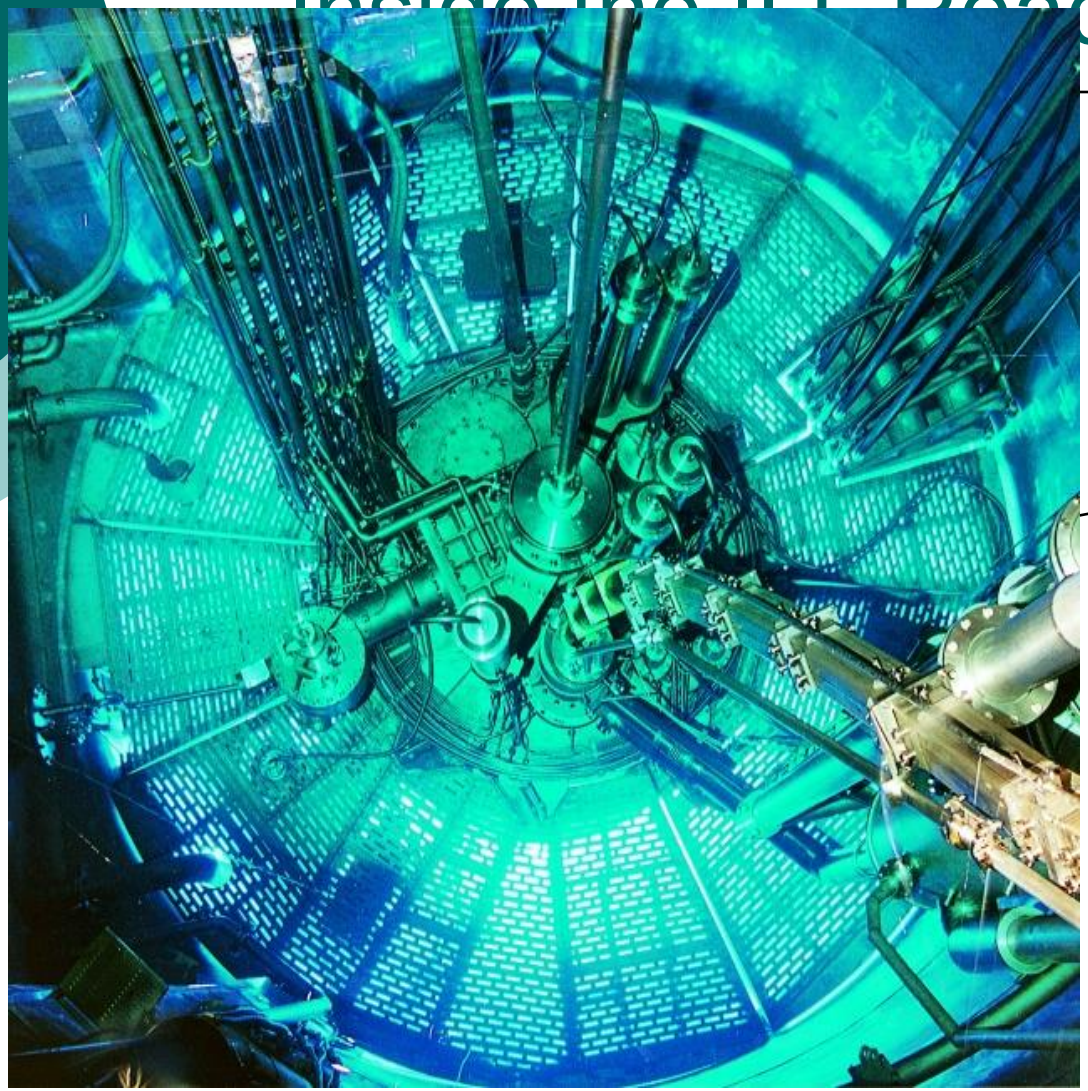
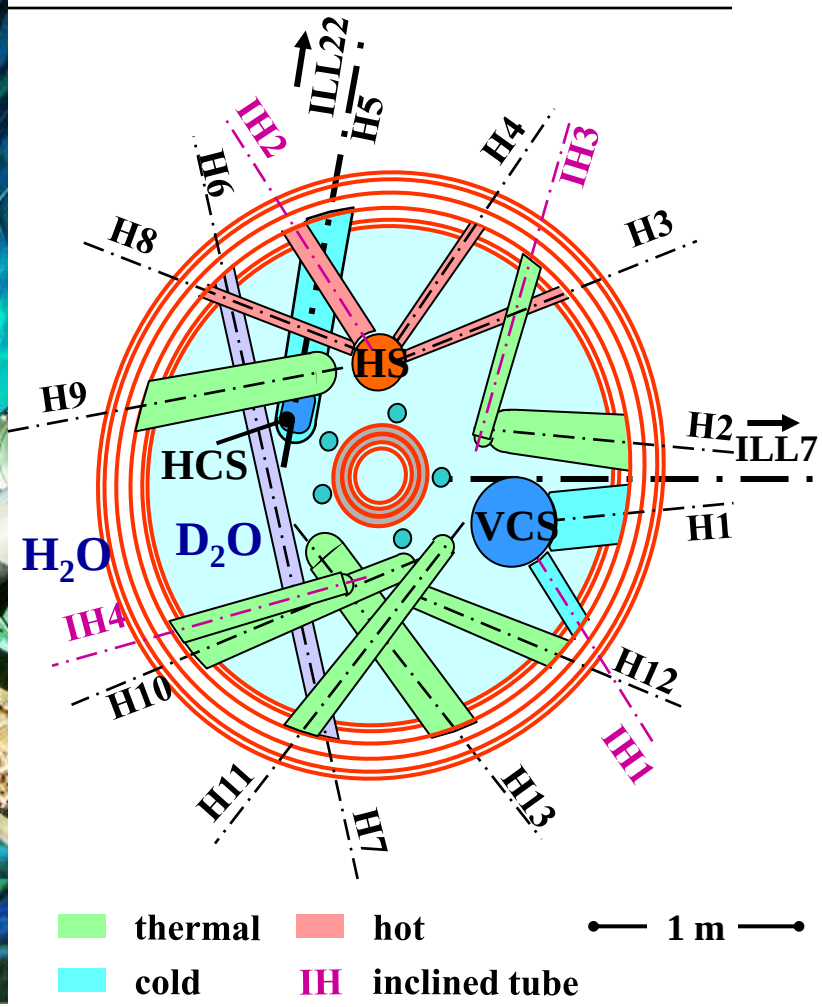
Нейтроны и фундаментальная физика (часть 2)

В.Ф.Ежов

Inside the ILL Reactor





From hot to ultracold: neutron energy, temperature, velocity and wavelength distributions

	Fission neutrons	Thermal neutrons	Cold neutrons	Ultracold neutrons	Gravity experiment
Energy	2 MeV	25 meV	3 meV	<100 neV	1.4 peV ($E_\perp$)
Temperature	10^{10} K	300 K	40 K	~1 mK	–
Velocity	10^7 m/s	2200 m/s	800 m/s	~5 m/s	$v_\perp \sim 2$ cm/s
Wavelength		0.18 nm	0.5 nm	~80 nm	

Быстрые нейтроны способны испытывать на ядрах неупругое рассеяние и вызывать эндотермические ядерные реакции, например (n,α), (n,2n), (n,pn). Медленные нейтроны в основном упруго рассеиваются на ядрах или вызывают экзотермические ядерные реакции, в первую очередь радиационный захват (n,γ), реакции типа (n,p), (n,α) и деление ядер.

Классификация нейтронов.

Нейтроны	E, эВ	v, см/с	λ, см	$T_{ср}$, К
Быстрые	$> 10^5$	$> 1{,}4\times10^9$	$< 10^{-12}$	10^{10}
Медленные				
Промежуточные	$10^4–10^5$	$1{,}4\times10^3$	3×10^{-11}	10^8
Резонансные	$0{,}5–10^4$	$1{,}4\times10^7$	3×10^{-10}	10^6
Тепловые	$0{,}5–5\times10^{-3}$	2×10^5	2×10^{-8}	300
Холодные	$5\times10^{-3}–10^{-7}$	4×10^4	9×10^{-8}	10
Ультрахолодные	10^{-7}	4×10^2	9×10^{-6}	10^{-3}

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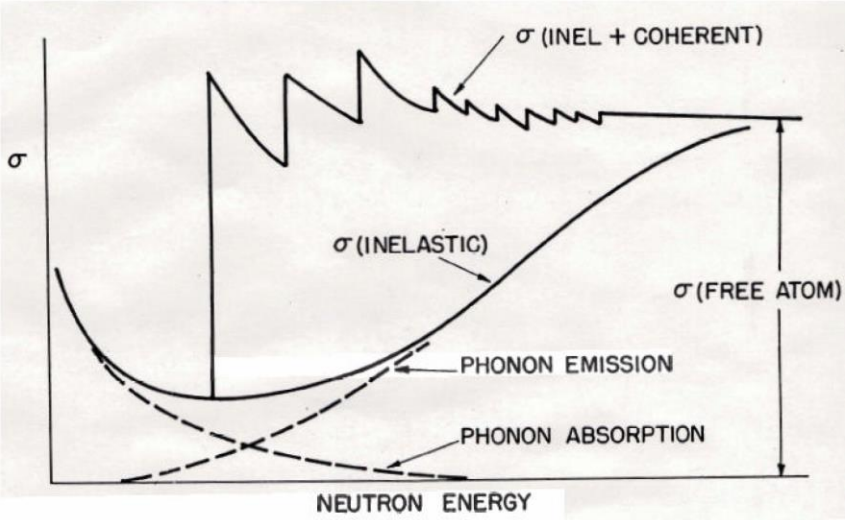
Термализация

Начиная с энергий 0.5 - 1 эВ при столкновениях нейтронов с ядрами становится существенной тепловая энергия атомов. Распределение нейтронов начинает стремиться к равновесному, т.е. максвелловскому:

$$f_{\max}(E') = \frac{2\pi}{(\pi kT)^{3/2}}\sqrt{E'}e^{-E'/kT}$$

Этот процесс называют ***термализацией***.



Процесс термализации достаточно сложен. В твердых средах необходимо учитывать упругое (дифракция) и неупругое (фононы) рассеяние на связанных атомах. Слева показан в качестве иллюстрации случай графита.

Средняя логарифмическая потеря энергии

Number of Collisions, on Average, to Moderate a Neutron from 2 MeV to 1 eV

Moderator	ξ	Number of Collisions	$\xi \Sigma_s / \Sigma_a$
H	1.0	14	–
D	0.725	20	–
H_2O	0.920	16	71
D_2O	0.509	29	5670
He	0.425	43	83
Be	0.209	69	143
C	0.158	91	192
Na	0.084	171	1134
Fe	0.035	411	35
^{238}U	0.008	1730	0.0092

Тяжелая вода более эффективный замедлитель, т.к. слабее поглощает нейтроны, чем обычная вода!

Энергия и скорость (тепловых) равновесных нейтронов

Из распределения Максвелла имеем:

$$\bar{E} = \frac{3}{2}kT$$ - средняя энергия;

$$\upsilon_T = \sqrt{\frac{2kT}{m_n}}$$ - наиболее вероятная скорость;

$$E_T = \frac{m_n \upsilon_T^2}{2} = kT$$ - наиболее вероятная энергия;

$$\bar{\upsilon} = \frac{2}{\sqrt{\pi}}\upsilon_T$$ - средняя скорость.

При T=293,6° K (20,4° C) имеем $E_T=kT$=0,0253 эВ и υ_T=2,2 км/с.

- Dimension of neutron: 10^{-13} cm
- Interatomic distance: 10^{-8} cm

$$\lambda = 1/k = h/p$$

- Neutrons with λ~1000 Å → v~1÷5 m/s
- Inside substances

$$\frac{mv_1^2}{2} = \frac{mv^2}{2} - V$$

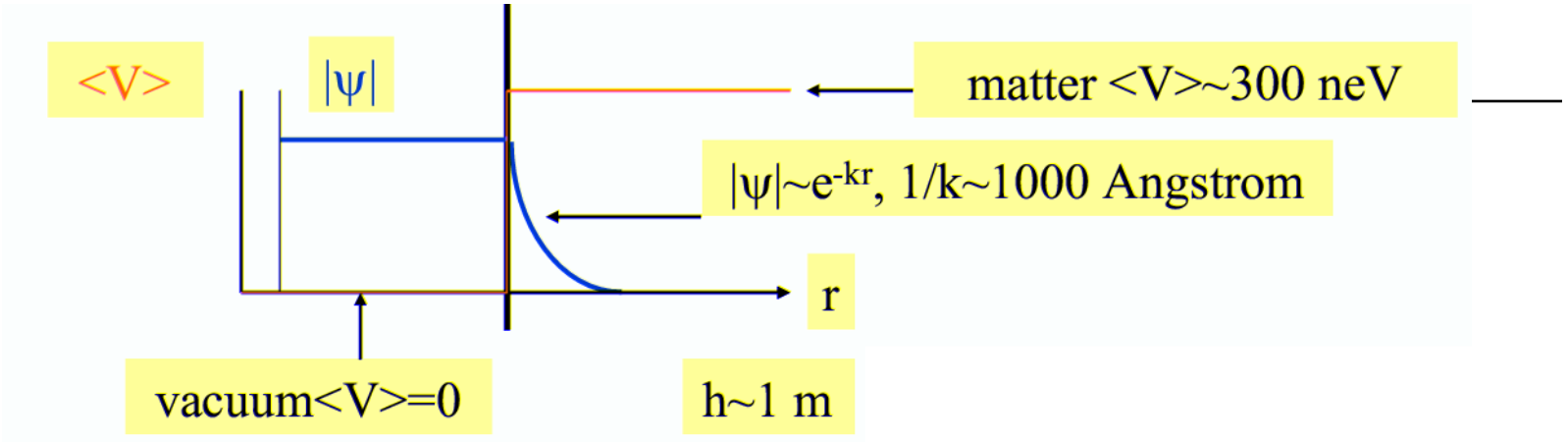
- Refractive index

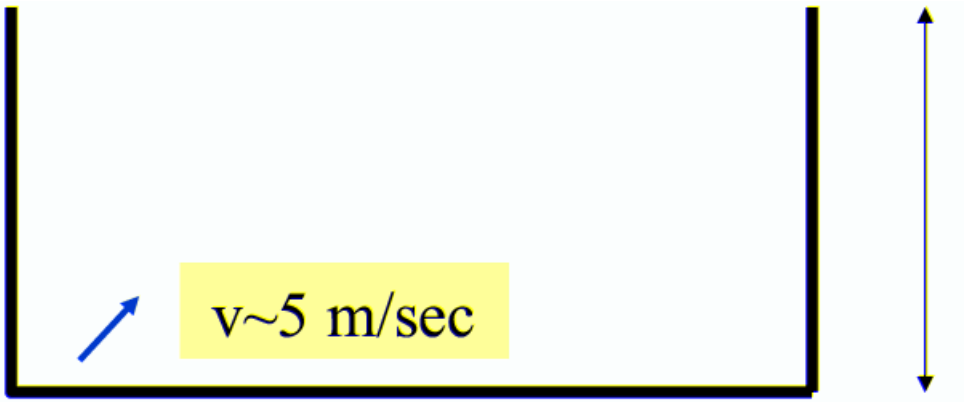
$$n^2 = \frac{v_1^2}{v^2}$$

- Fermi 1945

$$V = \frac{h^2}{2\pi m} Nb$$

For very low energies (E_k-<V> negative, <V>~300 neV), matter forms a potential barrier for neutrons.



