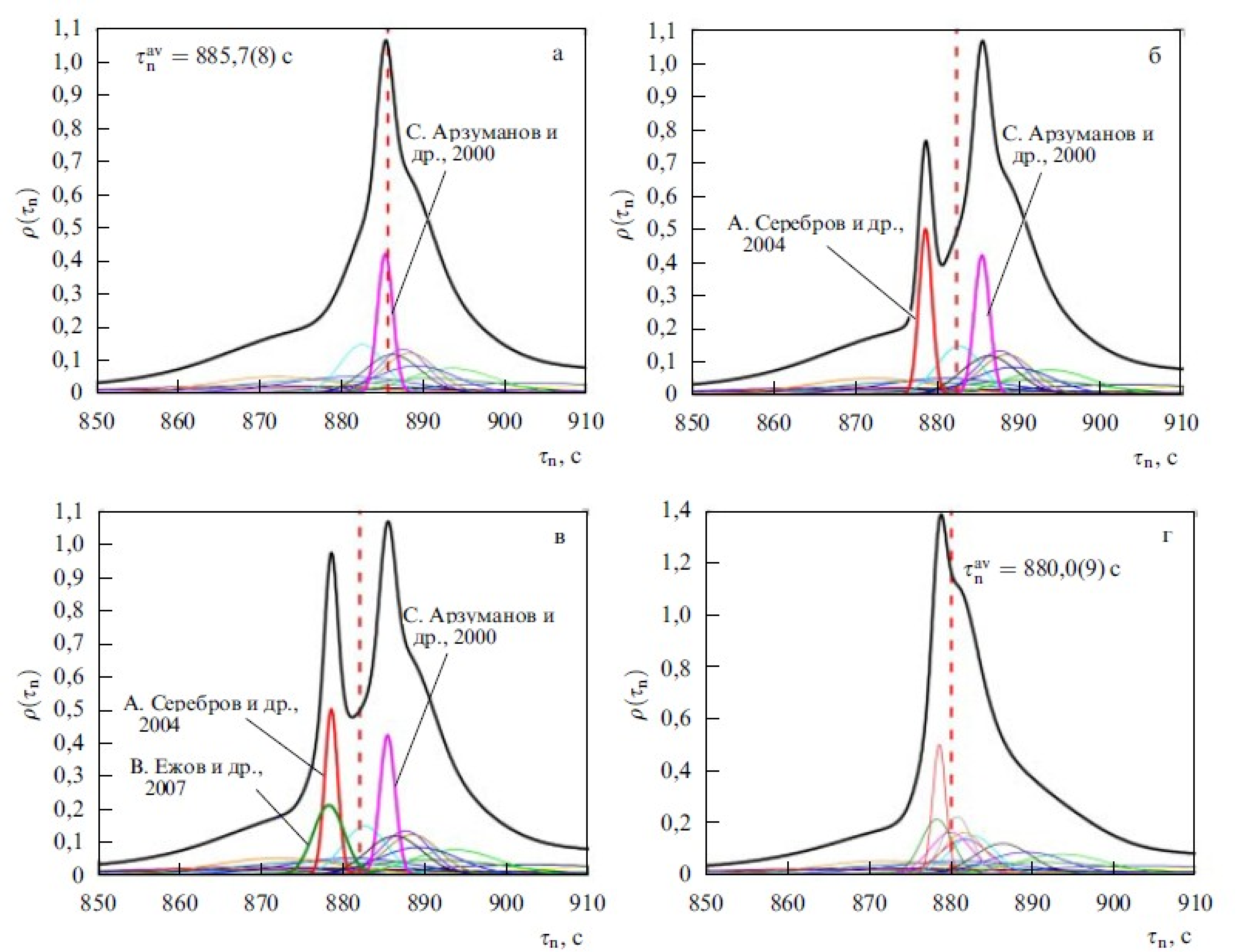
$$d + n \longrightarrow H^3 + \gamma$$

$$H^3 + p \longrightarrow He^4 + \gamma$$

$$d + p \longrightarrow He^3 + \gamma$$

$$He^3 + n \longrightarrow He^4 + \gamma$$

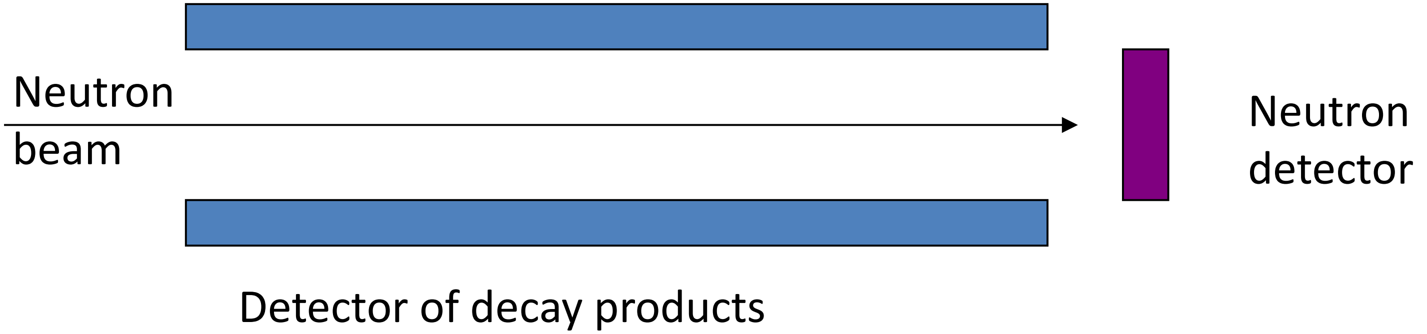
- **Реакции нуклеосинтеза. Поскольку энергия связи ядер гелия 28 МэВ, а температура уже упала до kT = 0.1 МэВ, то эти реакции идут лишь в одном направлении.**
- **Видим, что концентрация (распространенность) He в природе определяется временем жизни нейтрона. Изменение времени жизни на 1% меняет распространенность He на 17%.**


а
$\tau_n^{av} = 885{,}7(8)$ с
С. Арзуманов и др., 2000
$\rho(\tau_n)$
τ_n, с
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
850
860
870
880
890
900
910
б
А. Серебров и др., 2004
С. Арзуманов и др., 2000
в
А. Серебров и др., 2004
В. Ежов и др., 2007
С. Арзуманов и др., 2000
г
$\tau_n^{av} = 880{,}0(9)$ с
1,2
1,4

Magnetic storage - why is it interesting?

- Previous neutron lifetime measurements

1. Beam measurements



Accurate measurements of flux and decay products

2. UCN Storage measurement

Storage losses?

Neutron magnetic storage

Magnetic mirrors, channels and bottles neutrons.
Vladimirskii V.V. Sov. Phys. JETP 12, 740-746, (1961)

Magnetic potential $U = -\vec{\mu} \cdot \vec{B}$

$$F = -\nabla U = \nabla(\vec{\mu} \cdot \vec{B}) = \pm \mu \nabla \left| \vec{B} \right|$$

+ for $\vec{\mu} \uparrow\uparrow \vec{B}$ and

– for $\vec{\mu} \uparrow\downarrow \vec{B}$

For magnetic moment of neutron $U = 60 neV \cdot T^{-1}$

Nuclear potential of Be $250 neV$

Magnetic field 1 T reflects neutrons up to 3.4 m/s, as Al.

Magnetic trap: 1 T for trapping

Main problem: trap configuration

Depolarization

- Is it possible to avoid depolarization?
- Adiabatic condition

$$\frac{\dot{H}}{\gamma H} = \frac{(\vec{v}\cdot\vec{\nabla})H}{\gamma H} \ll 1\,,$$

$$P = e^{-\pi\omega\tau}\,,$$

where $\tau = H/\dot{H}$.

- Magnetic field in trap is too inhomogeneous
- Main task to exclude zero points of magnetic fields
- Counting of neutrons leaking from trap during storage time permits to monitor the losses

Experimental strategy and main problems of magnetic storage

- Choice of trap configuration
- Monitor of losses (the spin flipped UCN)
- Efficiency of losses monitor
- Filling of trap
- Monitor of trap filling

Neutron magnetic storage - (mile stones)

Magnetic mirrors, channels and bottles neutrons.
Vladimirskii V.V., Sov. Phys. JETP 12, 740-746, (1961) (ITEP)

Current systems

Kosvintsev Yu.Yu., Kushnir Yu.A., Morozov V.I., Plotnikov I.A. JETP Letters v. 27(1), 65, (1978) (SRIAR)

τ=35±10 sec

Abov Yu.G., Vasil’ev V.V., Vladimirskii V.V., Rozhnin I.B., JETP Letters v. 44(8), 472, (1986). (ITEP)

$\tau > 700$ sec

Superconducting

W. Paul, F. Anton, L. Paul, S. Paul, and W. Mampe, Z. f. Physik C 45, 25 (1989). (ILL + Munich)

$\tau = 877 \pm 10$ s

S.N. Dozbosuk et. al., J. Res. Natl. Inst. Stand. Technol. 110, 339, (2005) (Los-Alamos)

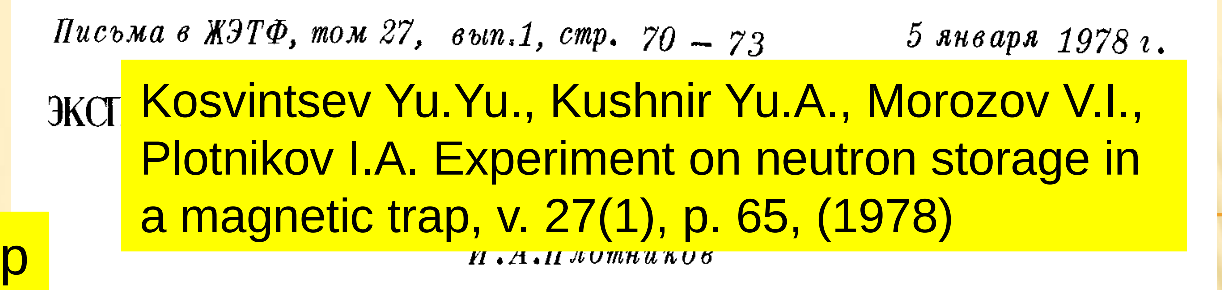
$\tau = 833^{+74}_{-63}$ s

Permanent magnets

V.F. Ezhov et. al., arXiv:1412.7434 [nucl-ex], (2014) (PNPI + ILL)

$\tau_n = 878.2 \pm 1.9\ s$

TRAP FILLING



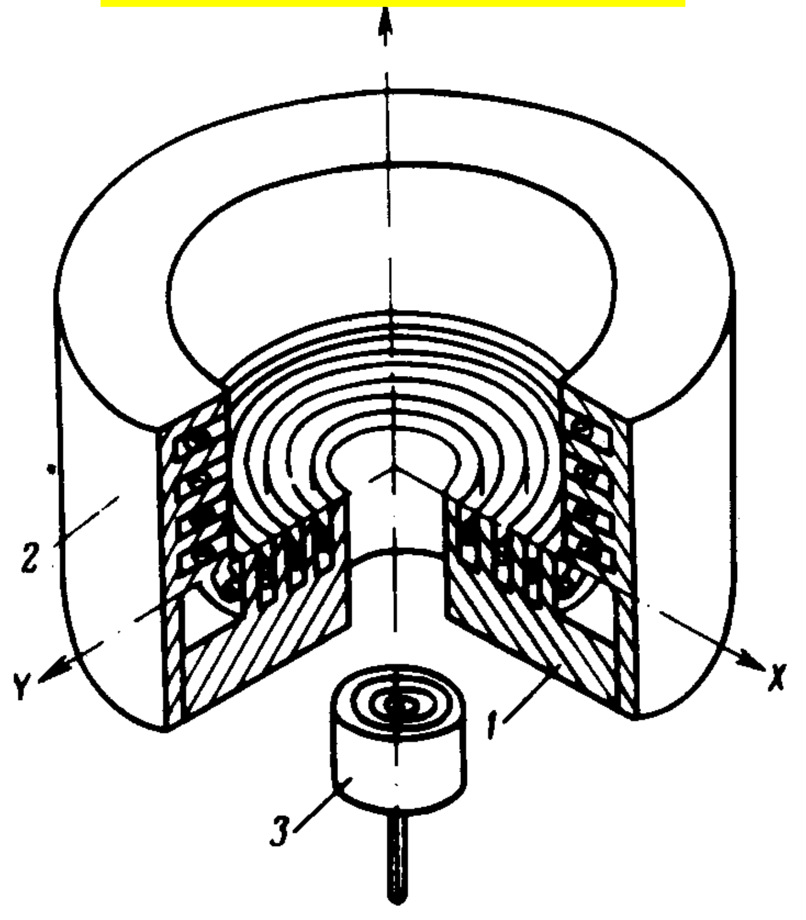
Письма в ЖЭТФ, том 27, вып.1, стр. 70 – 73 5 января 1978 г.