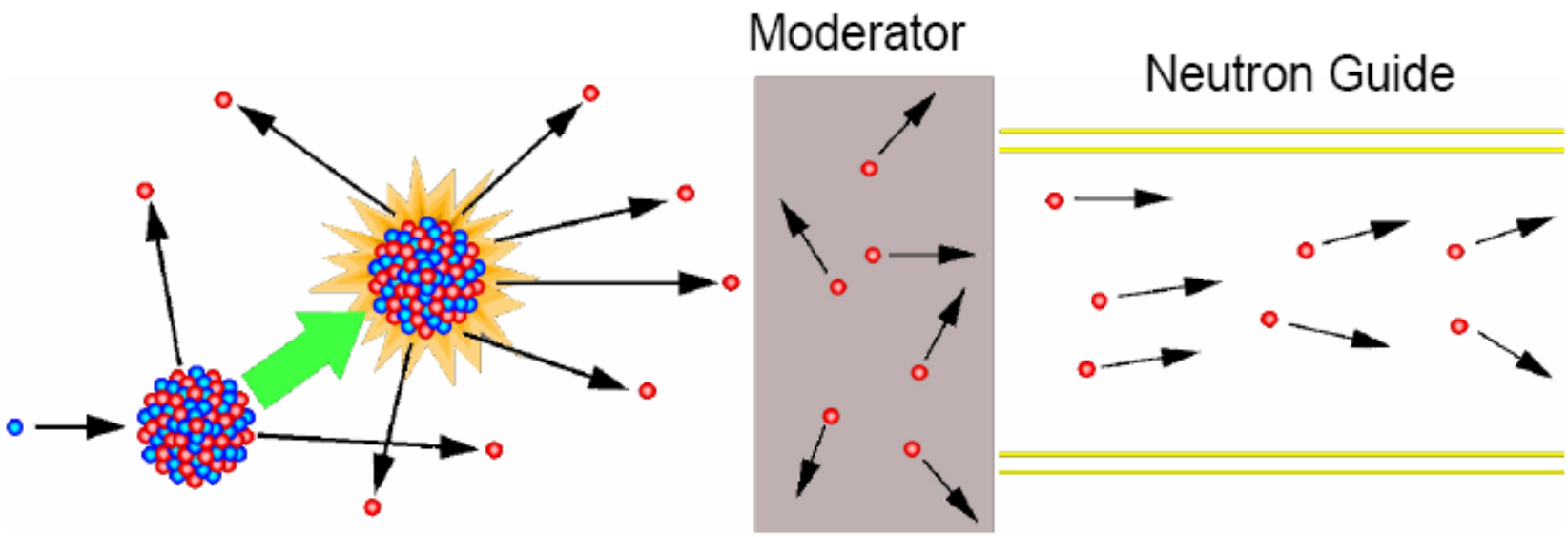


A neutron gas can be bottled (ρ~100/cc) using total external reflection. Due to gravity the bottle does not need a lid on top. Also B gradients can be used.

Y.B.Zeldovich Sov. Phys. JETP (1959)

"Ultracold" Neutrons (UCN)

- The cold or moderated neutrons, once released, can be transported through beam tubes (guides) into the laboratory and used for a wide variety of research instruments



How to make UCN

- Conventional Method:
  - Take neutrons from a reactor core
  - E_n = 5-10 MeV
  - bring into thermal equilibrium with nuclei
  - Energy distribution of "cooled" neutrons follows Maxwell-Boltzmann distribution:

$$N(E) \propto E^{\frac{1}{2}} e^{-\frac{E}{kT}}$$

Low efficiency

Fraction of neutrons below 8 m/s is only:

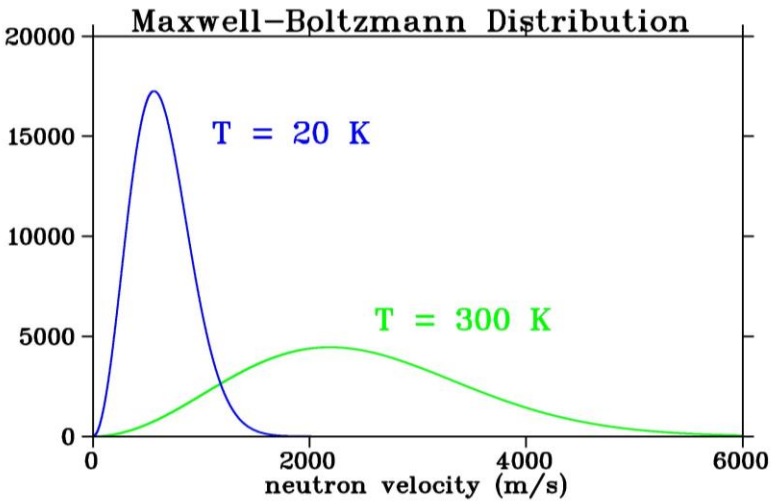
10^{-11} at 300 K

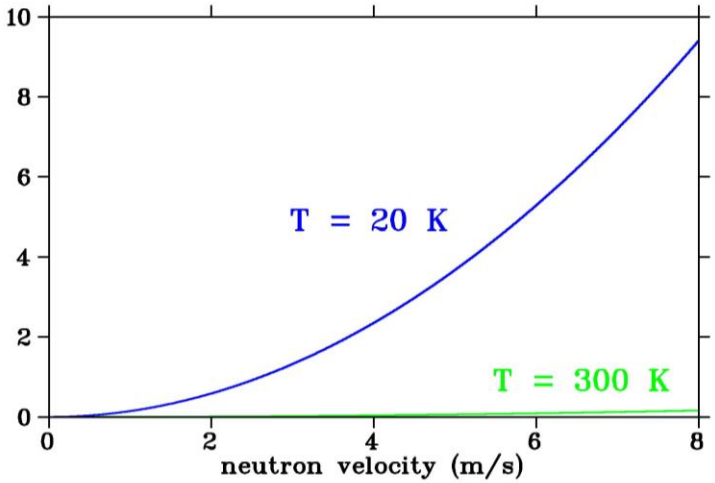
10^{-9} at 30 K

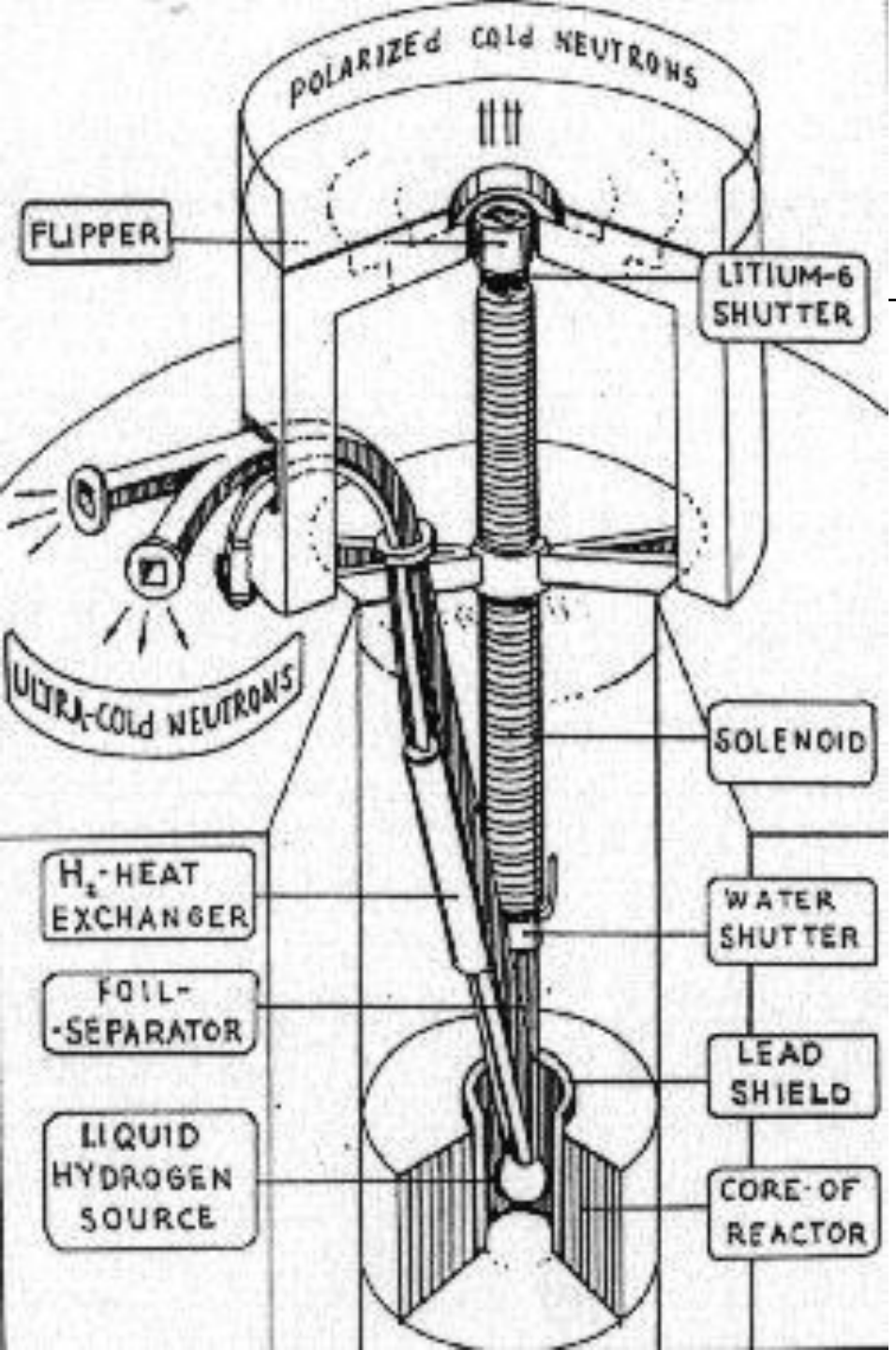
Use a few tricks to boost the UCN yield:

1. vertical extraction

2. turbine







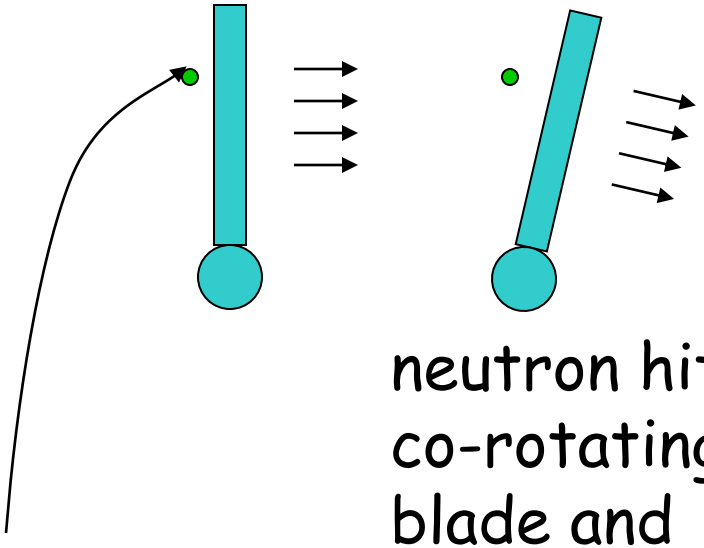
PNPI liquid hydrogen UCN source

- This neutron source has been operating at the WWR-M reactor since 1986. It is a universal source since it produces both ultracold and polarized cold neutrons. The chamber with the moderator is placed inside the flux trap in the center of the reactor core where the flux is (1.5 - 2)·$\mathbf{10^{14}}$ **n**·cm^{-2}·s^{-1} for thermal neutrons and 2·10^{13} **n**·cm^{-2}·s^{-1} for neutrons with energy E> 1 MeV The chamber, made of zircalloy, has a volume of 1 liter. The specific nuclear heating was 18-20 W/g for hydrogen and 0.7 W/g for zircalloy. The total nuclear heating with 100 percent hydrogen was 2.8 kW. The liquid mixture of 40 percent of hydrogen and 60 percent of deuterium is used as the moderator. In this case the total nuclear heating is 1.8 kW.

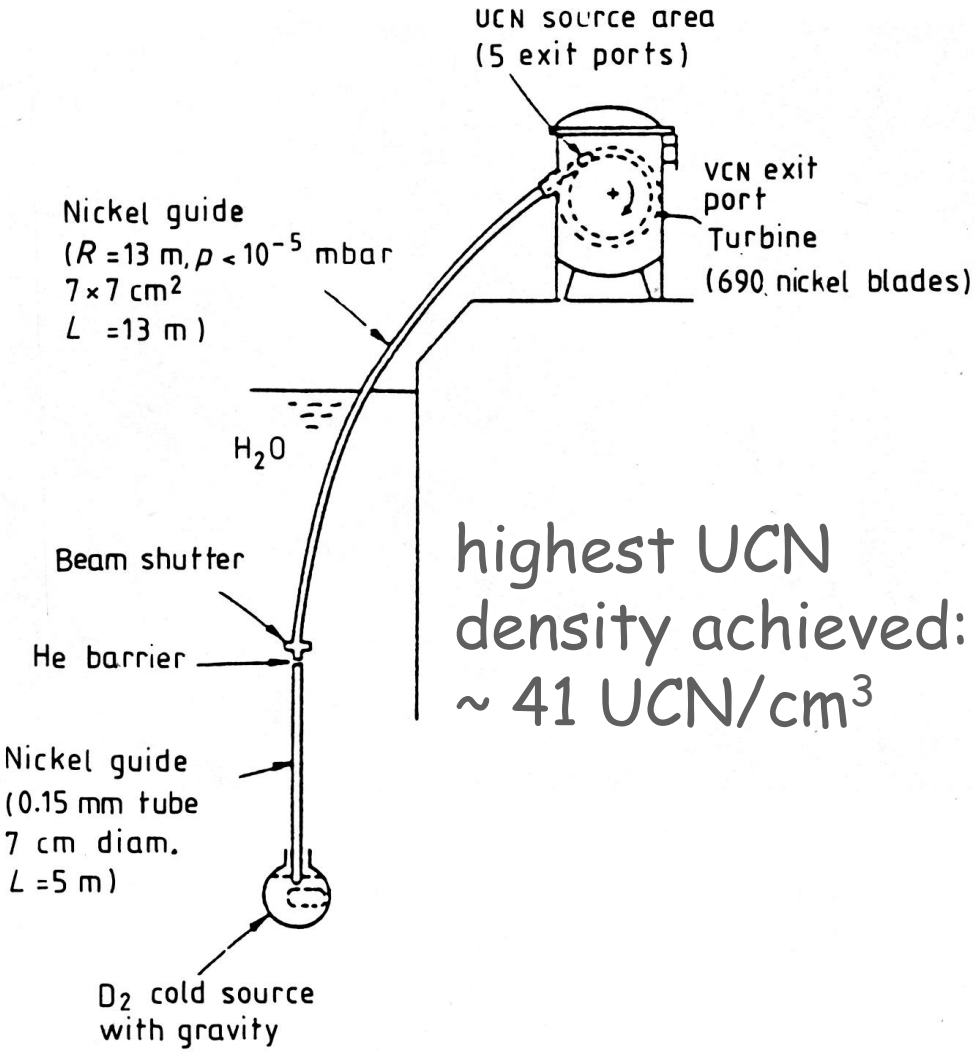
ILL Neutron Source

Institut
Laue-Langevin
Grenoble, France

Turbine operation:

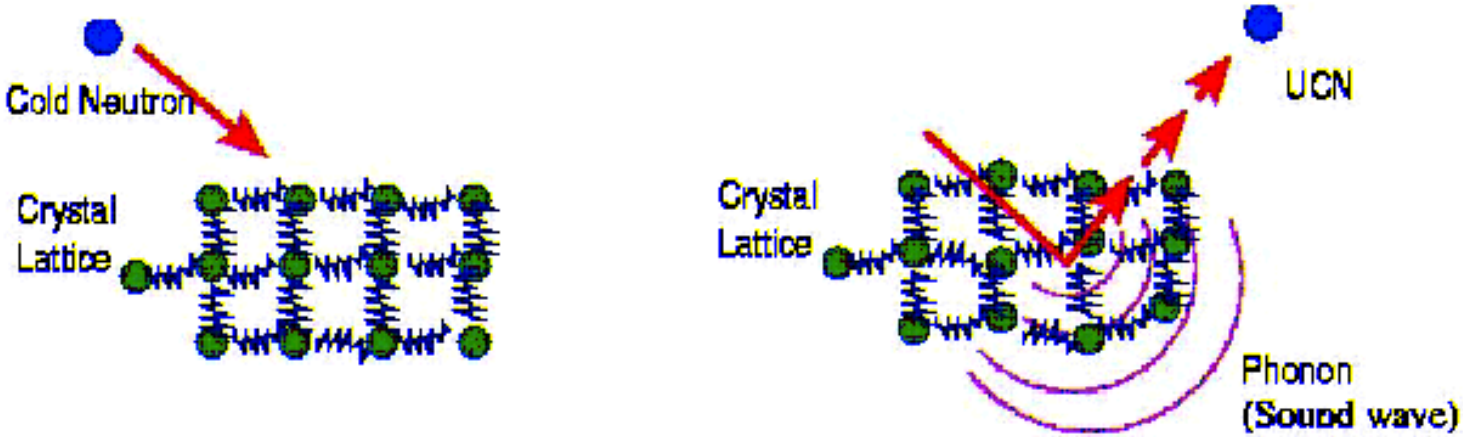


neutron hits co-rotating blade and stops

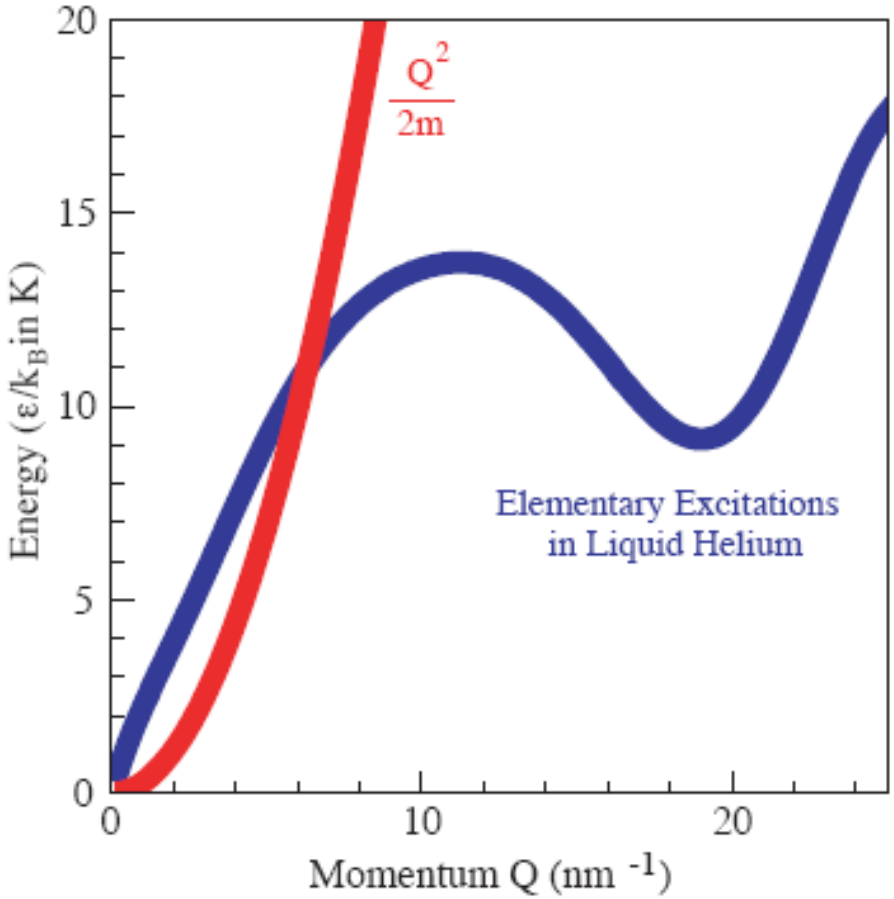


highest UCN density achieved: ~ 41 UCN/cm^3

- Cold neutrons downscatter in the solid, giving up almost all their energy, becoming UCN.



- UCN upscattering (the reverse process) is suppressed by controlling the moderator at low temperatures.



The neutron dispersion curve ($Q^2/2m$) and the Landau-Feynman dispersion curve for elementary excitations in superfluid ^{4}He. Neutrons with kinetic energy near the intersection point (12 K or 0.95 meV) can scatter to UCN energies (<100 neV or >100 nm) by emission of a single phonon.

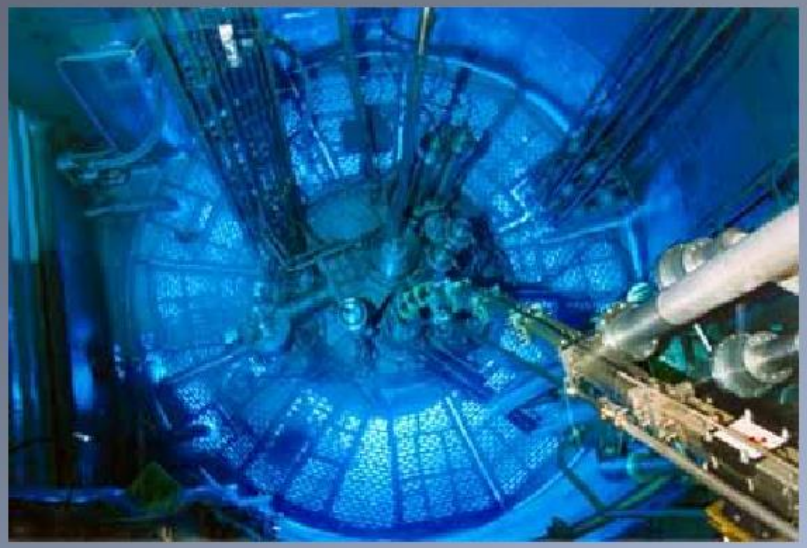
ESRF
(6 GeV)

Institut Laue-Langevin (ILL)

(High Flux Reactor)

The UCN/VCN facility PF2 at the ILL

NEUTRONS FOR SCIENCE



Properties of UCN

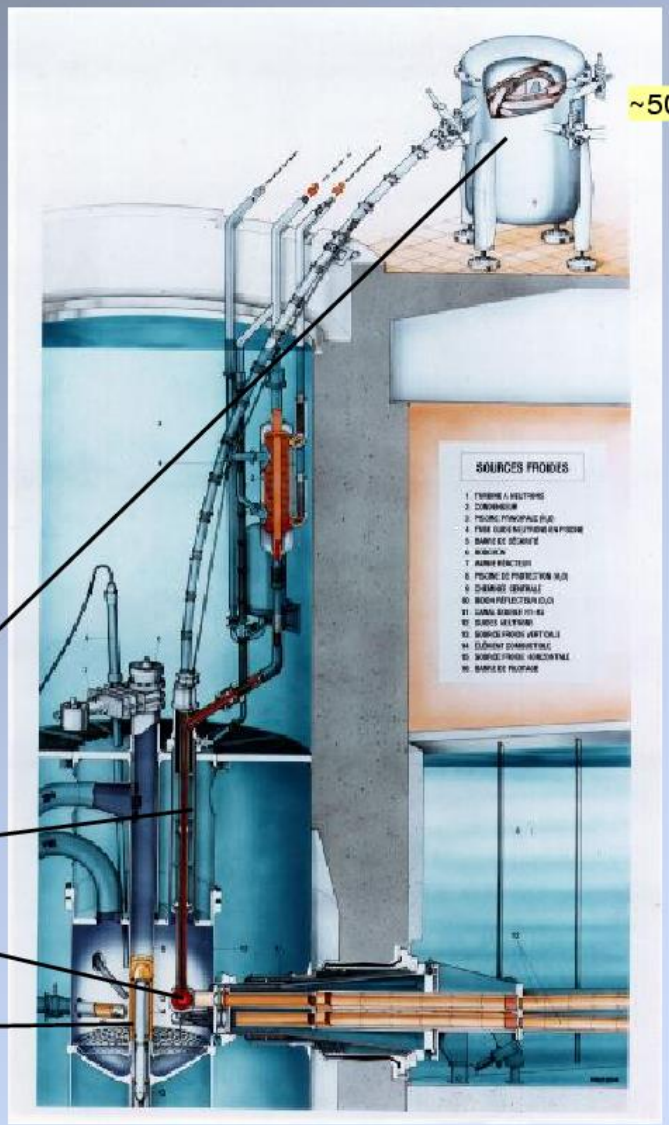
E_{kin} (~ 5 ms^{-1}) = 100 neV (10^{-7} eV)