ЭКС

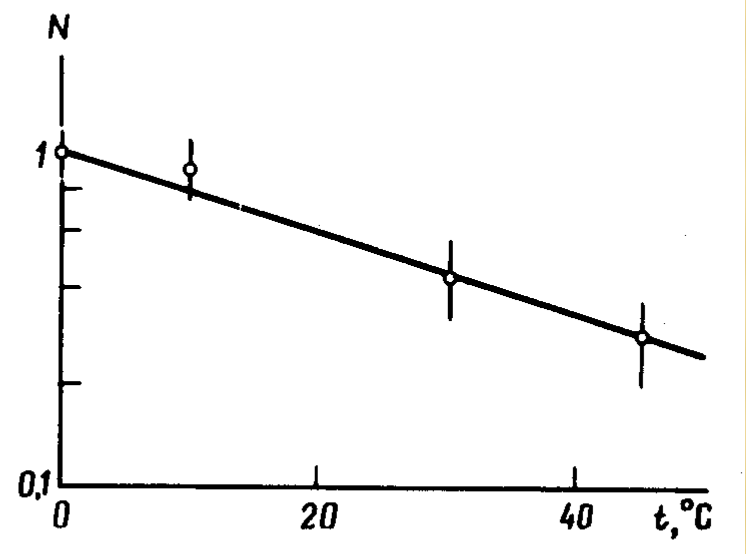
И.А.Плотников

Kosvintsev Yu.Yu., Kushnir Yu.A., Morozov V.I., Plotnikov I.A. Experiment on neutron storage in a magnetic trap, v. 27(1), p. 65, (1978)

First real magnetic trap



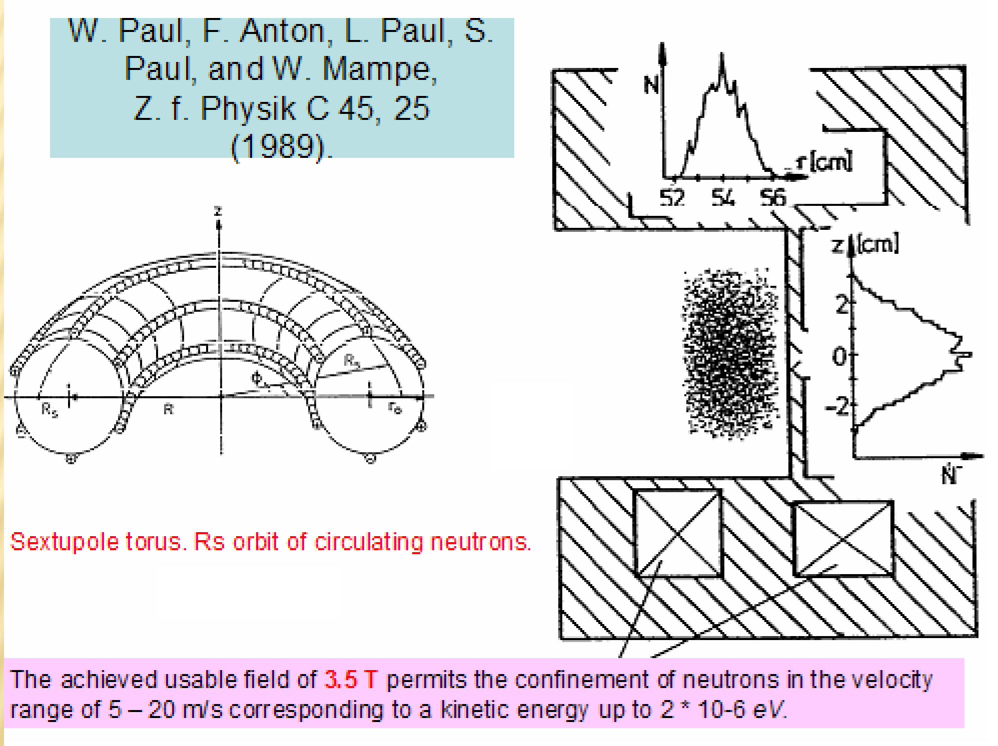
Reactor CM-2



W=20 kW

ج=35 s

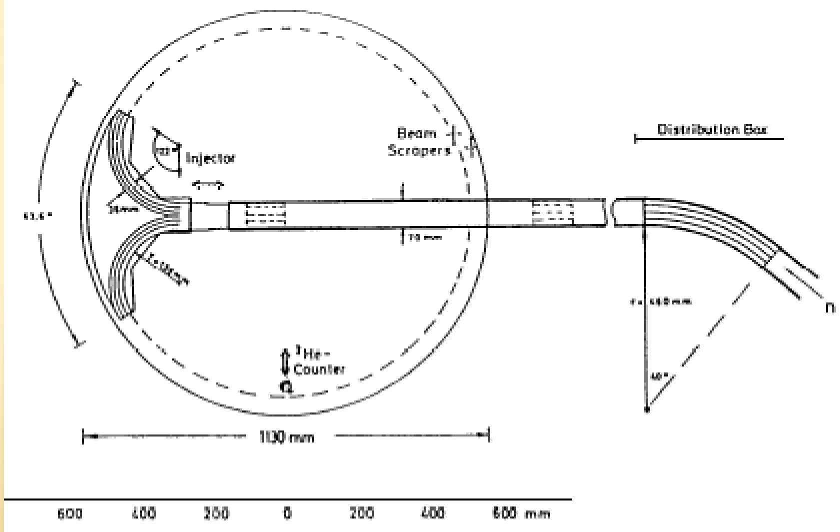
TRAP FILLING



W. Paul, F. Anton, L. Paul, S. Paul, and W. Mampe,
Z. f. Physik C 45, 25 (1989).

Sextupole torus. Rs orbit of circulating neutrons.

The achieved usable field of 3.5 T permits the confinement of neutrons in the velocity range of 5 – 20 m/s corresponding to a kinetic energy up to 2 * 10-6 *eV*.



چ=877ڨ10 s

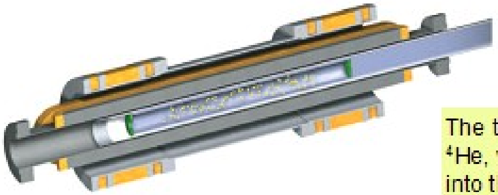
TRAP FILLING

Ioffe-Pritchard trap for neutrons

The main problems:

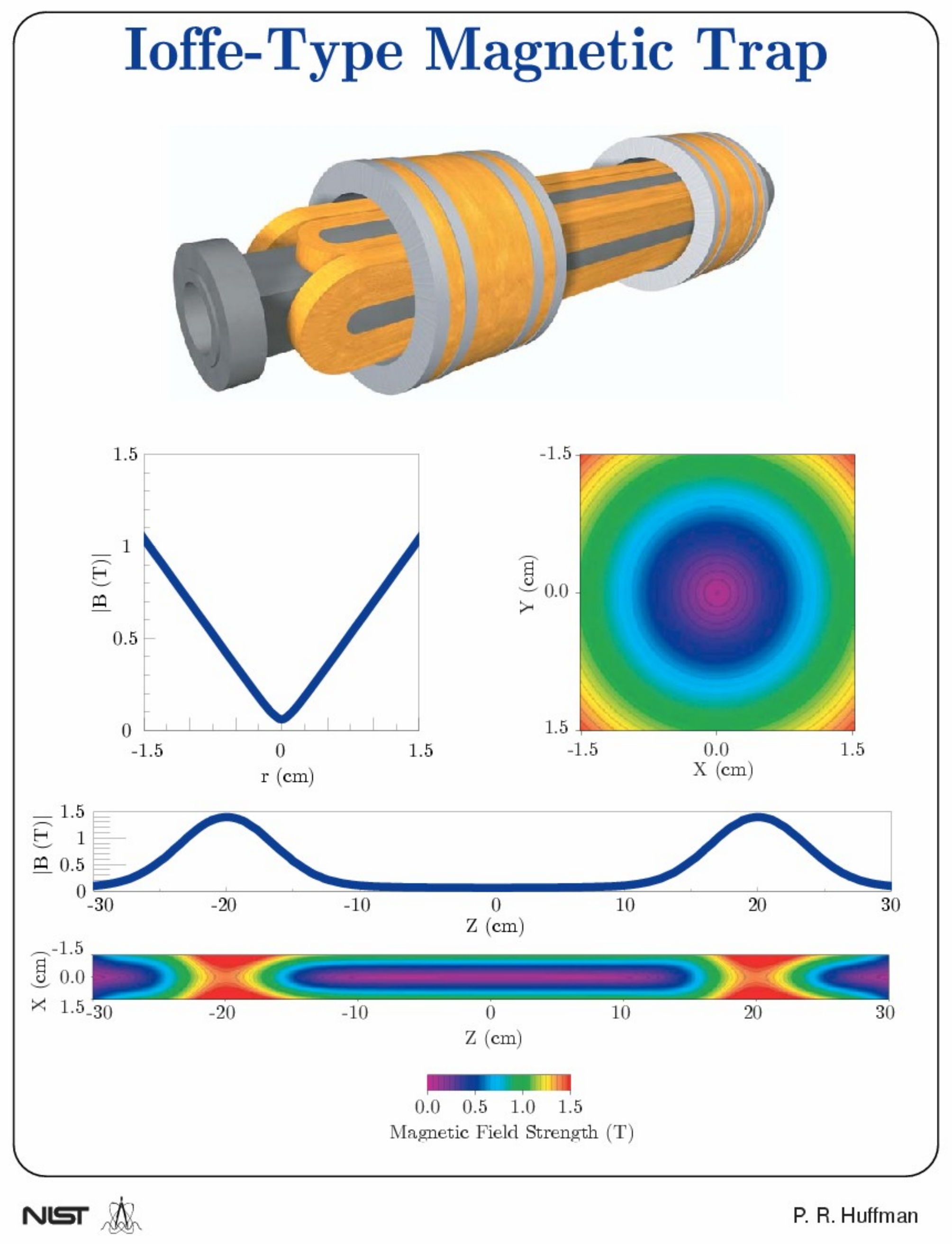
1. **Filling and empting. If one use superconducting system, then he can't switch on field too fast.**
2. **Huge setup and small storage volume**
3. **Field only 1 T**

S.N. Dozhosuk *et al.*, J. Res. Natl. Inst. Stand. Technol. **110**, 339 (2005).



The trapping region is filled with superfluid ^{4}He, which is used to load neutrons into the trap and as a scintillator to detect their decay. Neutrons have a lifetime in the trap of

$$\tau = 833^{+74}_{-63}\ \mathrm{s}$$



Ioffe-Type Magnetic Trap

P. R. Huffman

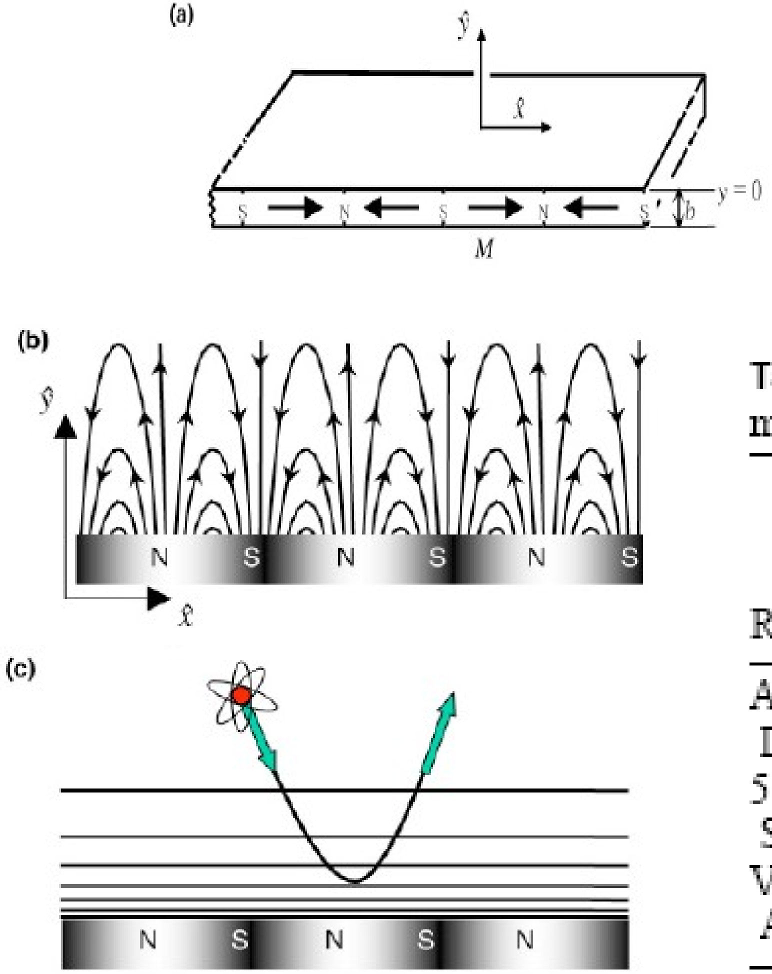
Magnetic wall of Permanent magnets?

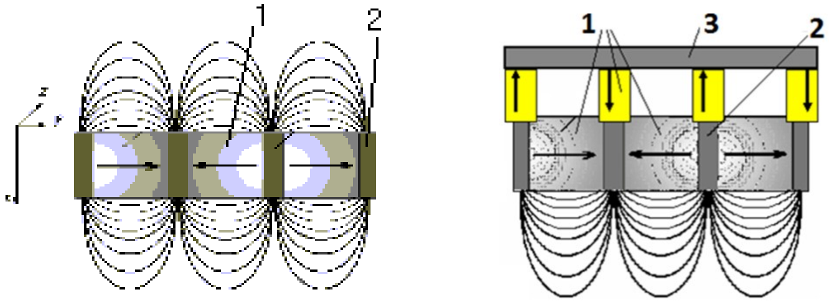
J. Phys. D: Appl. Phys. 32 (1999) R119–R146. Printed in the UK PII: S0022-3727(99)95361-5

REVIEW ARTICLE

Magnetic atom optics: mirrors, guides, traps, and chips for atoms

E A Hinds and I G Hughes





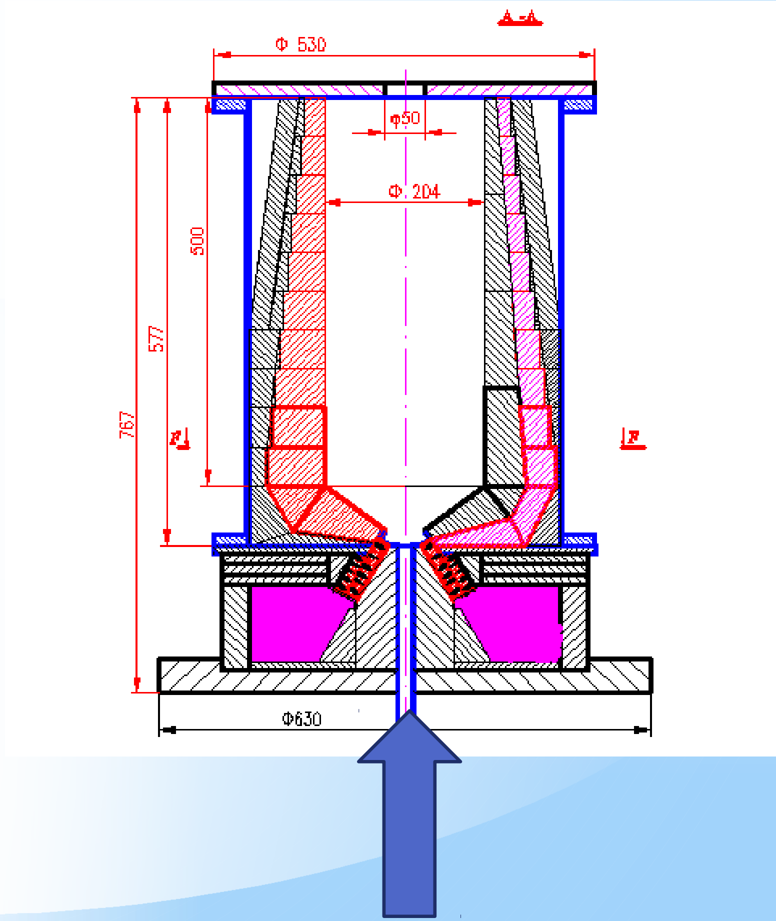
1 – постоянный магнит
2 – полюс из материала с максимальной индукцией насыщения
3 – **магнитопровод**

Table 1. Manufacturers' specifications for the magnetic recording media used to make atom mirrors.