λ_{UCN} ~ 1000 Å T_{UCN} ~ 2 mK

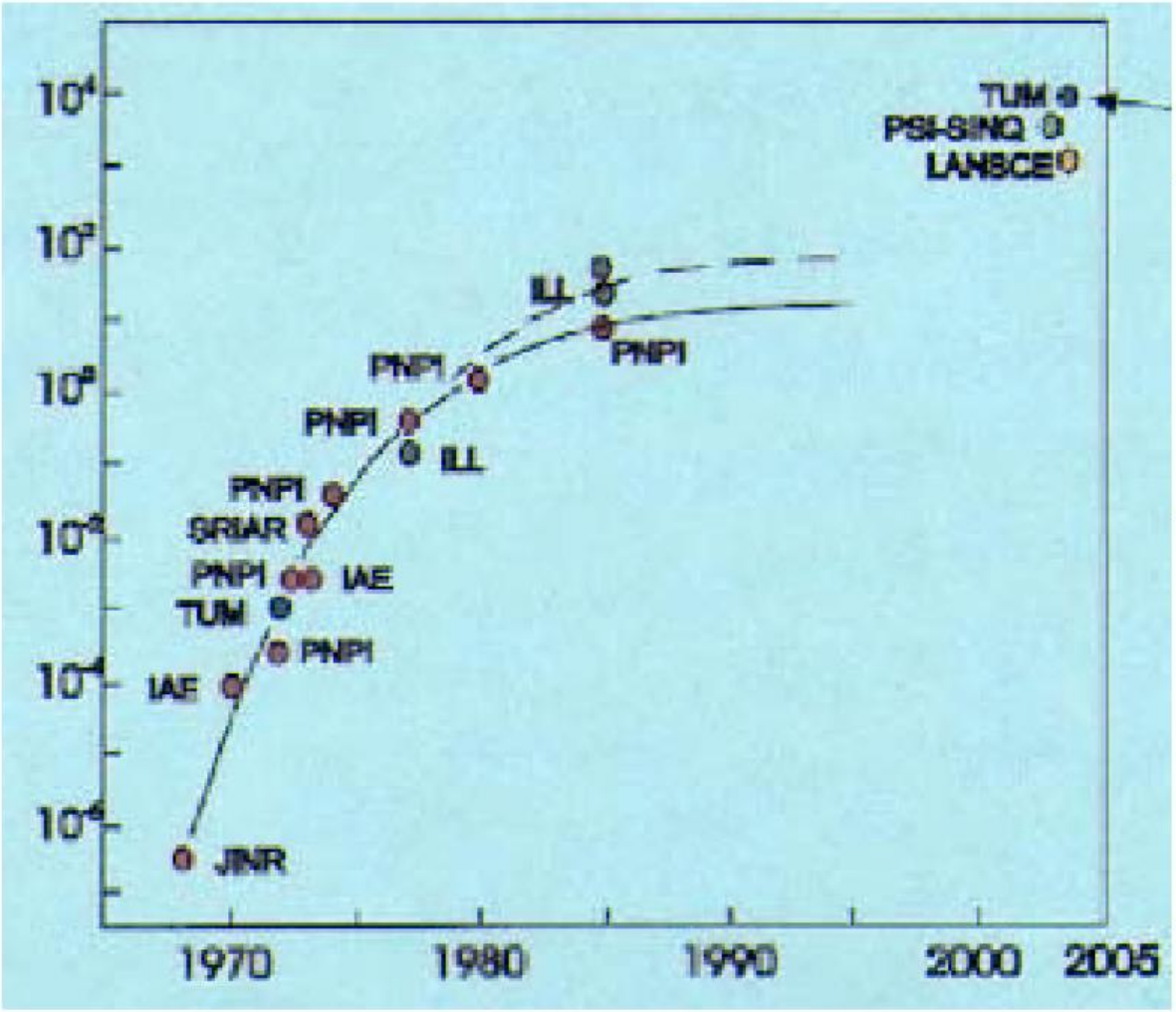
UCN are totally reflected from suitable materials at *any* angle of incidence, hence storable!

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, ..)

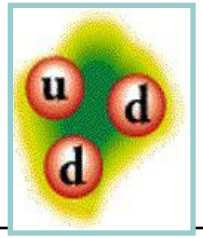


Overview of existing UCN Sources

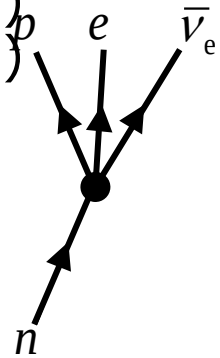


- Neutron moderation
  - Tail of Maxwell-Boltzman distribution
  - Nucn = $10^{-13}\ \Phi_0$
- Conservative force
  - Gravity deceleration
  - Turbine deceleration
  - could not increase the phase space density.
- Superthermal source.

Passport of the neutron



- Mass $m_n = 1.001\,378\,418\,70(58)\ m_p$
  $= 939.565360(81)$ MeV
- Charge $q = -0.4(1.1)\cdot 10^{-21}\ e$
- Spin $\sigma = ½\ \hbar$
- Magnetic moment $\mu_n = -1.913\,042\,73(45)\ \mu_N$
  $= -6.030\,774\,0(14)\cdot 10^{-8}$ eV/T
- Electric dipole moment $d_n \leq 0.63\ \cdot 10^{-25}\ e\cdot$cm
- Life time $\tau = 885.7(8)$ s
- Decay modes $n \to p\ e\ \nu_e \approx 100\%$
  $n \to p\ e\ \nu_e\ \gamma \approx 10^{-3}$ (to be detected)
  $n \to H\ \nu_e \approx 4\cdot 10^{-6}$ (to be detected)



Determination of the Neutron Mass

The best method for the determination of the neutron mass considers the reaction:

$$n + p \rightarrow d + \gamma$$

and measures two quantities with high accuracy:

1. *A gamma ray energy*

   The actual experiment is an absolute determination of the 2.2MeV gamma ray wavelength in terms of the SI meter.

2. *A mass difference*

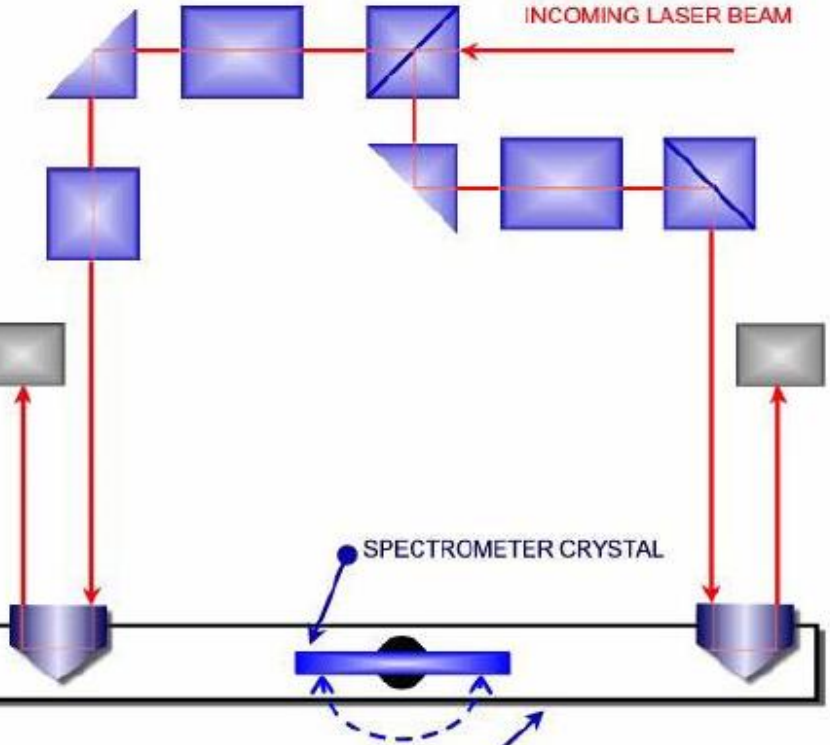
   The actual experiment is the determination of the D - H mass difference in atomic mass units.

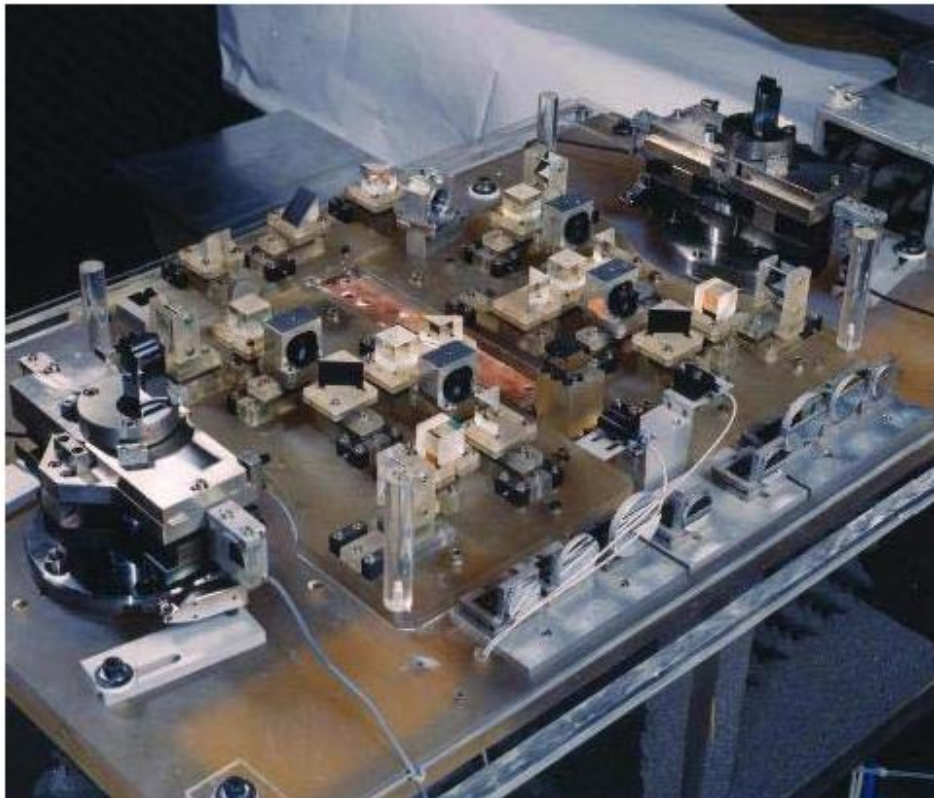
Absolute Measurement of 2.2MeV n-p Capture Gamma Energy

asure Bragg angle for diffraction of 2.2MeV gamma from a perfect gle crystal of Silicon with an accurately measured lattice spacing d.

$$n\lambda^* = 2d\sin\theta \qquad E_\gamma = h\nu = \frac{hc}{\lambda^*}$$

Bragg Angle is a few milli-radian
Need nano-radian precision!





Determination of the Neutron Mass

$\lambda^* = 5.573\ 409\ 78(99) \times 10^{-13}$ meters

G.L Greene, et. al., Phys. Rev. Lett. 24, 819 (1986)
E. G. Kessler, et. al., Phys Lett A, 255 **(1999)**

$M(D) - M(H) = 1.006\ 276\ 746\ 30(71)$ atomic mass units (u)

F. DiFilippo, et. al., Phys Rev Lett, 73 **(1994)**

which gives

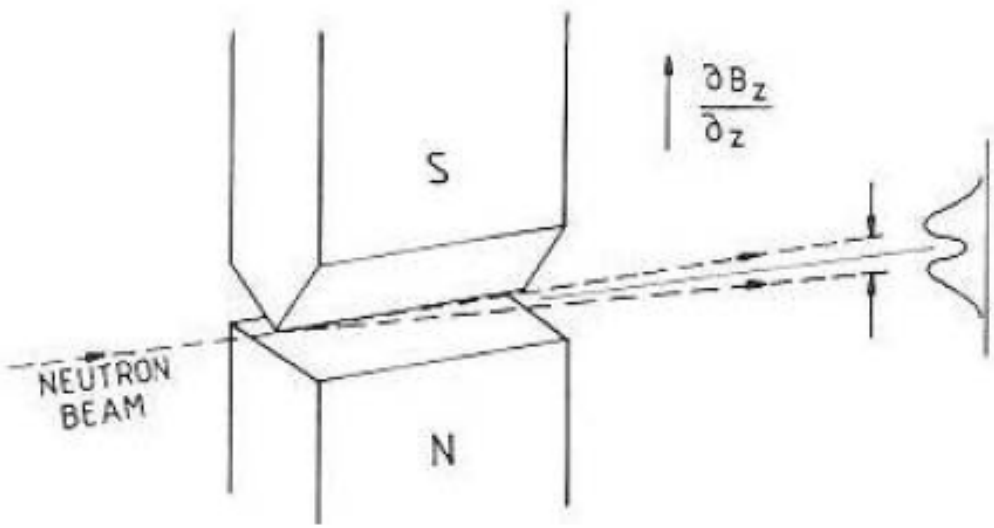
$M(n) = 1.008\ 664\ 916\ 37(99)$ atomic mass units (u)

The Neutron has an Intrinsic Spin of $s=\frac{1}{2}$

1934 *Schwinger concludes that s=½ based on the band spectrum of molecular D_2 and the scattering of neutrons from ortho and para H_2.*

1949 *Hughes and Burgey observe the mirror reflection of neutrons from magnetized iron. They observe 2 critical angles definitively showing the neutron has two magnetic sub-levels.*

1954 *Neutron Stern-Gerlach experiment explicitly demonstrates s=½ .*



See also Fischbach, Greene, Hughes, PRL 66, 256 (1991) showing $\vec{L} = \hbar\vec{s}$

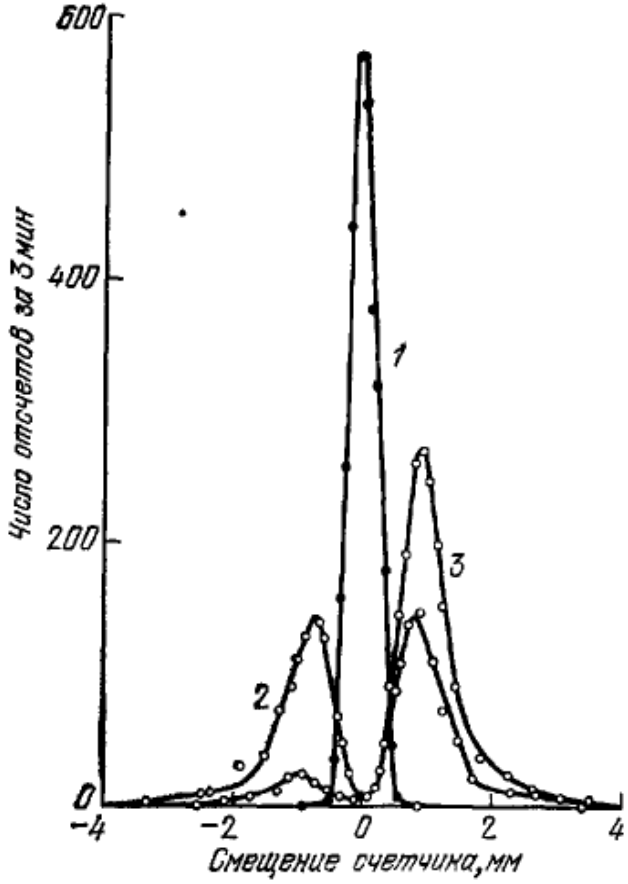


Рис. 3. Опыт типа Штерна — Герлаха на нейтроне: разделение пучка нейтронов в неоднородном магнитном поле (из работы [52]).

1 — пучок в отсутствие магнитного поля, 2 — разделенный неполяризованный пучок, 3 — поляризованный пучок.

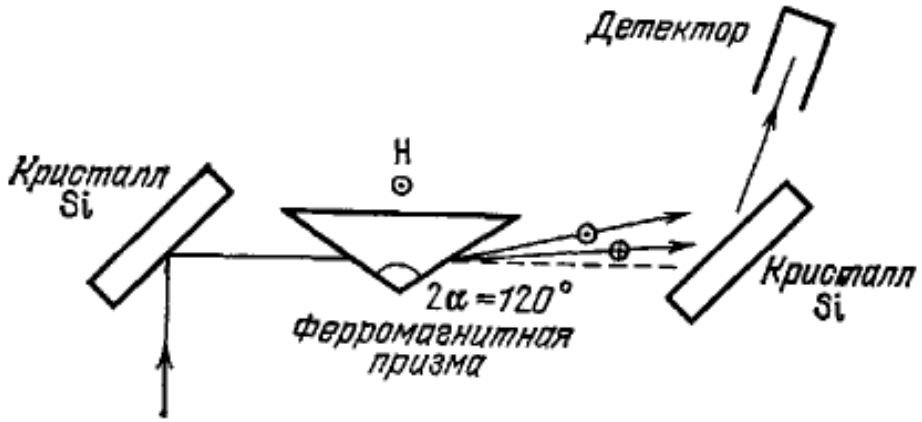
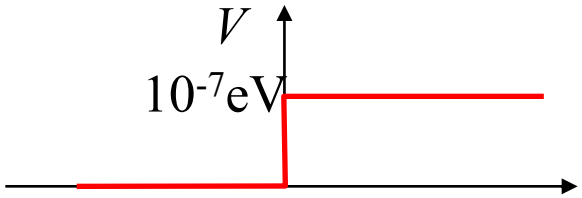


Рис. 4. Схема эксперимента Шалла по наблюдению двулучепреломления нейтронов в ферромагнитной призме.

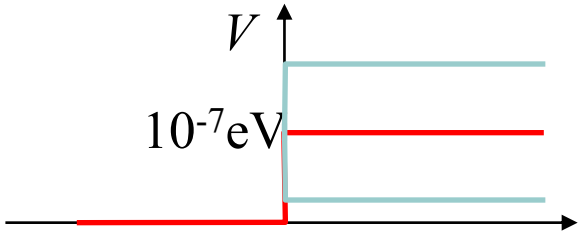
Cold Neutrons

Transport

$$n \approx 1 - \frac{\lambda^2 b \rho}{2\pi}$$

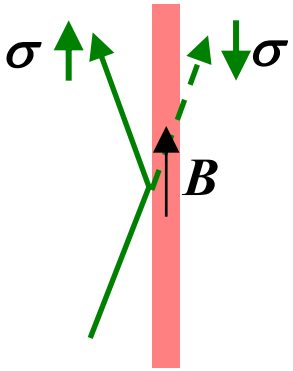


$$V = V_{\text{Fermi}} \mp \mu B$$



10^{-7}eV 10^{-7}eV

(same for UCN)



Метод отражения от намагниченных зеркал

Данный метод основан на существовании двух критических углов скольжения при отражении нейтронов от намагниченных зеркал.

$$\theta_c = \frac{\lambda}{\sqrt{\pi}} \sqrt{N b_{\text{ког}} \pm \frac{m_n}{2\pi\hbar^2} \left|\mu_n\right| B}.$$

Если падающий пучок моноэнергетический, то критические углы скольжения имеют определенные значения. Отбирая нейтроны, отраженные в промежутке между этими углами, можно получить пучок нейтронов, поляризованный вдоль направления намагничивающего поля.

Метод пропускания пучка сквозь намагниченный образец

Впервые поляризованные нейтроны были получены при пропускании пучка нейтронов через намагниченную до насыщения железную пластину толщиной ~ 5 см (метод предложен Ф. Блохом в 1936 г. и исследован Д. Юзом с сотрудниками в 1947 г., США). Нейтроны, спины которых параллельны направлению намагниченности ферромагнетика, сильнее рассеиваются и выбывают из пучка. В результате пучок нейтронов, прошедший через пластину, обогащается нейтронами со спинами, антипараллельными намагниченности. Метод требует сильных намагничивающих полей. В полях $H \sim 10^4$ Э наибольшая степень поляризации $P = 0{,}6$.

Степень поляризации

Т. к. *нейтрон* обладает спином ½, то в магнитном поле ***H*** возможны 2 ориентации его спина: параллельно или антипараллельно ***H***. Нейтронный пучок поляризован, если он содержит разное количество N нейтронов со спинами, ориентированными вдоль (N_+) и против поля (N_-). Степень поляризации характеризуют величиной

$$P = (N_+ - N_-)/(N_+ + N_-).$$

Если $P = \pm 1$, то пучок полностью поляризован. В общем случае $-1 \leq P \leq +1$.

Эффект двукратного прохождения

Для измерения степени поляризации пучка может быть использован ***эффект двукратного прохождения***. Для этого пучок нейтронов пропускается последовательно через два намагниченных до насыщения железных блока, из которых 1-й играет роль поляризатора, а 2-й – анализатора. Поляризатор и анализатор намагничивают один раз в одинаковых, а другой раз в противоположных направлениях. Измеряя интенсивность нейтронного пучка после анализатора в этих двух случаях ($J_{\uparrow\uparrow}$ и $J_{\uparrow\downarrow}$), можно определить степень поляризации пучка после поляризатора.

Behavior of the Neutron's Spin in a Magnetic Field

- The time evolution of any two-state quantum system can be represented by the movement of a classical vector

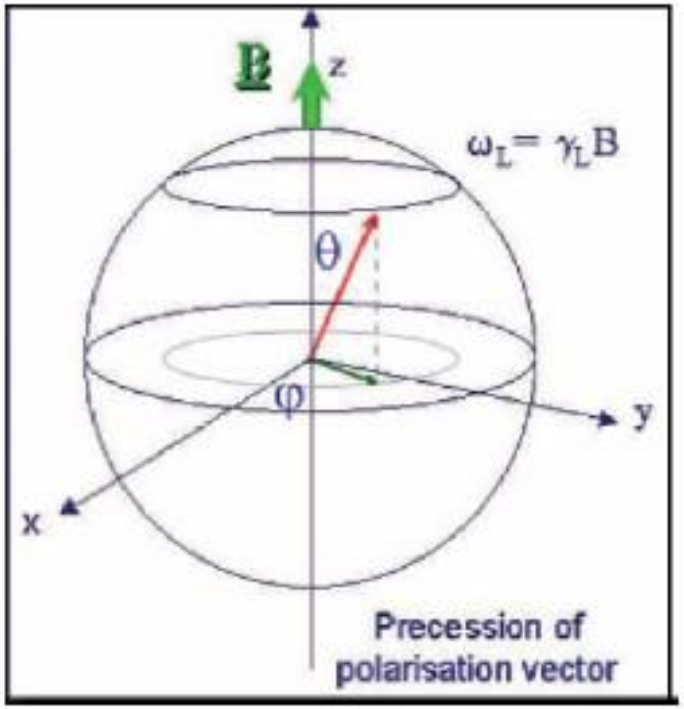
$$\frac{d\vec{P}}{dt} = -\gamma_L \vec{P} \wedge \vec{B}$$

where γ_L is the gyromagnetic ratio of the neutron

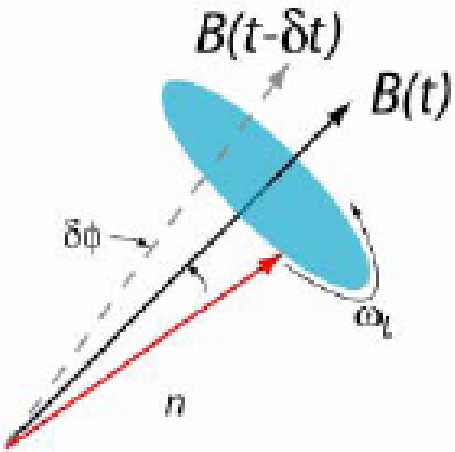
The solutions are

$$P_x(t) = \cos(\omega_L t)P_x(0) - \sin(\omega_L t)P_y(0)$$
$$P_y(t) = \sin(\omega_L t)P_x(0) + \sin(\omega_L t)P_x(0)$$
$$P_z(t) = P_z(0)$$

where $\omega_L = \gamma_L B = -1.832\text{x}10^8 \text{ rad.s}^{-1}.\text{T}^{-1}$



Adiabatic rotation of neutron spin



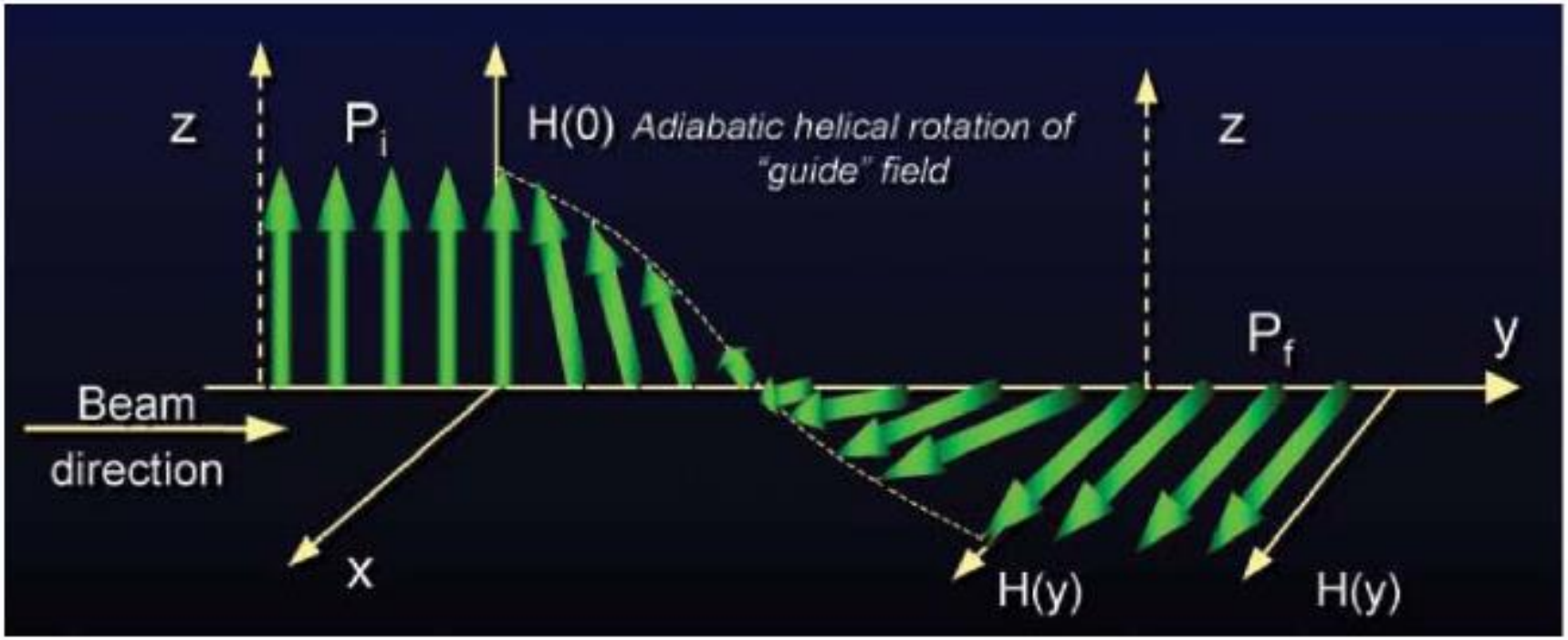
$$\varpi_L = \gamma \left| \vec{B} \right| = -1.833 \times 10^4 \, \mathrm{rad/G\text{-}s}$$

$$\frac{d\phi}{dt} << \left| \varpi_L \right|$$

Condition to maintain polarization of the neutron beam.

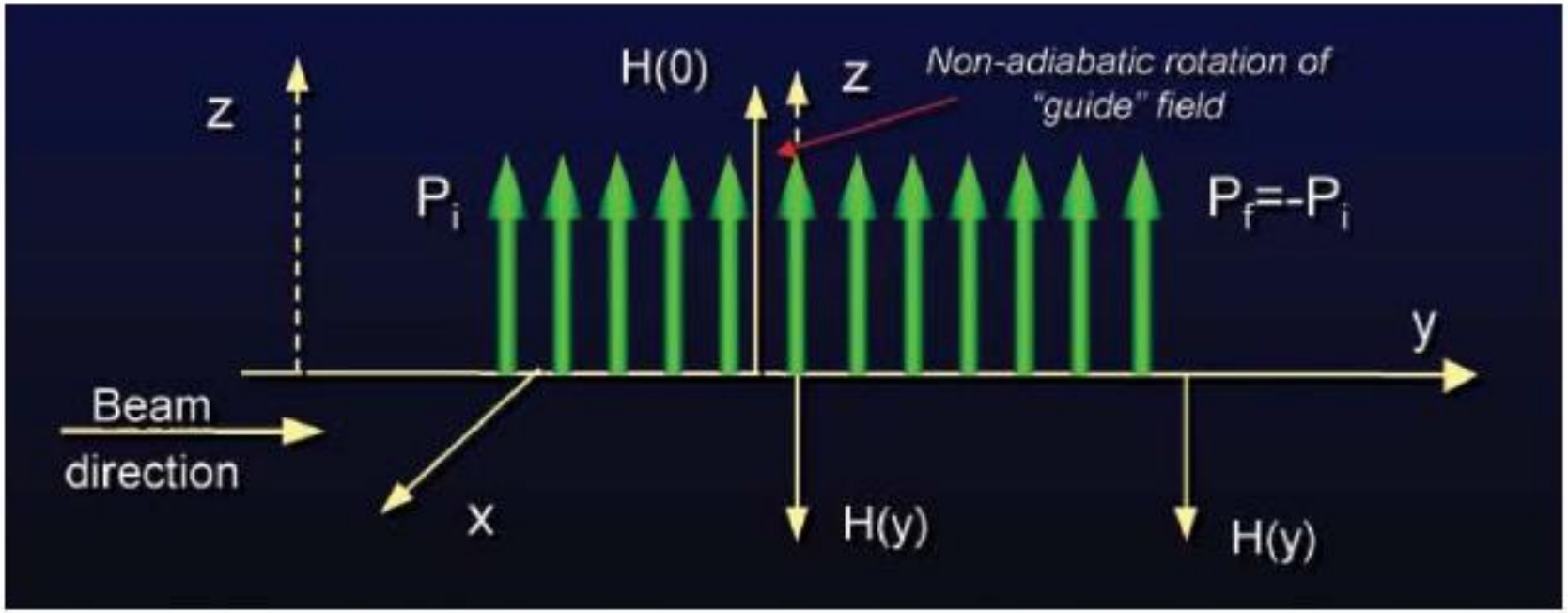
Guiding the Neutron Polarization

- If the direction of a magnetic field varies sufficiently slowly in space, the component of neutron polarization parallel to the applied field is preserved. This is adiabatic polarization rotation.