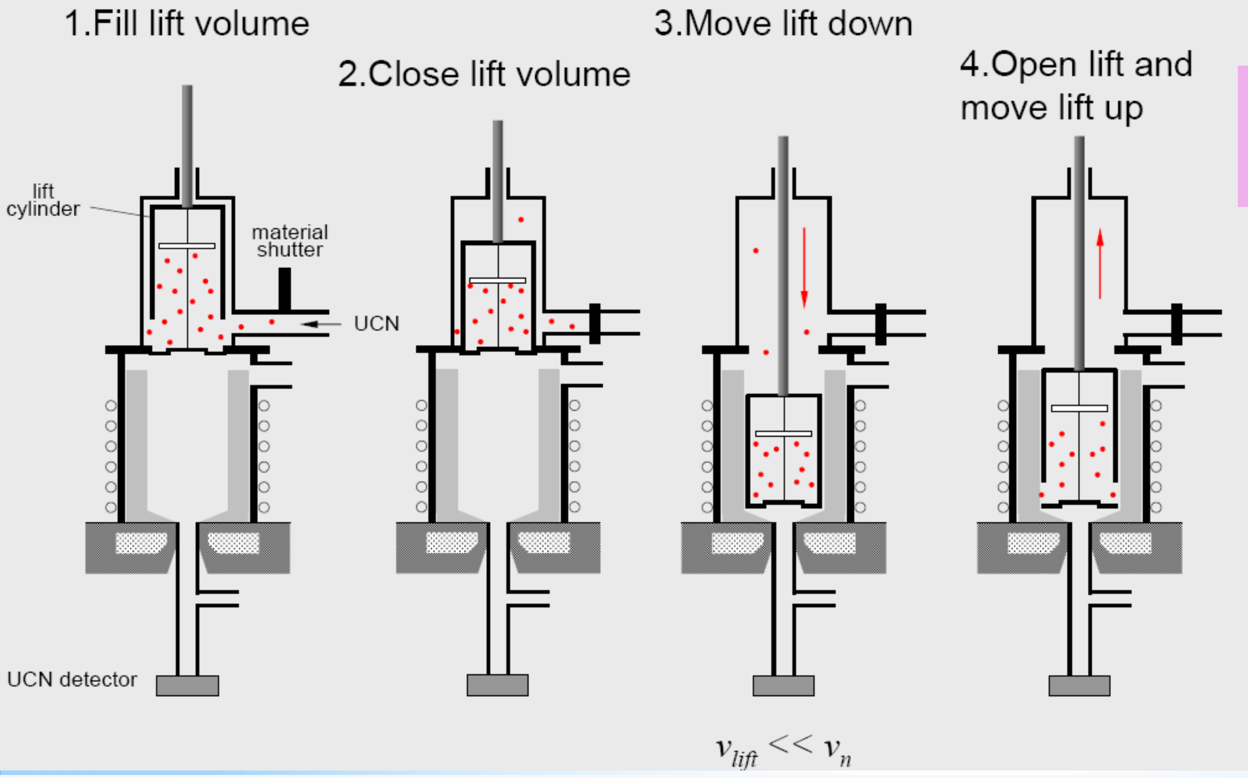
Recording medium	Remanent field (G)	Magnetic layer thickness (μm)	Coercivity (Oe)
Audio-tape			
Denon HD-M	3500	4.0	1200
$5\frac{1}{4}$ inch floppy disk			
Sony MD-2D	700	2.5	290
Videotape			
Ampex 398 Betacam SP	2300	3.5	1500

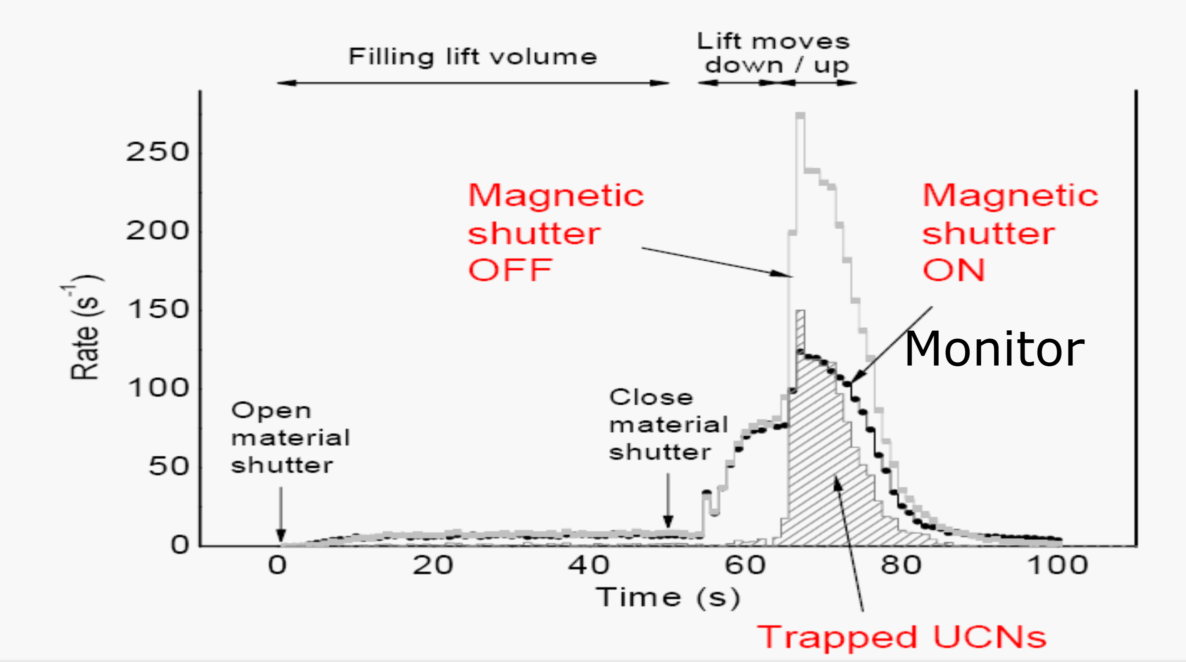
* Filling through lower neutron guide

*Neutrons heating at the moment of magnetic shutter switching on



Trap filling

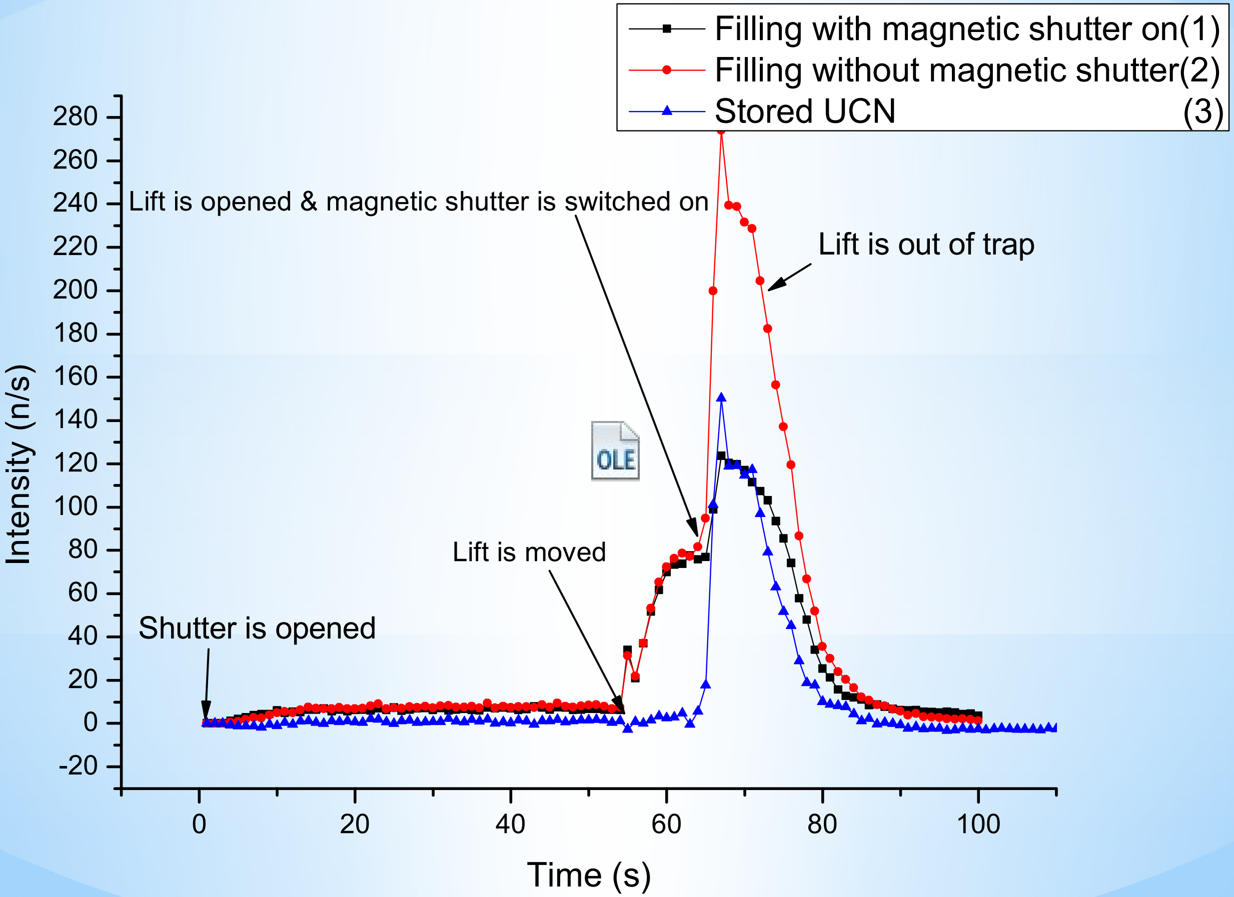




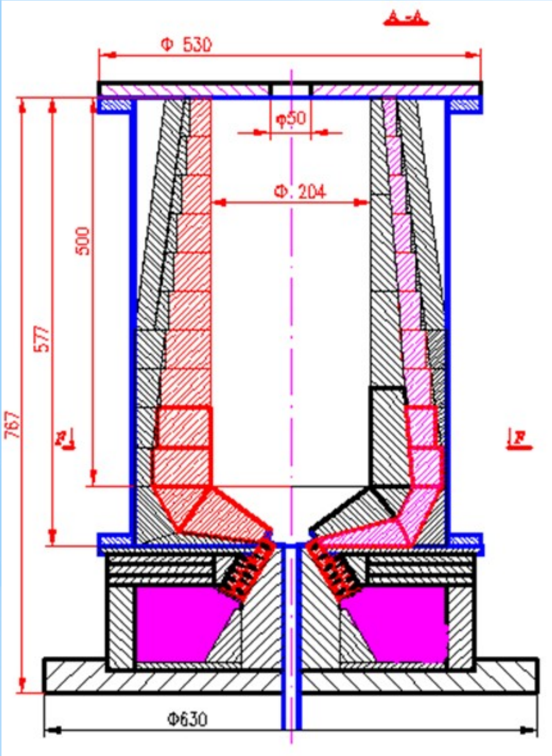
Effective cleaning

* Monitor of trap filling

1. We have used: Trap filling with unpolarized UCN. In this case half of UCN will be detected just during the filling

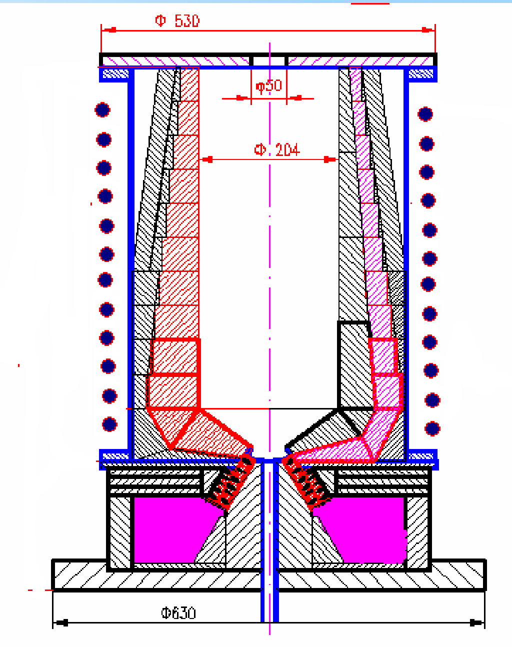


Control of the spin flipped UCN



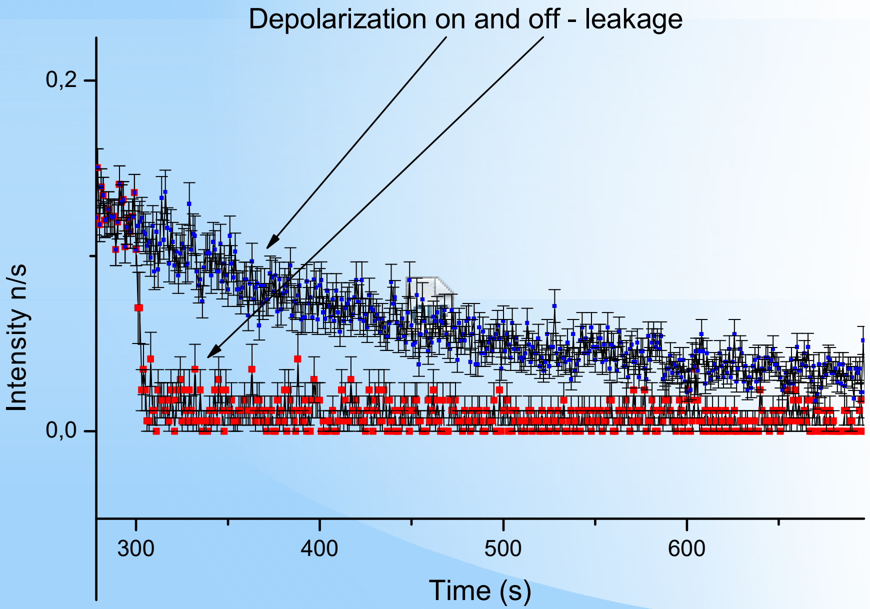
- To control the spin flipped UCN the inner trap walls are covered with thin layer of fomblin that reflects spin flipped UCN. After some collisions (order of some 10-th) the spin flipped UCN penetrate through the magnetic barrier of solenoid and are detected by the UCN detector installed below the solenoid. Hence this intensity may be used as the detector of UCN losses during storage time.