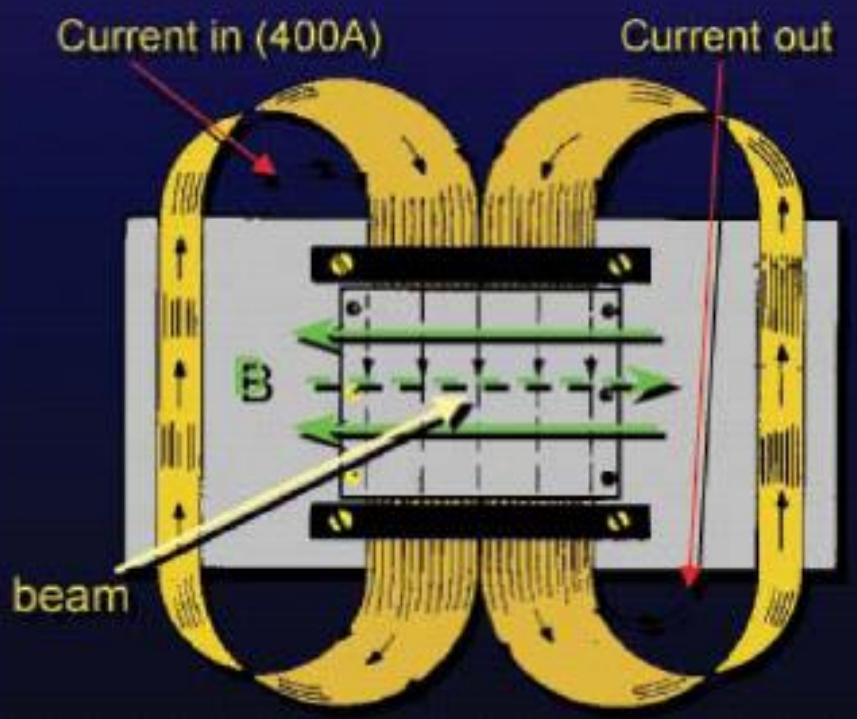
Non-Adiabatic Transitions

- If the guide field direction is suddenly changed (i.e. the adiabaticity parameter tan $\delta \longrightarrow \infty$, the neutron polarization vector will precess about the new field direction.
- If the field is reversed, the neutron polarization is flipped with respect to the field



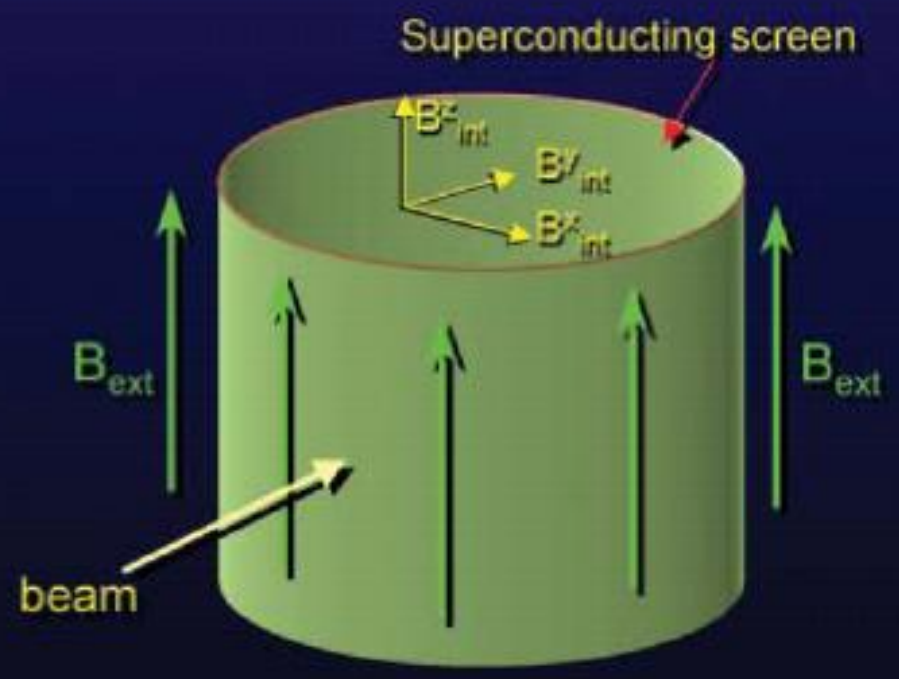
Non-adiabatic spin flippers

A variety of devices have been employed as effective non-adiabatic "spin-flippers":



Dabbs' foil current sheet

see eg, Jones and Williams
NIM 152, 463 (1978)



Meissner shield

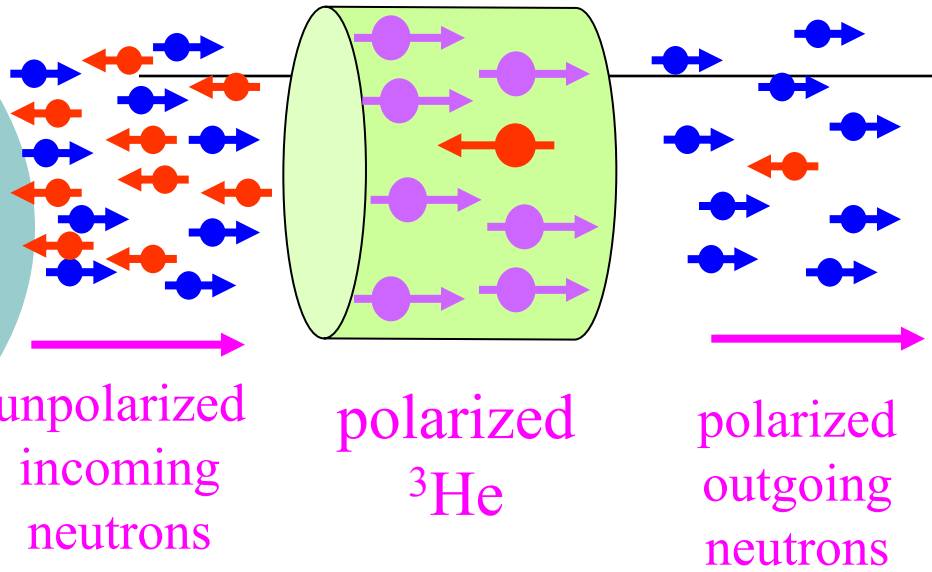
Concentric Meissner shields surround the sample on CRYOPAD

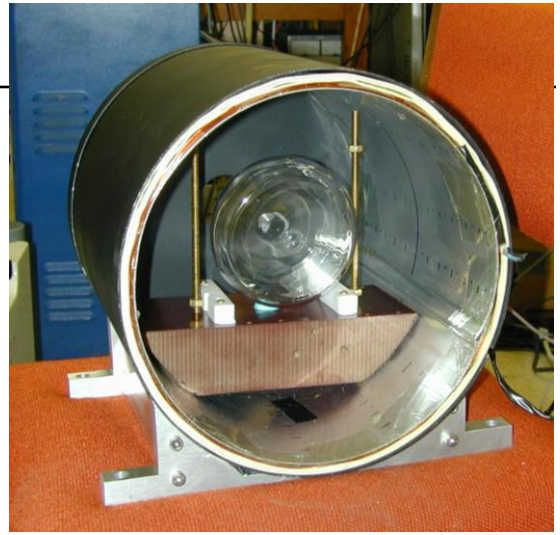
see eg, Tasset et al
Physica B 267-268 69 (1999)

Viewgraph from Bob Cywinski

Production of Polarized Beams

POLARIZED ^{3}He NEUTRON SPIN FILTERS

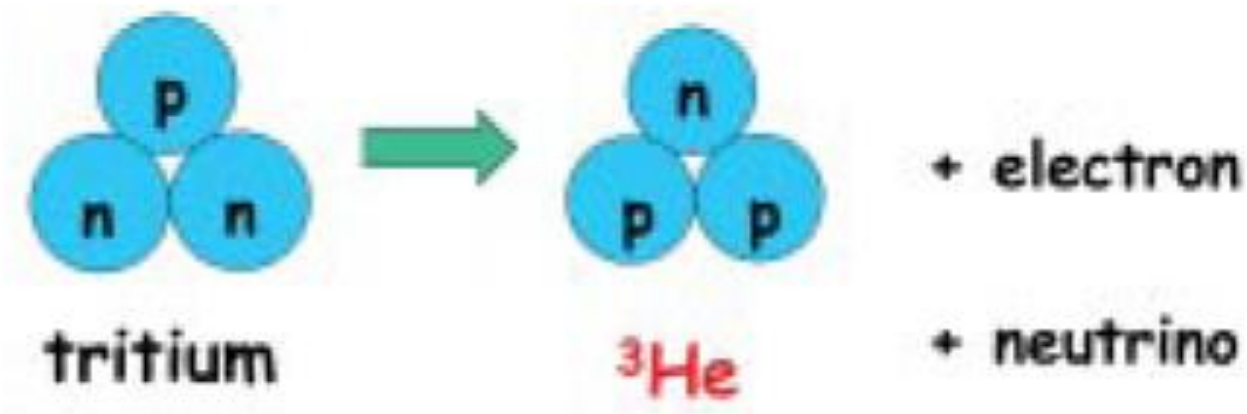




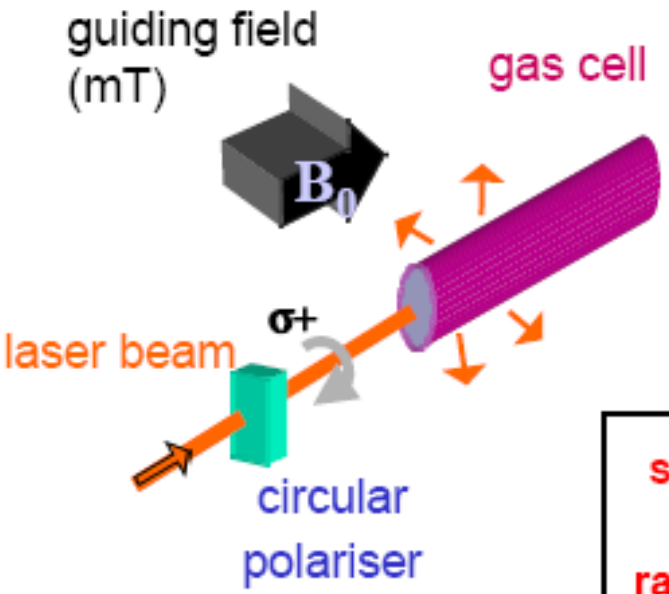
Polarized ^{3}He cell (11 cm diameter)

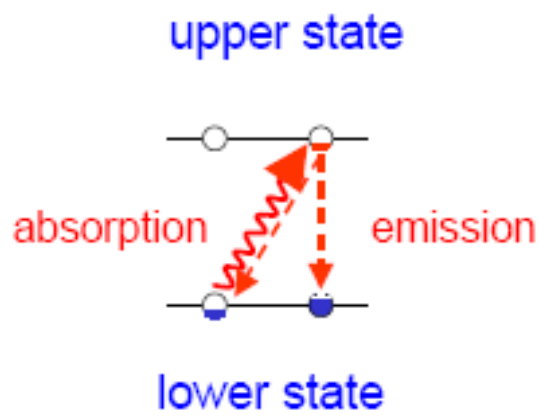
Large neutron phase space acceptance
Polarizer/analyzer pair can measure B using neutron spin rotation

Tritium, a radioactive isotope of hydrogen used in nuclear bombs, consists of two neutrons and a proton, which decay into two protons and a neutron: ^{3}He, plus a couple of other little things.