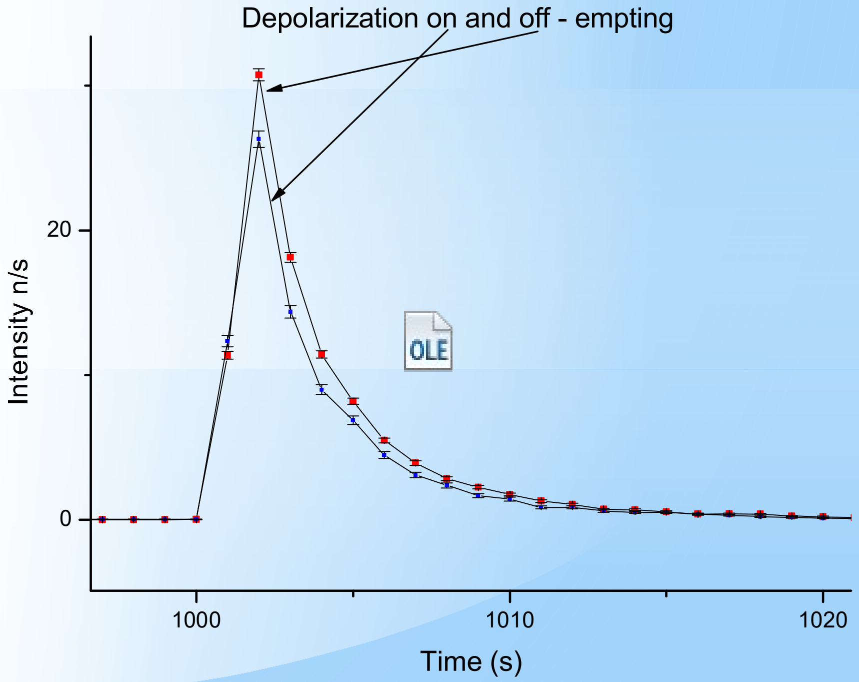
Efficiency of spin flipped neutron collection (direct measuring using artificial depolarization)



$$\varepsilon = \frac{\sum_{t_i=301}^{1000} (N_1(t_i) - N_2(t_i)) \cdot e^{\frac{t_i - 300.5}{\tau_{decay}}}}{\sum_{t_i=1001}^{1100} (N_2(t_i) - N_1(t_i)) \cdot e^{\frac{t_i - 300.5}{\tau_{decay}}}}$$

ε =0.903±0.007





Income of efficiency

In case of constant value of ε

$$\lambda_{decay} = \frac{1}{T} ln\left(\frac{N_{trap}(T)}{N_0}\right)\left(1 - \left(\frac{N_{leak}(T)}{\varepsilon\left(N_0 - N_{trap}(T)\right)}\right)\right)$$

One can see that correction to λ_{decay} provided by efficiency of spinflipped neutron collection has an additional smallness in case of

One can see that correction to λ_{decay} provided by efficiency of spinflipped neutron collection has an additional smallness in case of

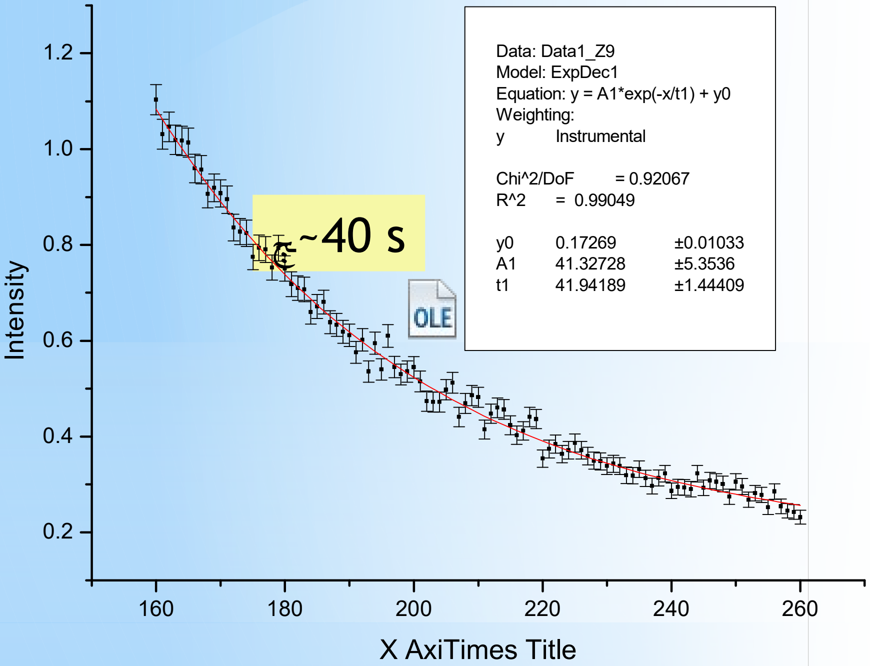
$$N_{leak}(T) \ll N_0 - N_{trap}(T)$$

Approximation for ε as a constant value is a sufficiently good one for this experiment. Really losses of UCN hitting the wall depend on neutron velocity but spinflipped neutrons (just these neutrons can be lost) are accelerated in magnetic gradient before their hitting a wall. The field near the wall of trap is about 1 T, but the field used in lower magnetic shutter (just this field determines highest energy of stored UCN) is only 0.45 T. It means that velocity interval of UCNs hitting the wall after their acceleration in magnetic field gradient lays in very narrow velocity diapason (between 3.4 and 3.9 m/s). So one can use mean value ε as a constant with a good accuracy.

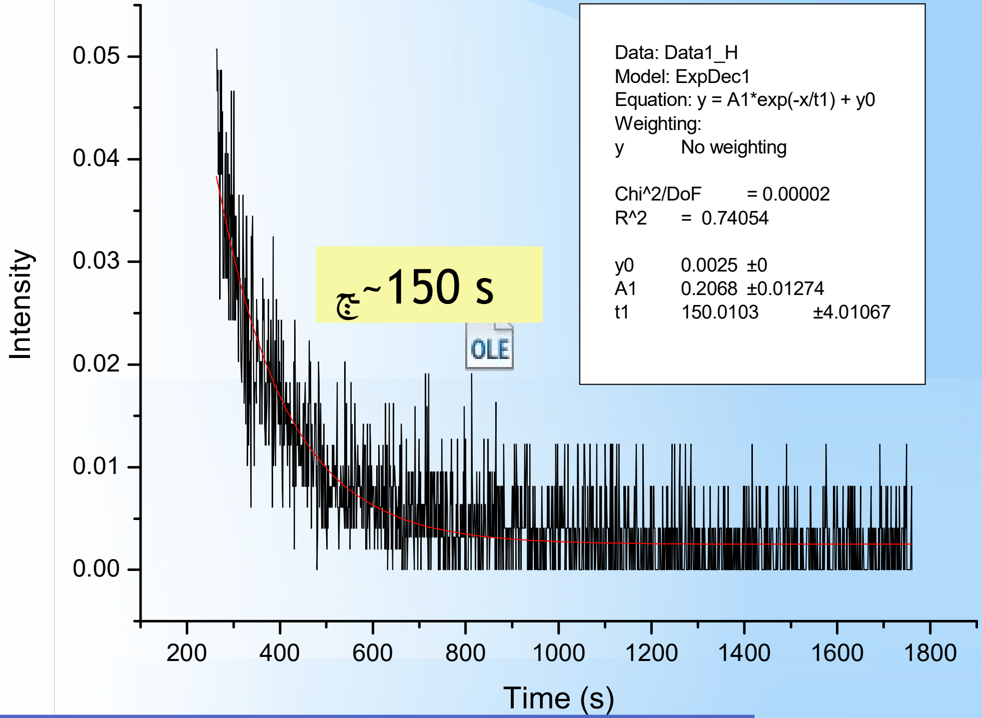
*Cleaning of the neutron spectrum

Comparing cleaning time with forced spin flip and without (no normalized data)

Cleaning with depolarisation is switched on



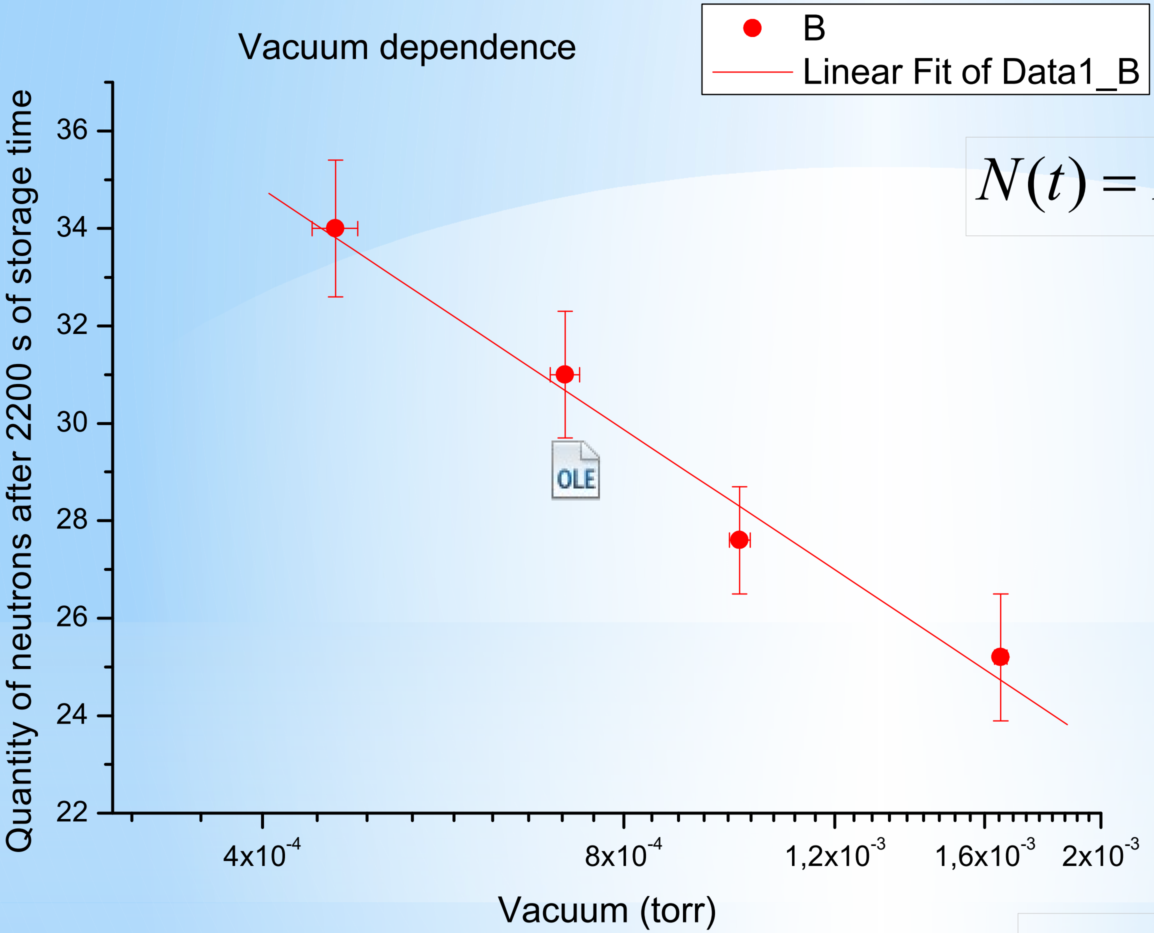
Cleaning with depolarisation is switched off



Depolarization accelerates cleaning time about 3 times

Criterion of sufficient cleaning time – the absence of efficiency changing

* Vacuum dependence (rest gases)



$$N(t) = N0\exp((-\lambda_{decay} - \lambda_p p)t)$$

$$\lambda_p = \frac{\ln\left(\frac{N_1(t)}{N0}\right) - \ln\left(\frac{N(t)}{N0}\right)}{t(p - p_1)}$$

$$\lambda_p = 0.15 \pm 0.04 \ {}^{1}\!/_{s \cdot torr}$$

$$\lambda_{decay} = 1/880 = 0.00113 \ \text{1/s}$$

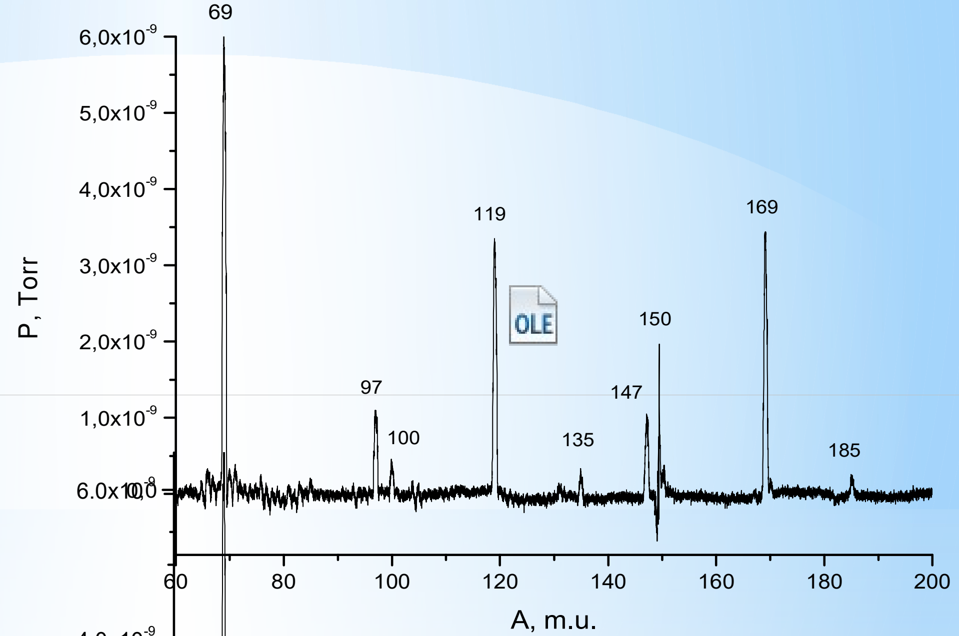
$$p \Rightarrow 10^{-6} \ \text{torr}$$

$$\lambda_p p \ll \lambda_{decay}$$

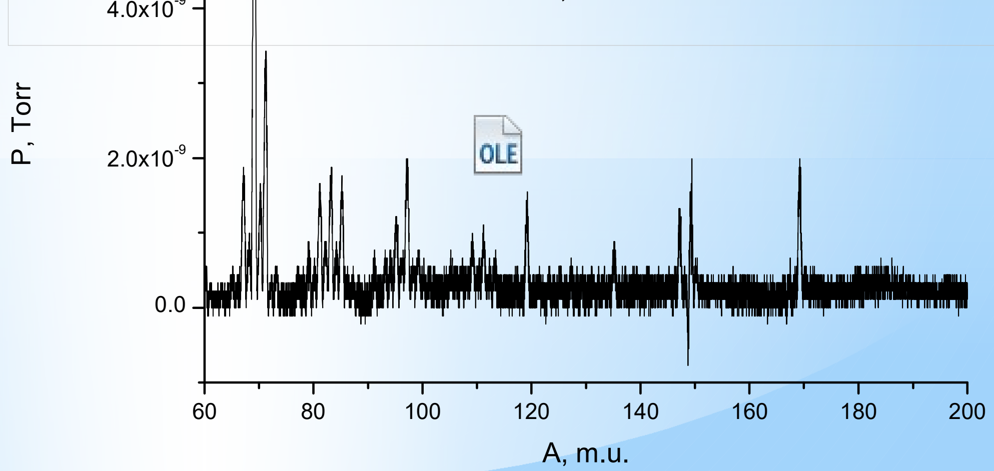
* Fomblin vapor scattering?

Calibration

Fomblin spectrum under 98 C



Spectrum of the rest vapor in the trap



LIFETIME MEASURING

RUN A:

- the aperture of the UCN guide inside the magnetic shutter was Ø20 mm and without the forced depolarization (two points)
- Storage time

  $\tau_{st} = 874.6 \pm 1.7$ s
- After correction using ε =0.903±0.007 from run B

$$\tau_n = 878.3 \pm 1.9\ s$$

RUN B:

- the aperture of the magnetic shutter was enlarged to Ø60 mm and the outer solenoid was used to induce the forced spinflip
- First emptying was done after 400 s and storage times before the second were equal to 600, 900, 1400 and 1800 s.
- ε =0.903±0.007.

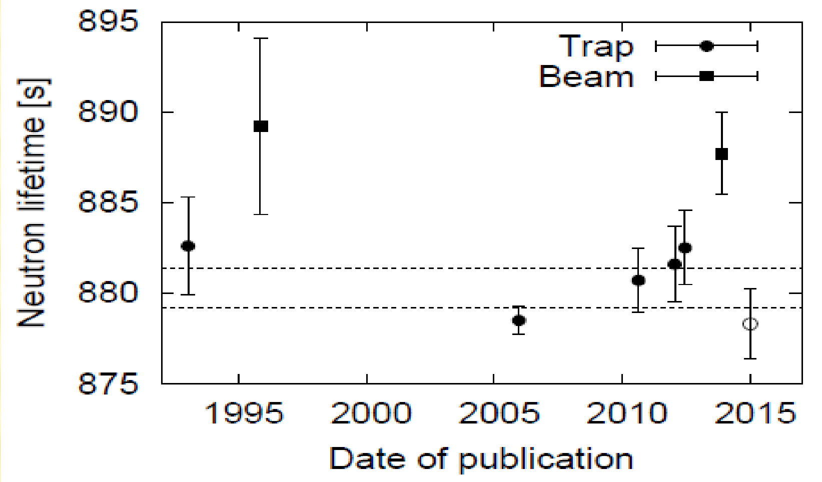
$$\tau_n = 878.2 \pm 1.9\ s$$

MEASUREMENT OF THE NEUTRON LIFETIME WITH ULTRA-COLD NEUTRONS STORED IN A MAGNETO-GRAVITATIONAL TRAP

V.F. EZHOV, A.Z. ANDREEV, G. BAN, B.A. BAZAROV, P. GELTENBORT, A.G. GLUSHKOV, V.A. KNYAZKOV, N.A. KOVRIZHNYKH, G.B. KRYGIN, O. NAVILIAT-CUNCIC, V.L. RYABOV

(SUBMITTED ON 23 DEC 2014)

arXiv:1412.7434 [nucl-ex]

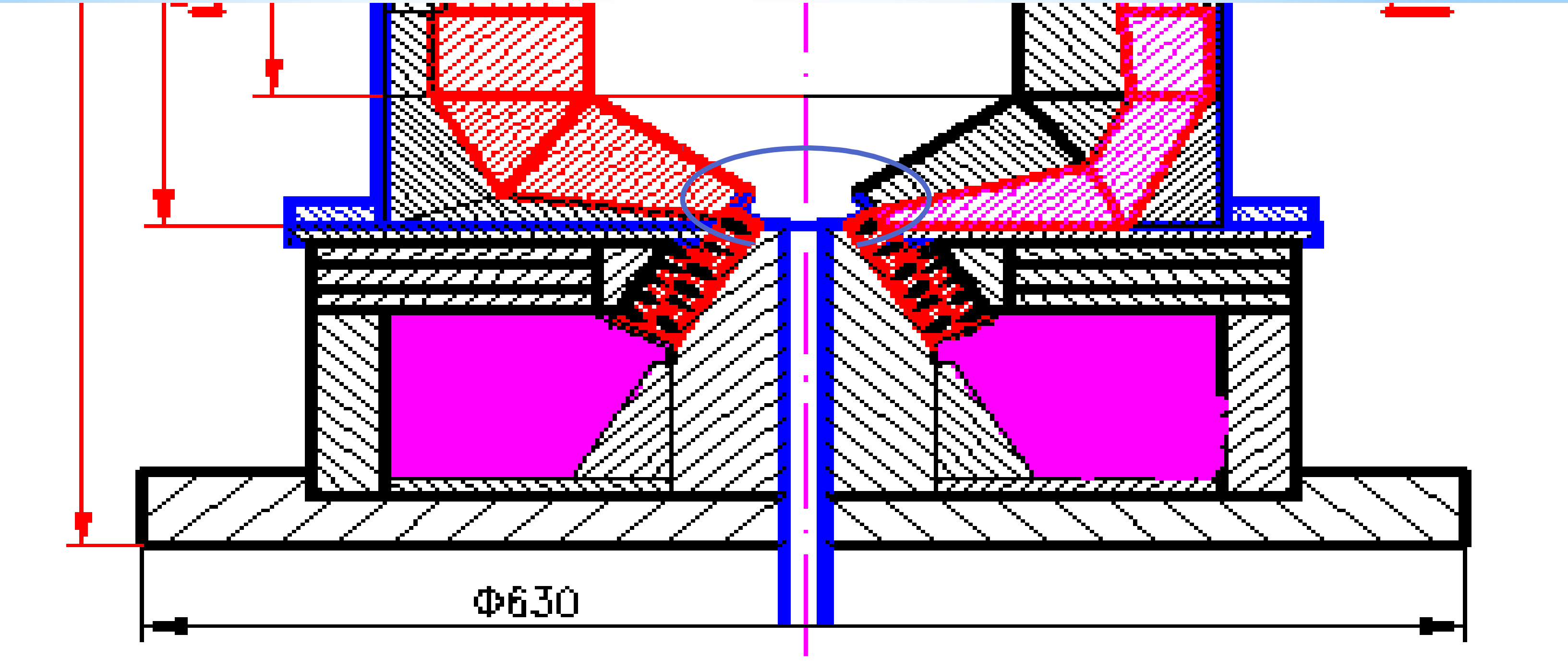


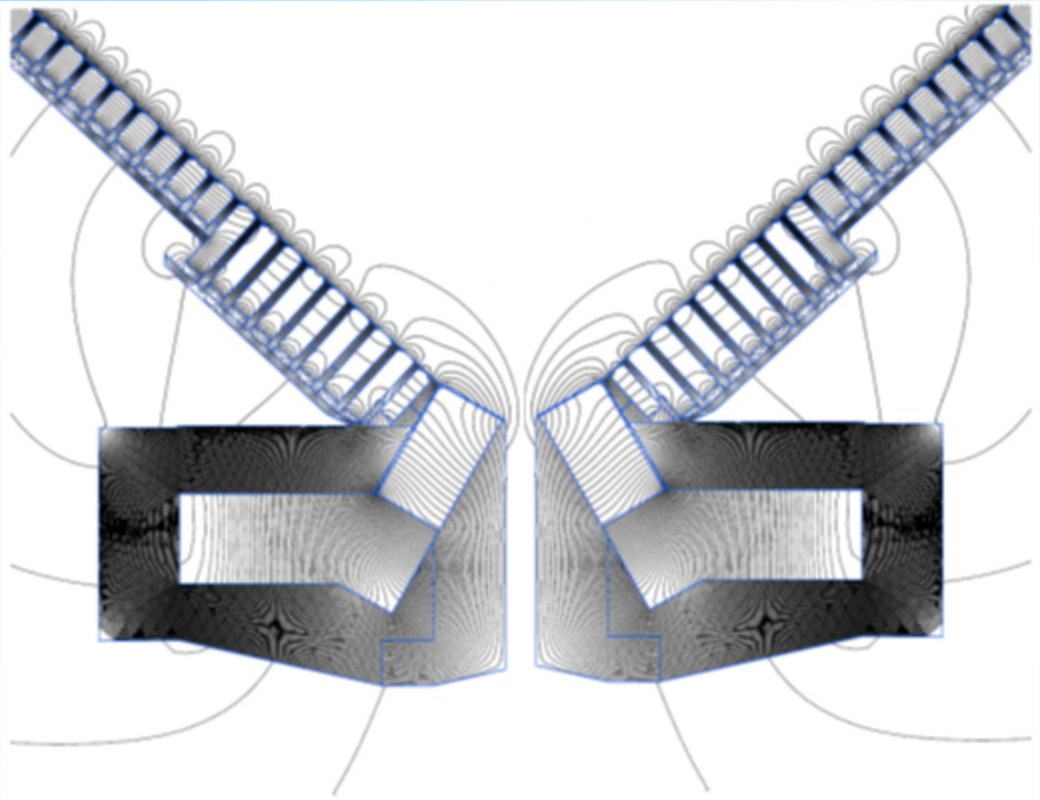
Comparison of the value for the neutron lifetime obtained from this work (open circle) with the values included in the current PDG average (filled squares and circles). The dotted lines indicate the ±1σ limits of the current average.