Optical pumping (OP) to produce hyperpolarisation



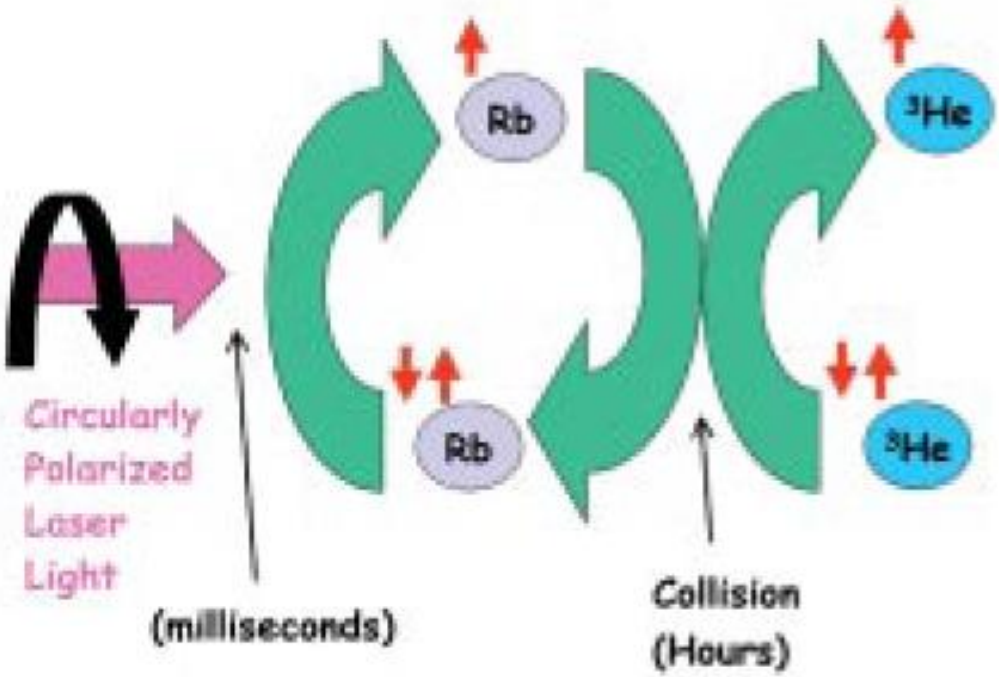


A. Kastler, ENS
Nobel prize 1966

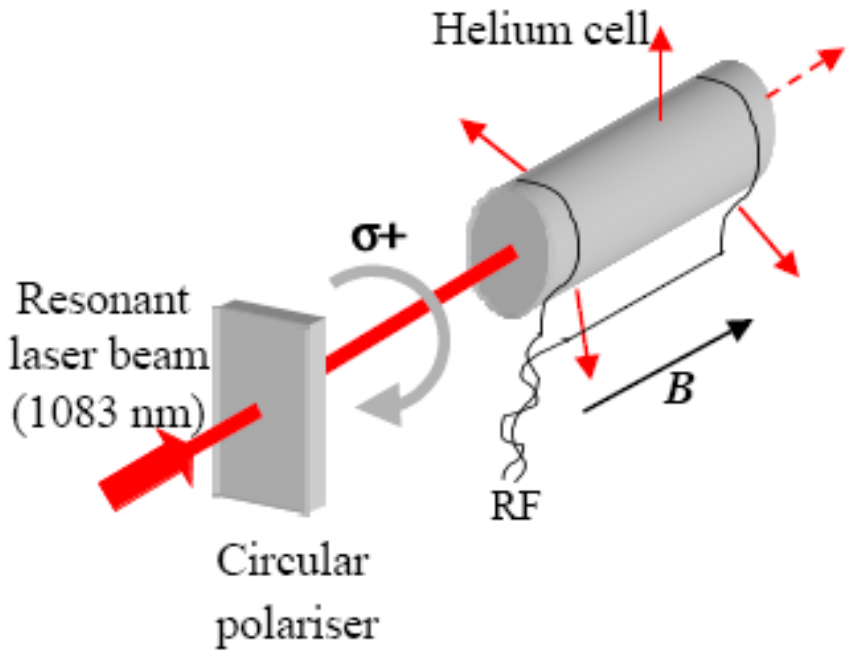
selective excitation
+
random spontaneous emission
→ net transfer from ↓ to ↑

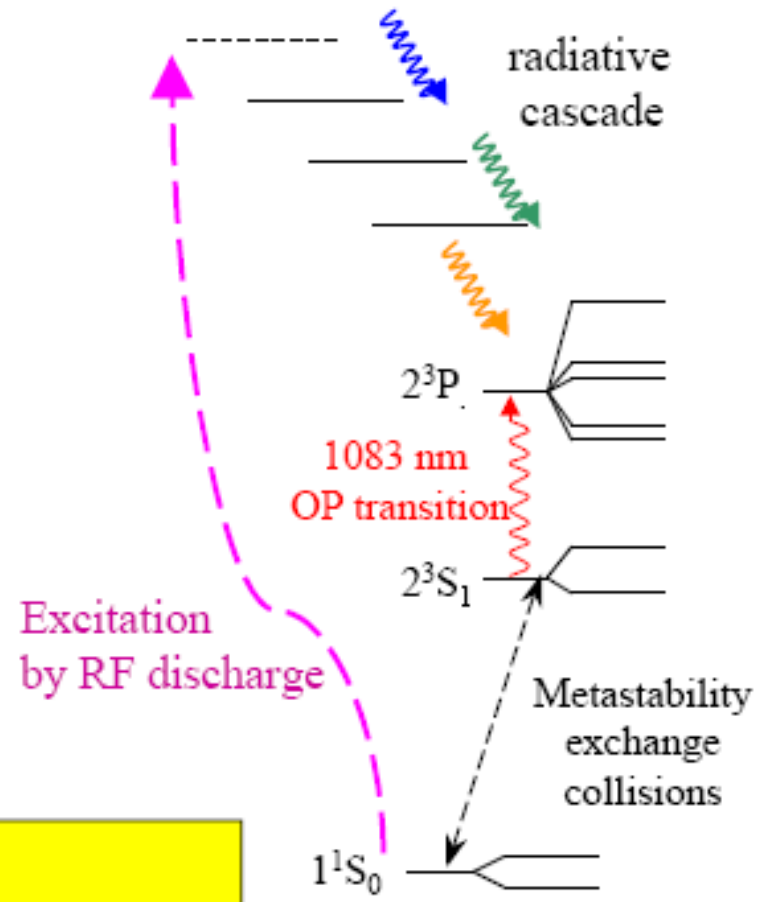
Pumping rates : rough numbers
1 Watt absorbed ↔ 2×10^{22} photons/hour
1 litre of gas at 1 bar ↔ 3×10^{22} atoms

To polarize ^{3}He, you hit a rubidium atom with circularly polarized laser light, giving the atom spin up. When that atom collides with a spin-down helium atom, they reverse spin, but the rubidium immediately gets repolarized to spin up again and ready to change the spin of another helium atom. The first part of the process is very fast, but keeping it going long enough to obtain a liter of 50-percent polarized spin-up helium demands patience.



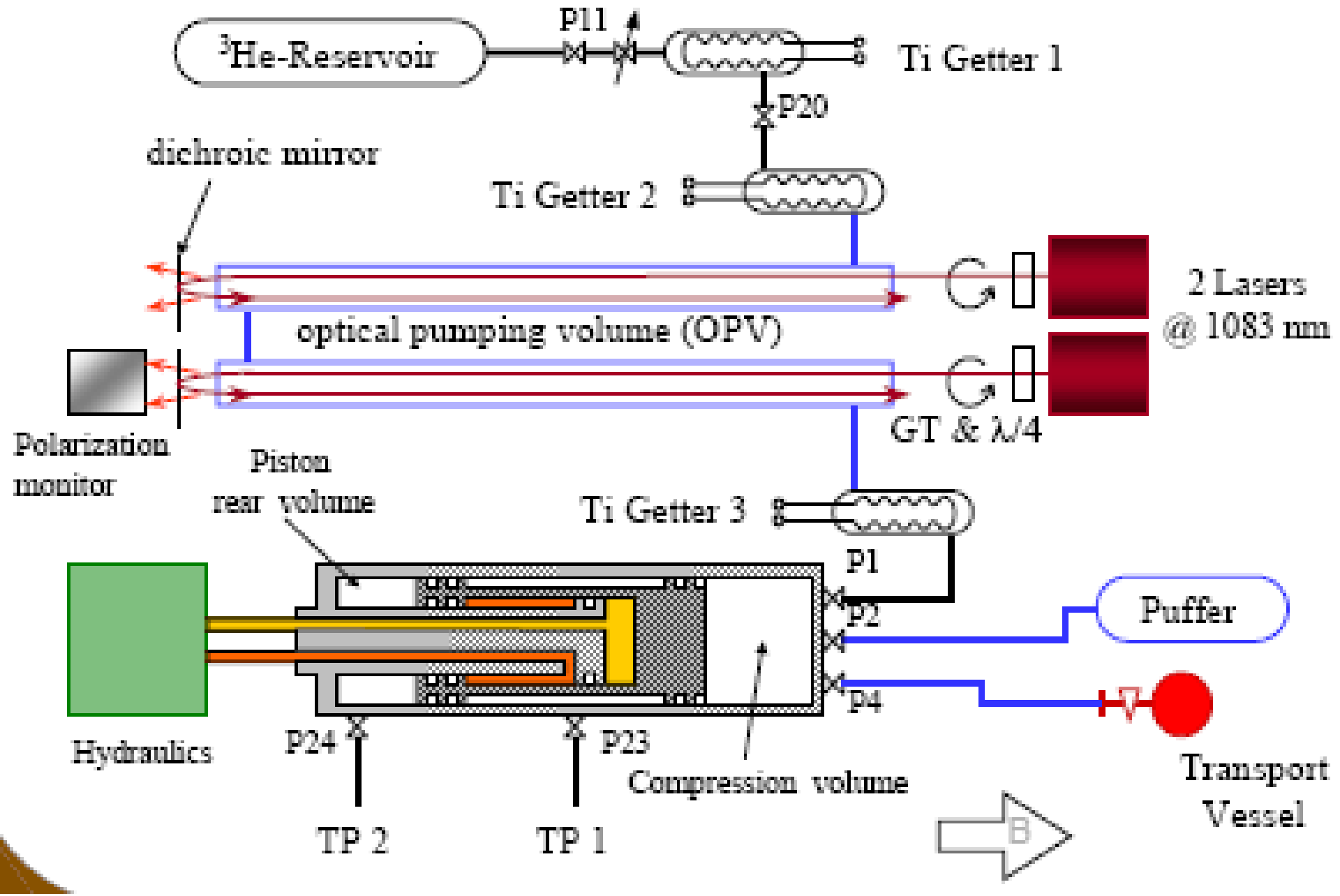
Metastability exchange optical pumping in He3 (ME OP, since 1963)



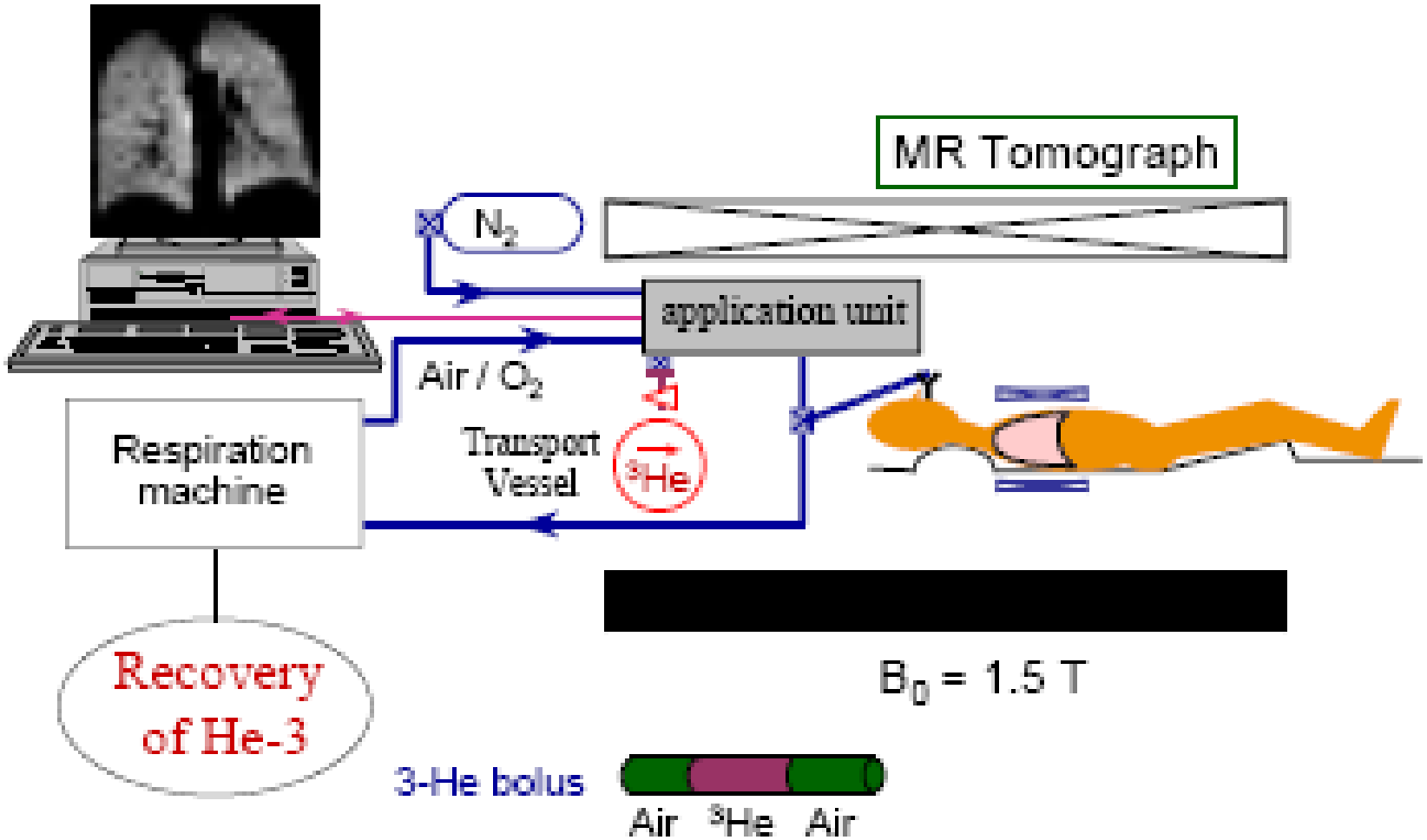


OP orients electronic spin in excited states
Hyperfine (HF) coupling : nuclear spin oriented as well
ME collisions : transfer to ground state nuclear spin

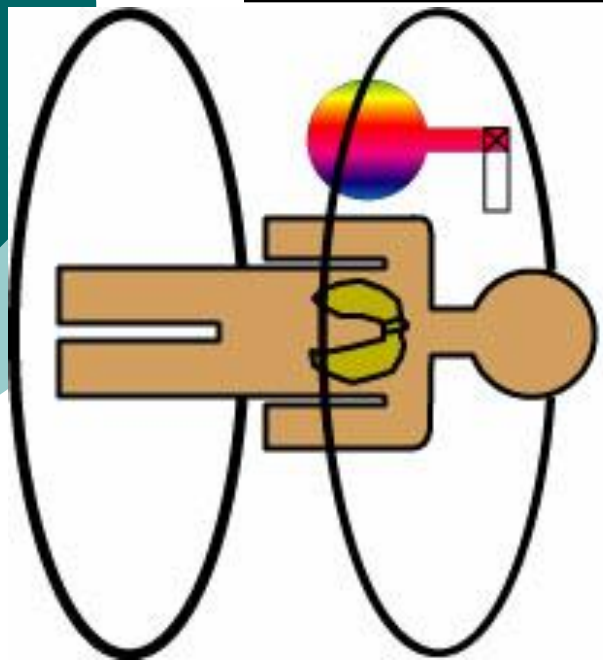
Department of Physics, Mainz: M. Batz, J. Bermuth, A. Deninger, M. Ebert, F. Filbir, T. Großmann, W. Heil, S. Hiebel, W. Ketter, N. Krowas, L. Lauer, H. Mayer, E. Otten, D. Rudersdorf, J. Schmiedeskamp, R. Surkau, M.Wolf

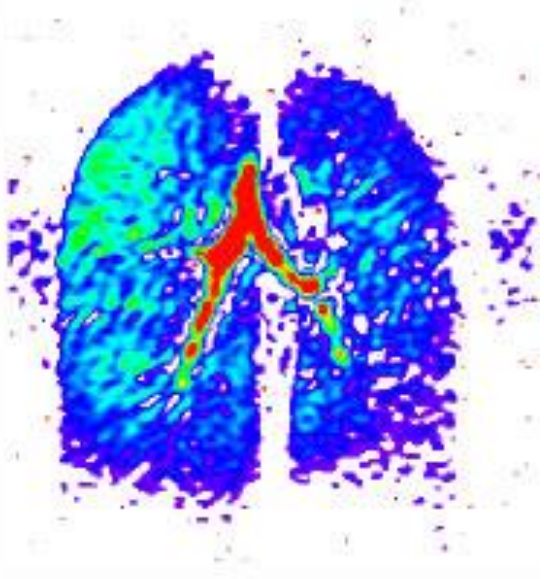


Predefined volumes of hyperpolarized Helium-3 boli can be injected into the normal inhaling cycle of a patient.
Breathhold pictures and in- and exhaling movies are feasible.