$$\tau_n = (878.3 \pm 1.9)\ \text{s.}$$

*Unsolved problem of first trap

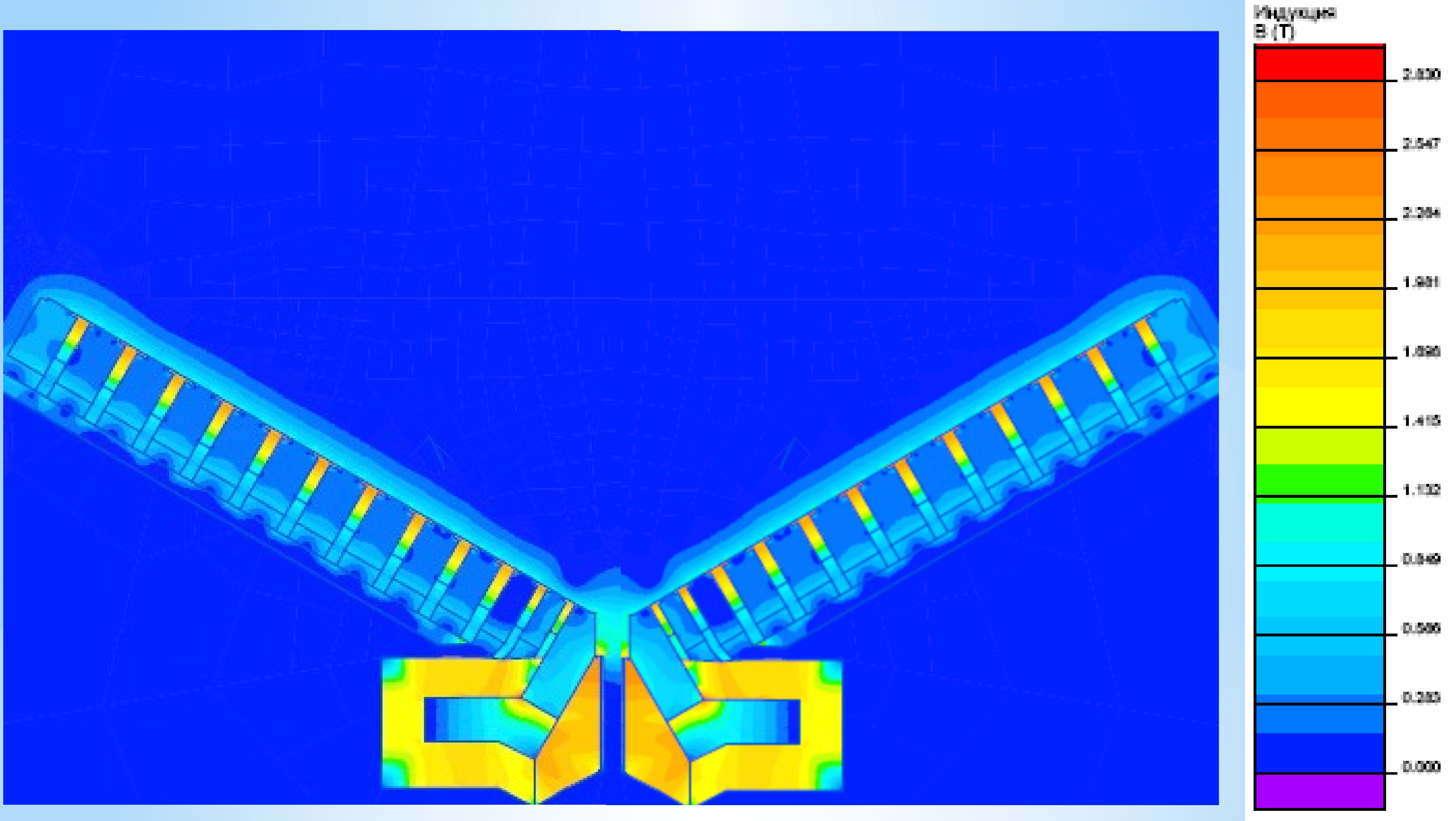
- *Interference of shutter and wall magnetic fields
- *To exclude it we have to decrease the shutter magnetic field to 2 times (0.45 T instead of 1 T)





Shutter magnetic field looks as field of two additional poles with the same geometry as magnetic field of the wall

*Magnetic field of new trap: trap + shutter



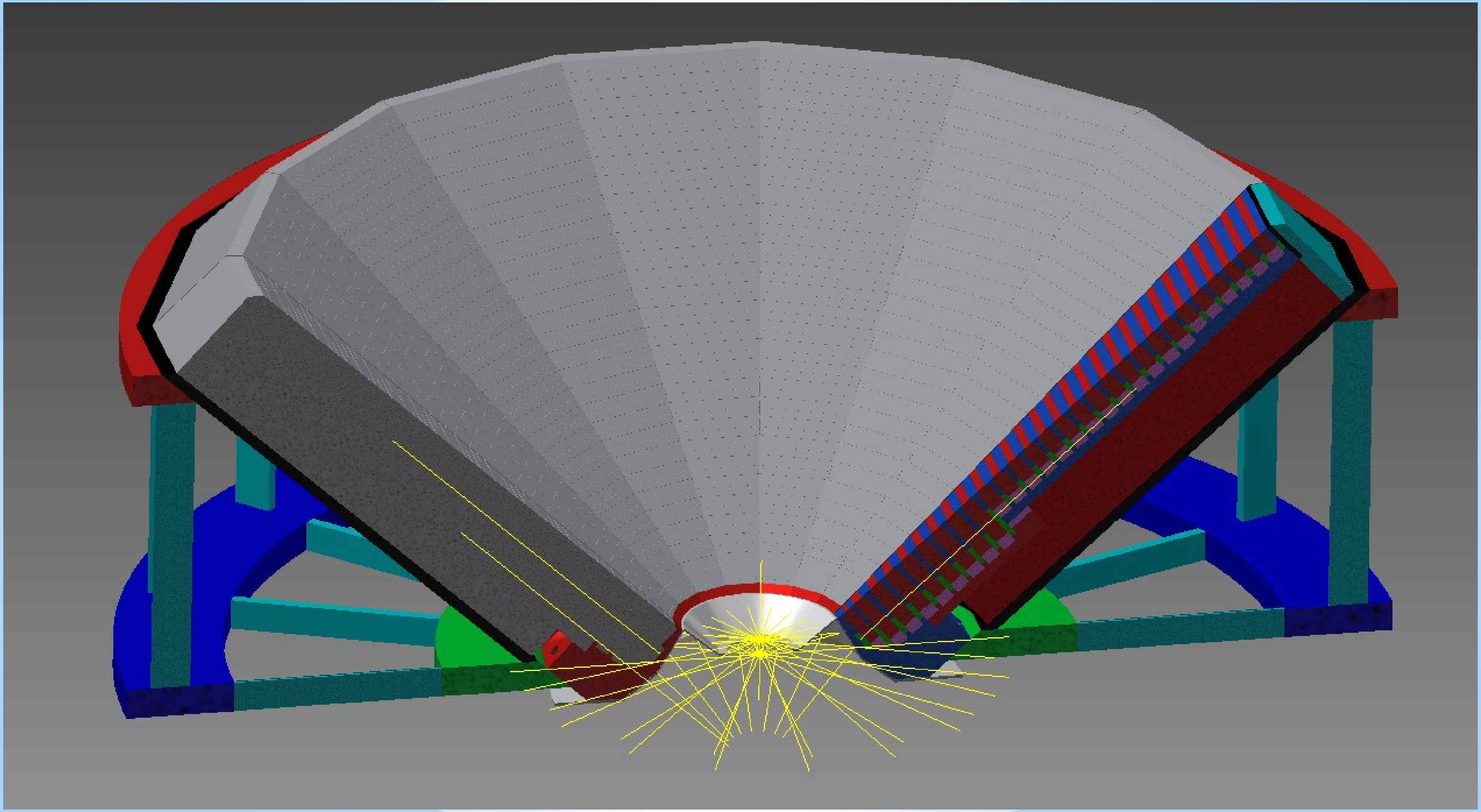
Calculated map of magnetic field for a new trap

Increasing of volume about 15 times

Increasing of stored UCN quantity due to increasing of stored UCN energy is about 8 times

Our waited accuracy about 0.2-0.3 s.

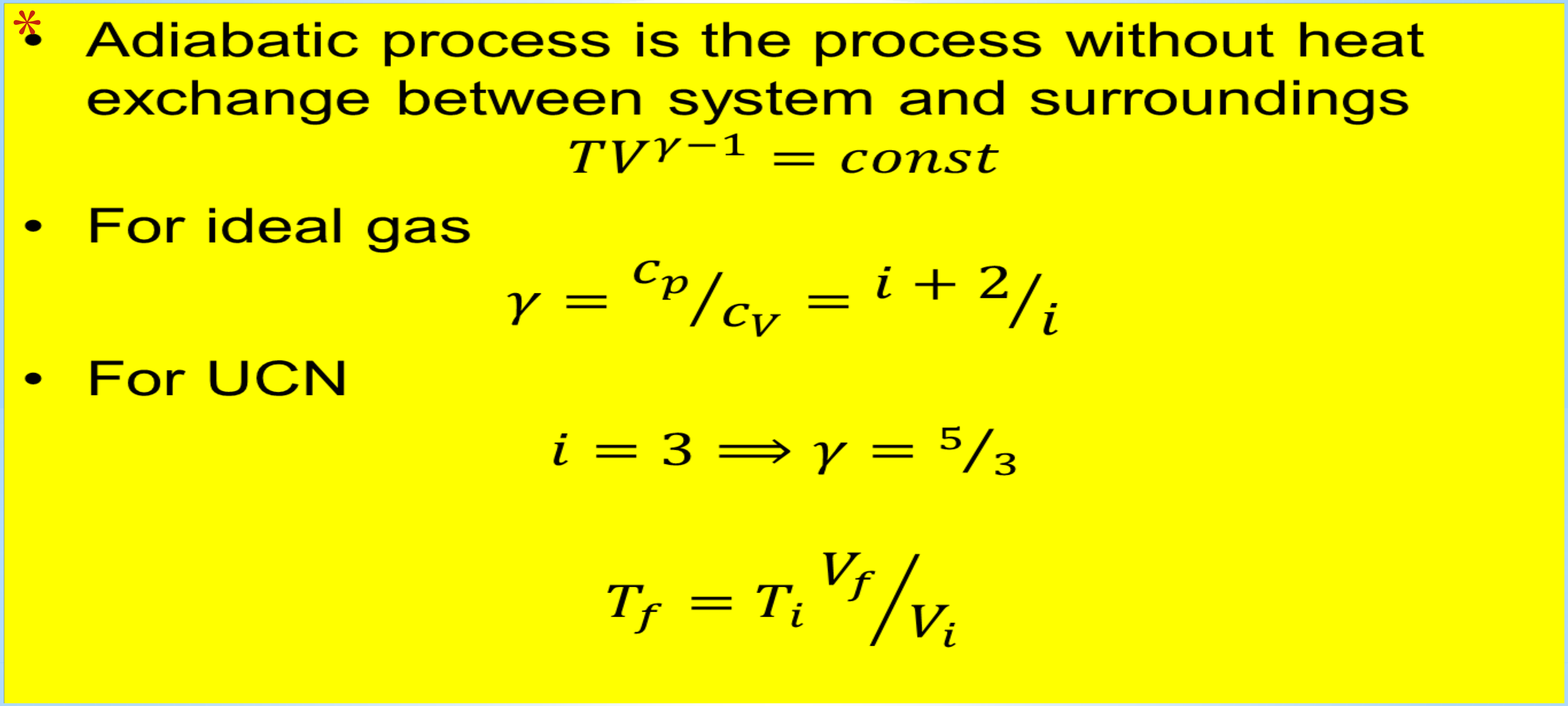
New trap design



Vacuum chamber and filling system for new trap (ILL, Level D)

*Thank you for your attention

Definition of adiabatic process



- Adiabatic process is the process without heat exchange between system and surroundings

$$TV^{\gamma-1} = const$$

- For ideal gas

$$\gamma = {}^{c_p}/_{c_V} = {}^{i+2}/_{i}$$

- For UCN

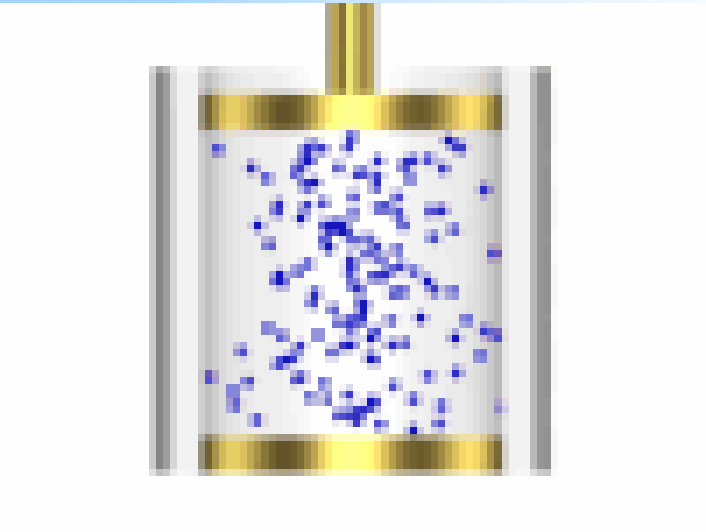
$$i = 3 \Longrightarrow \gamma = {}^{5}/_{3}$$

$$T_f = T_i \, {}^{V_f}\Big/_{V_i}$$

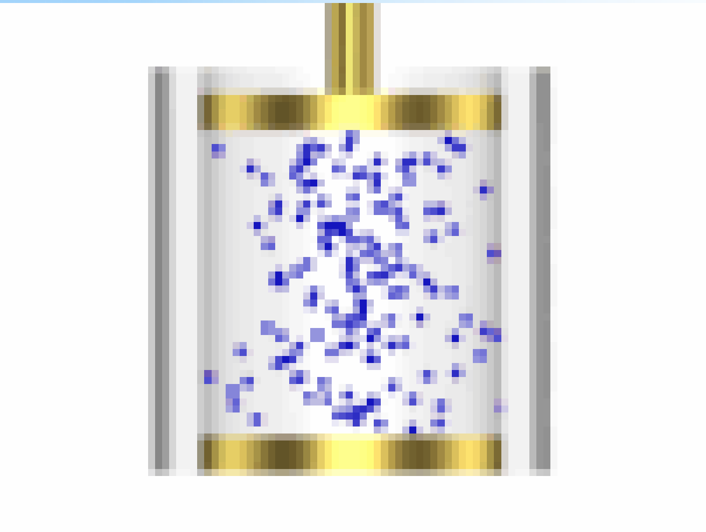
$$T_f = T_i \left({}^{V_i}\Big/_{V_f}\right)^{2/3}$$

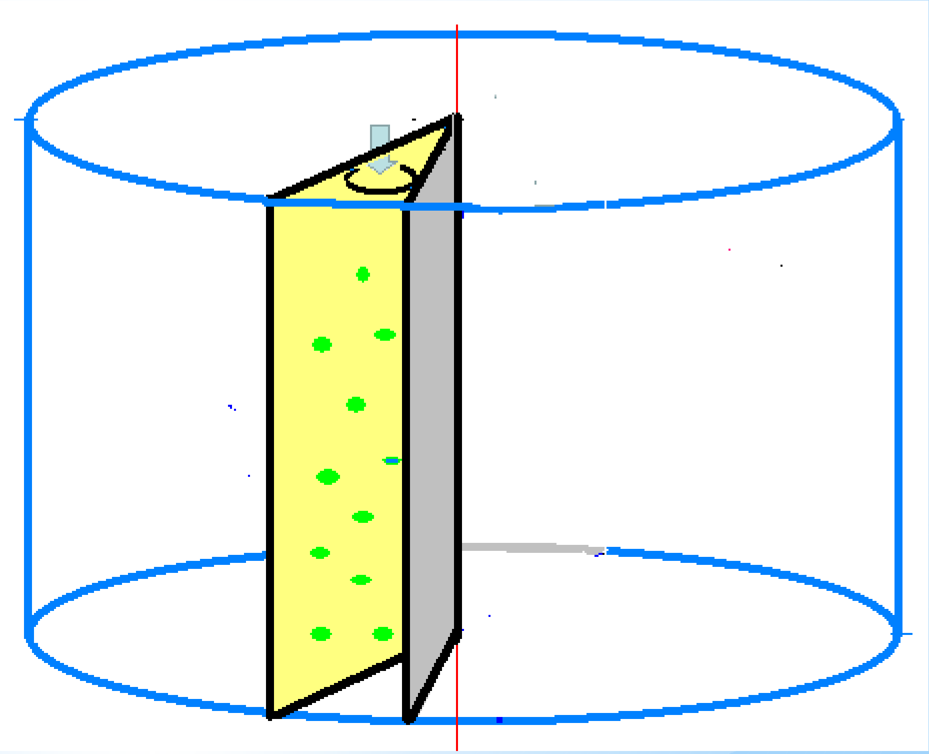
Problems for UCN

- To have maximum of volume change
- Reverse motion
- Accumulation during repeating

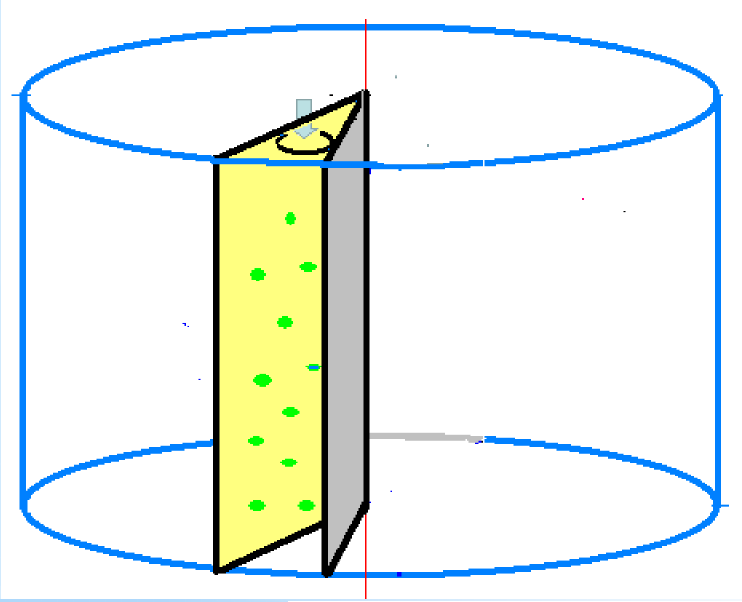


Volume change with maximum of efficiency (change cooler and height)

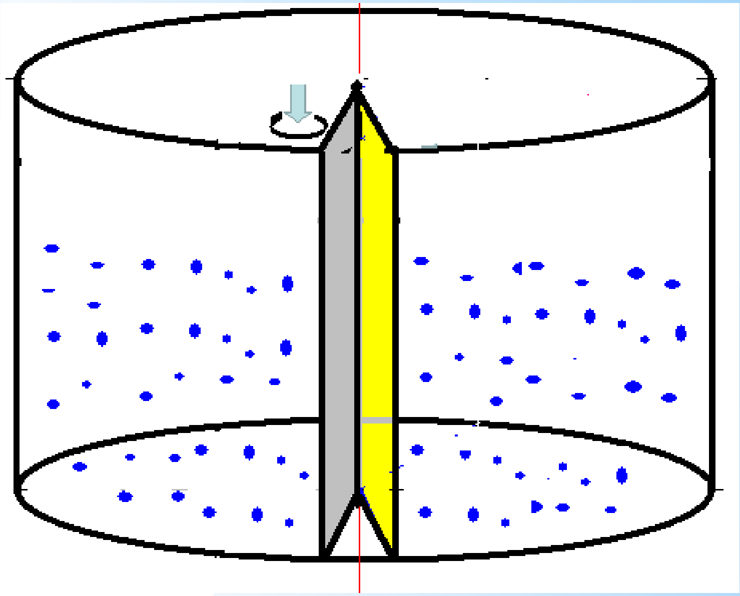


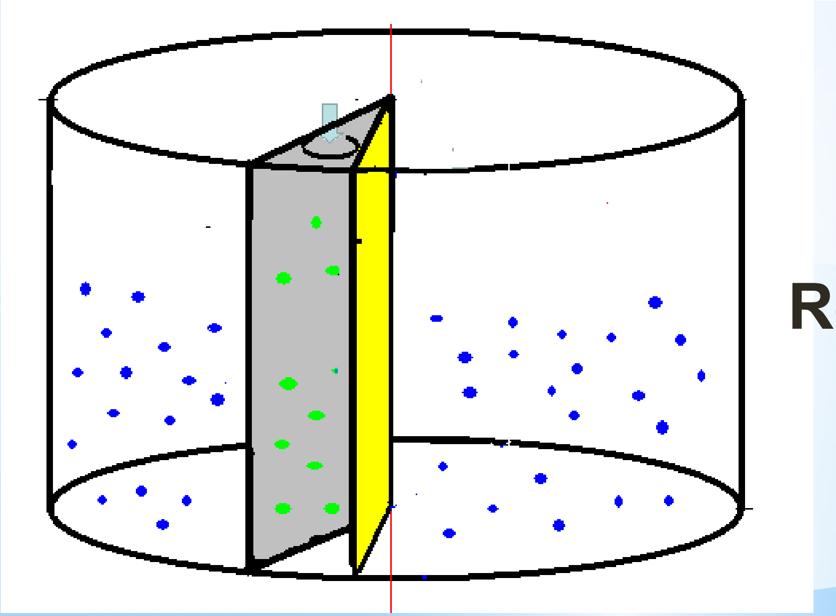


Initial position

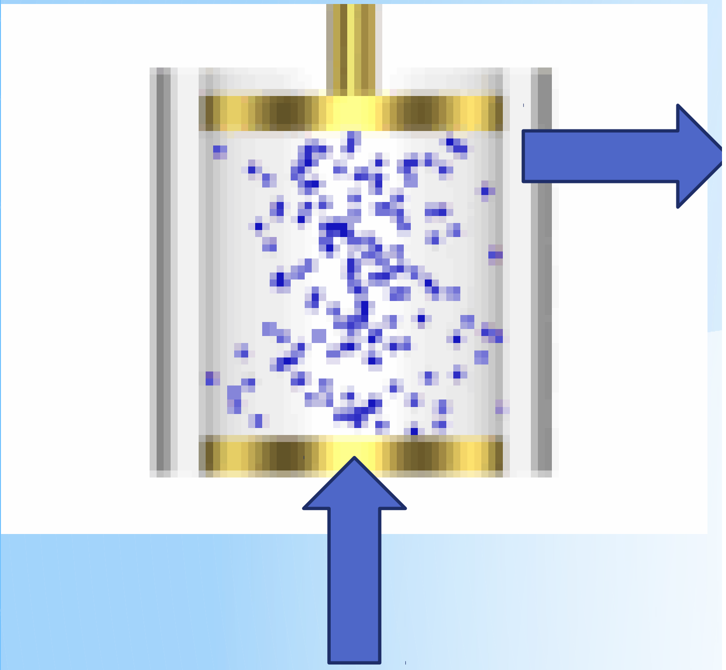


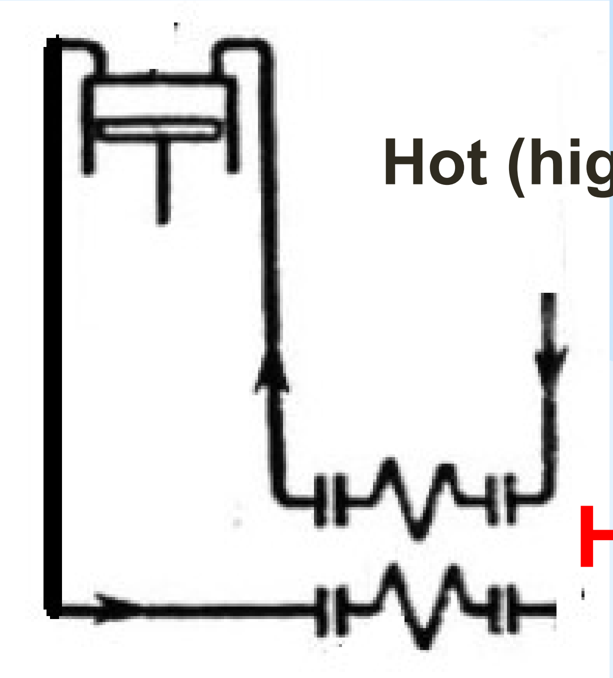
Position after expansion





Ready for new start

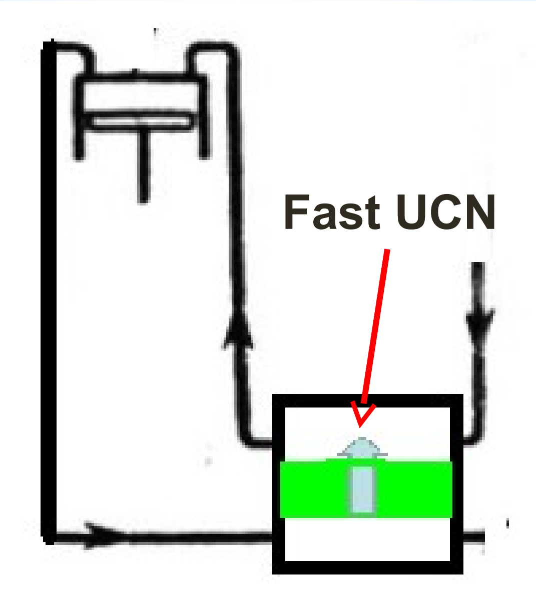




Hot (high pressure)

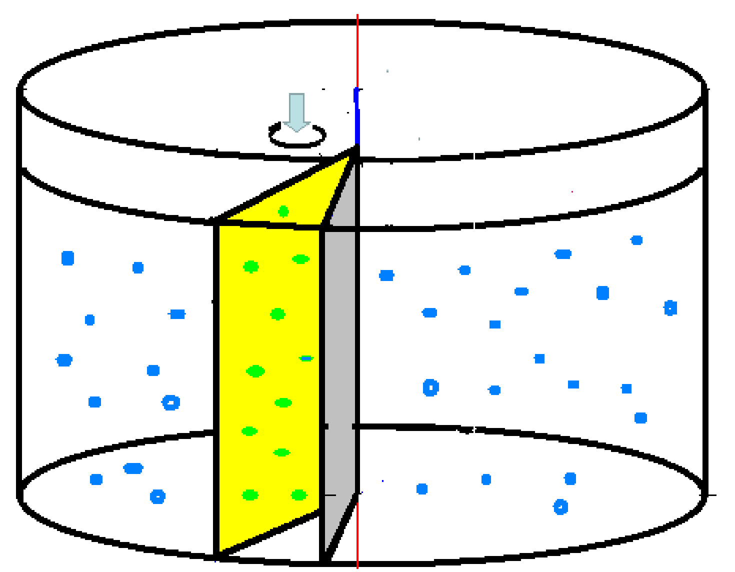
Heat exchange

Cold (low pressure)

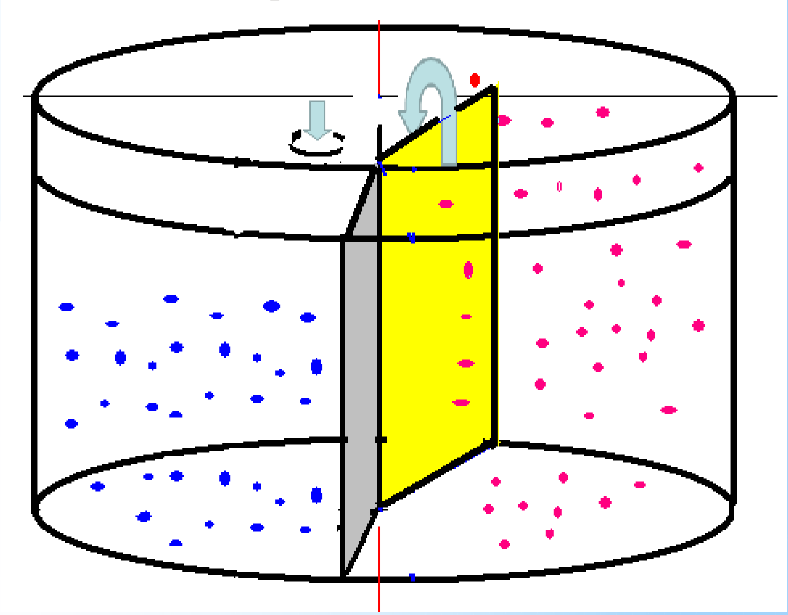


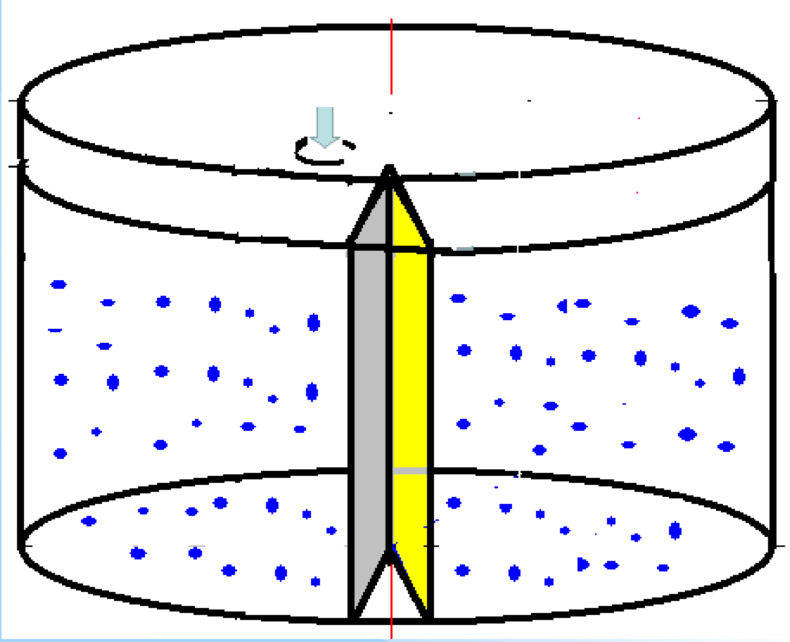
Maxwell demon

Initial position

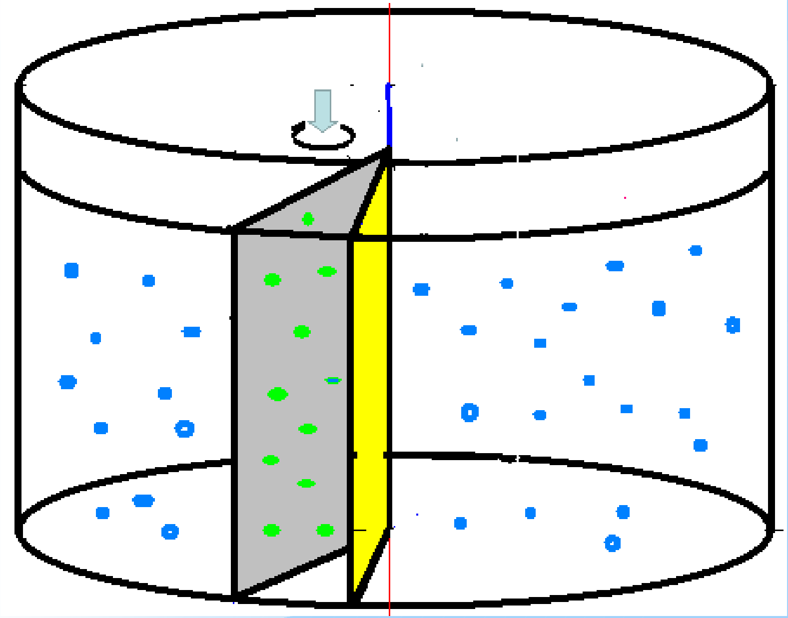


Expansion





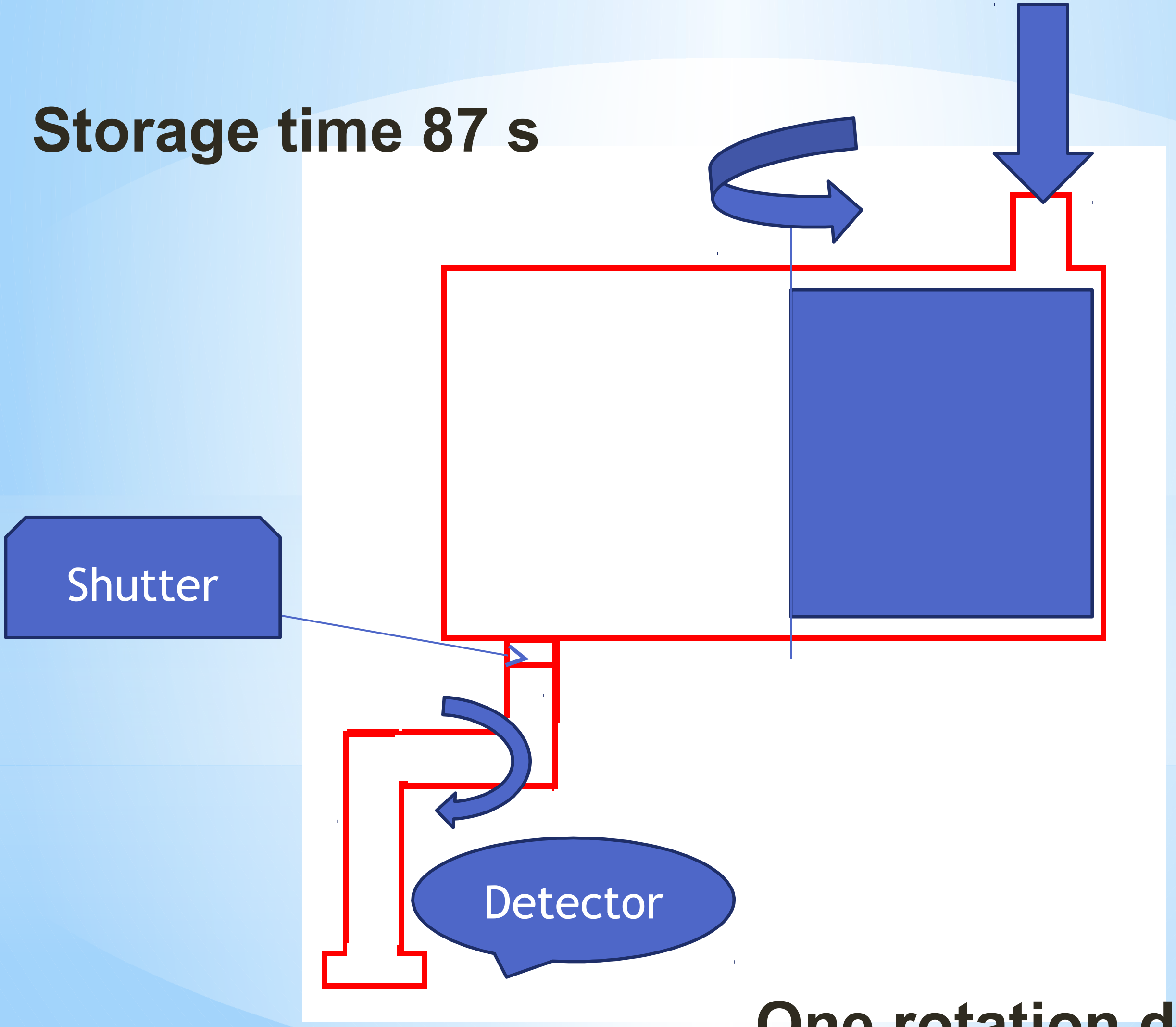
End of cycle



Ready for new start

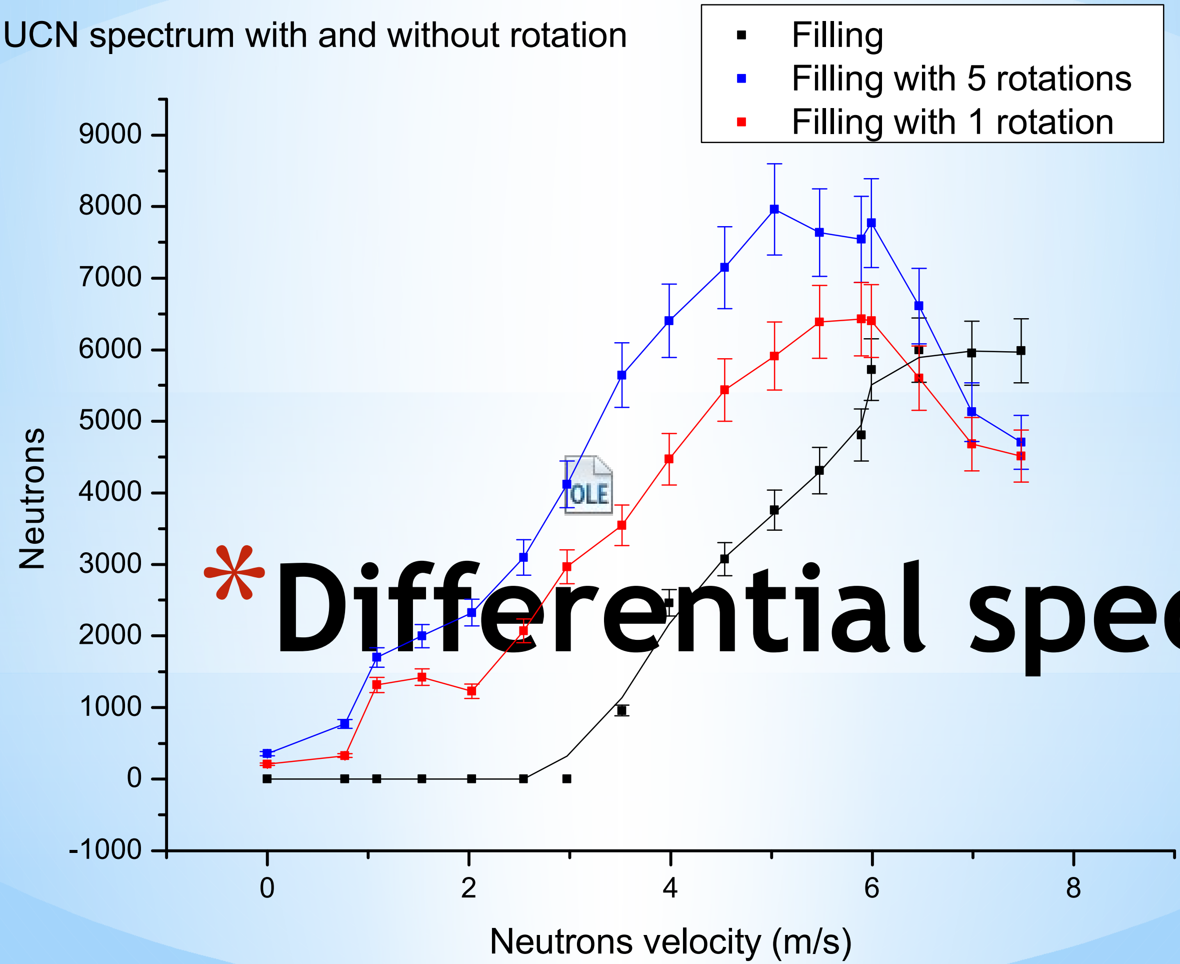
*Experimental setup

Storage time 87 s



One rotation during 33 s

Differential spectra

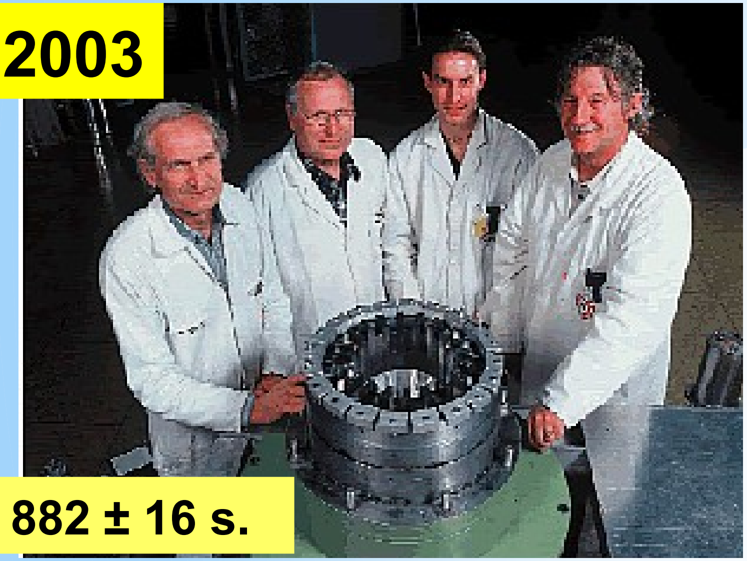


*

UCN magnetic storage and neutron lifetime PNPI-ILL
Step by step

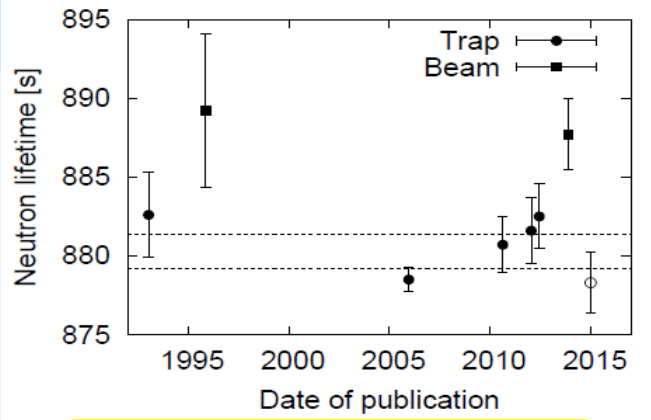
First trap of permanent magnets

2003



882 ± 16 s.

2014

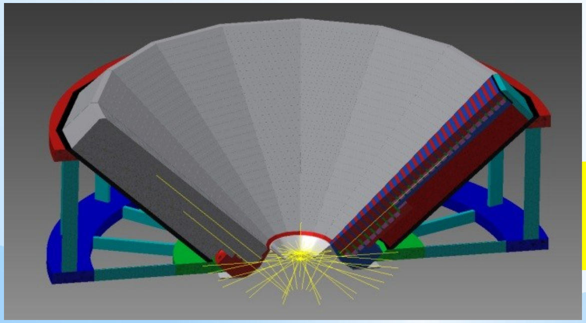


$\tau_n = (878.3 \pm 1.9)$ s.

(Submitted on 23 Dec 2014)
arXiv:1412.7434 [nucl-ex]

2015 -

New trap of permanent magnets



Waited accuracy 0.2 s