Medical Imaging With Polarized 3He

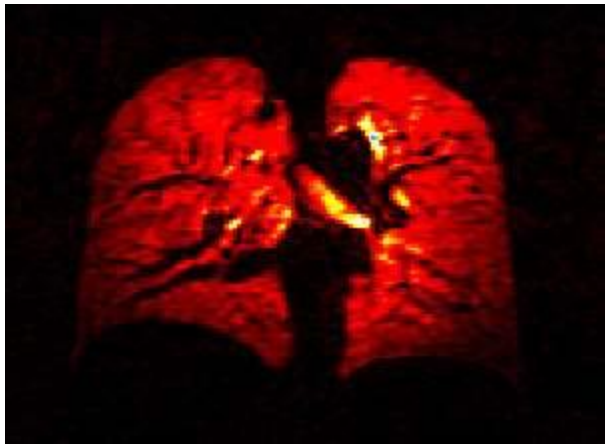




Introduction:

Respiratory disorders, coughing – signs for a serious disease of the lung or just a temporary indisposition?

Magnetic Resonance Tomography with Helium-3 is a new method of diagnosing lung diseases which not only provides a high-resolution spatial representation of lung ventilation but also gives information about the functional state of the lung - and all this without any harmful effects on the organism.



How Do We Detect Neutrons?

- What does it mean to "detect" a neutron?
  - Need to produce some sort of measurable quantitative (countable) electrical signal
  - Can't directly "detect" neutrons
- Need to use nuclear reactions to "convert" neutrons into charged particles
- Then we can detect the charged particles electrically
  - $n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 0.764$ MeV
  - $n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.79$ MeV
  - $n + {}^{155}Gd \rightarrow Gd^{*} \rightarrow \gamma$-ray spectrum $\rightarrow$ conversion electron spectrum

Магнитный момент нейтрона

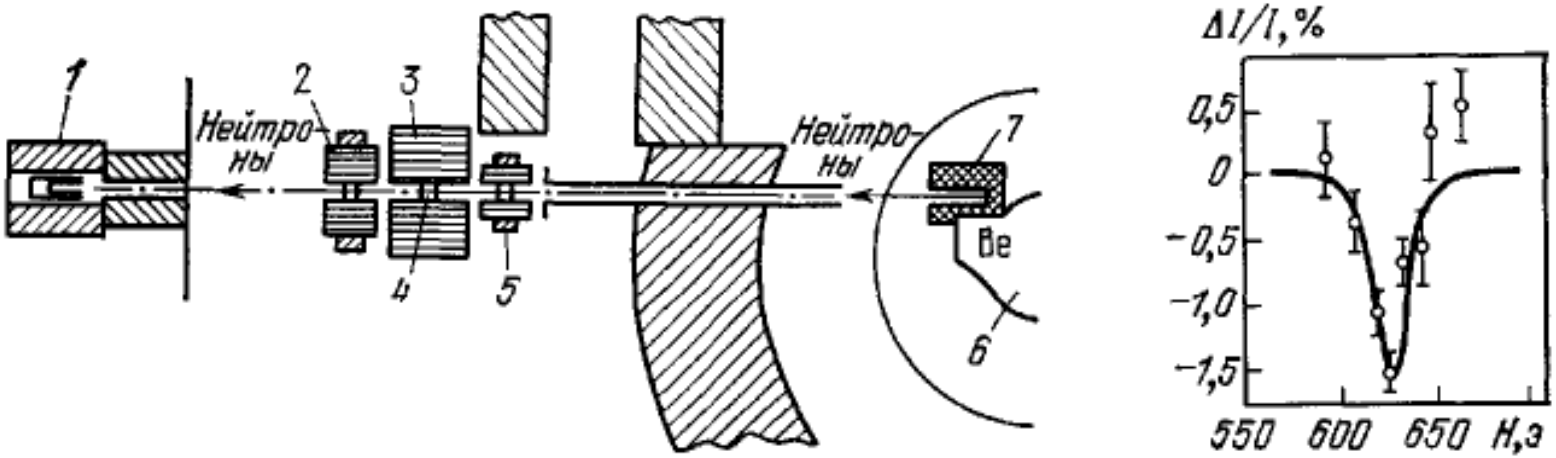
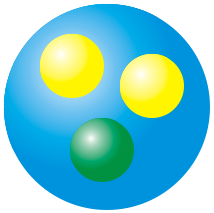
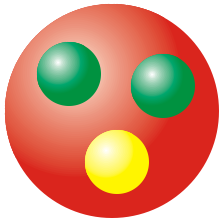


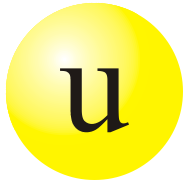
Рис. 1. Схема эксперимента Альвареса и Блоха по измерению магнитного момента нейтрона.

1 — детектор, *2* — магнит-анализатор, *3* — магнит для создания постоянного магнитного поля, *4* — область, занятая осциллирующим полем, *5* — магнит-поляризатор, *6* — камера циклотрона, *7* — замедлитель.

Nucleons





	Proton	Neutron
Charge:	+ e	0 e
quarks		
Charge:	+ 2/3 e	- 1/3 e

"Naive" Quark Model

Static SU(6) Model:

1. *Baryons wavefunctions are quark color singlets with correct symmetry*

2. *Baryon magnetic moments arise solely from the static sum of the quark moments*

3. *Individual quark moments are proportional to quark charges (i.e.* $\mu_u = -2\mu_d$*)*

1.

$$n_\uparrow = \sqrt{\tfrac{2}{3}}\, d_\uparrow d_\uparrow u_\downarrow - \sqrt{\tfrac{1}{3}}\left(\frac{d_\uparrow d_\downarrow + d_\downarrow d_\uparrow}{\sqrt{2}}\right) u_\uparrow$$

$$p_\uparrow = \sqrt{\tfrac{2}{3}}\, u_\uparrow u_\uparrow d_\downarrow - \sqrt{\tfrac{1}{3}}\left(\frac{u_\uparrow u_\downarrow + u_\downarrow u_\uparrow}{\sqrt{2}}\right) d_\uparrow$$

2.

$$\mu_n = -\tfrac{1}{3}\mu_u + \tfrac{4}{3}\mu_d$$

$$\mu_p = -\tfrac{1}{3}\mu_d + \tfrac{4}{3}\mu_u$$

3.

$$\boxed{\frac{\mu_n}{\mu_p} = -\frac{2}{3}}$$

WHY IS THE AGREEMENT SO GOOD?

$$\boxed{\frac{\mu_n}{\mu_p} = -0.68497935(17)}$$ experiment

vs.

$$\boxed{\frac{\mu_n}{\mu_p} = -0.67}$$ theory

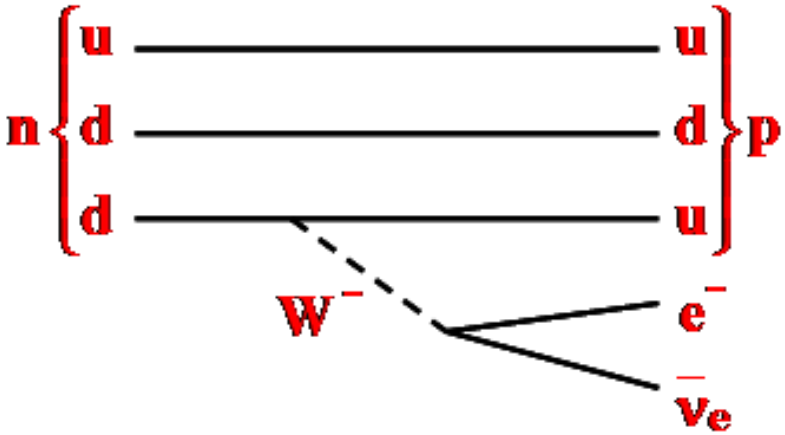
The spin structure of the nucleon is one of the outstanding problems at the interface between nuclear and particle physics.

Over the past 20 years more than 1000 theoretical papers have been published and major experiments have been carried out at practically all major accelerator laboratories.

The work is ongoing...

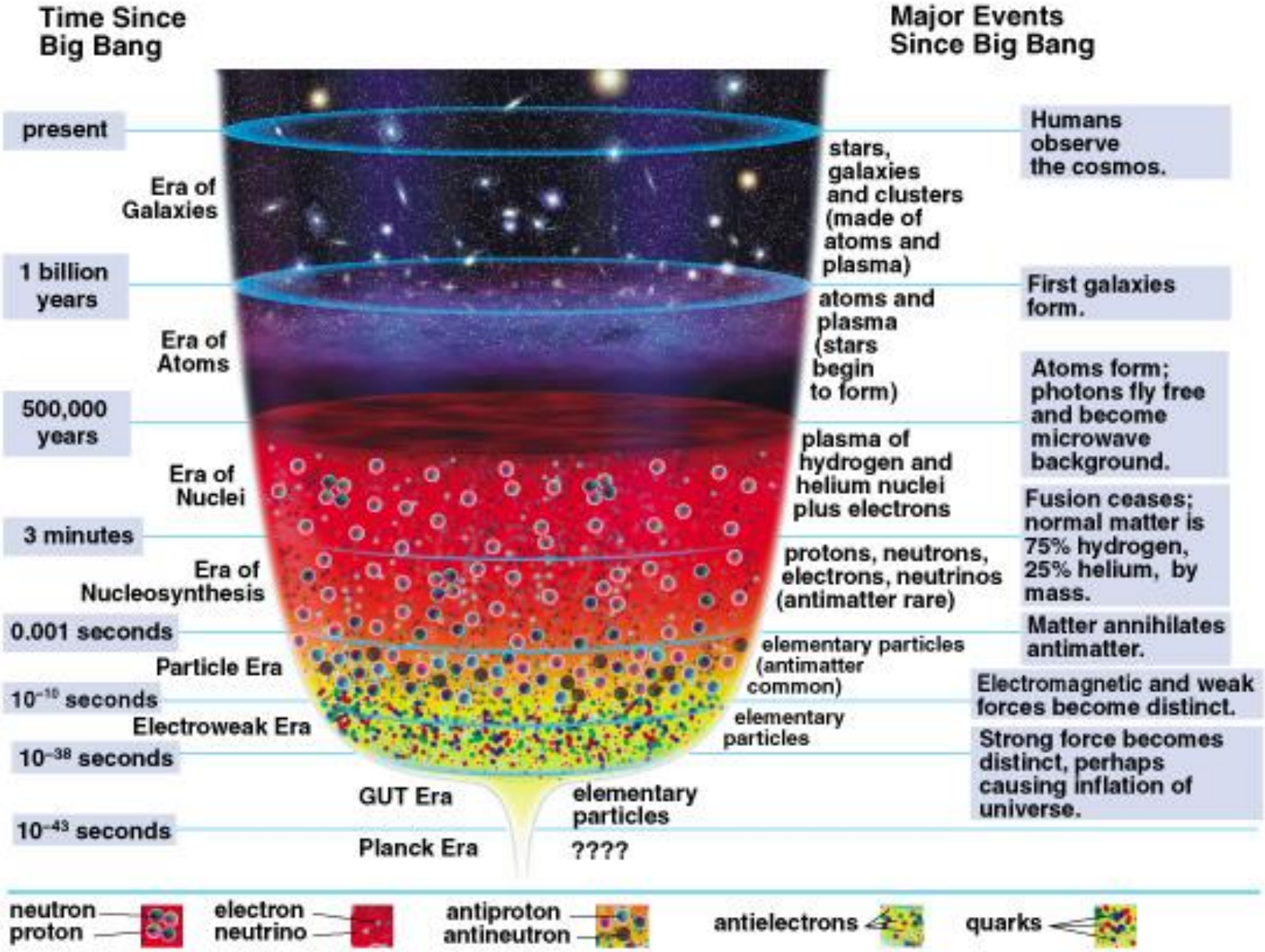
РАСПАД НЕЙТРОНА

What Can we Learn from Neutron Beta Decay?



Particle Physics:

A comparison between the neutron lifetime and neutron decay correlations provides a unique test of the standard model.



Big Bang nucleosynthesis

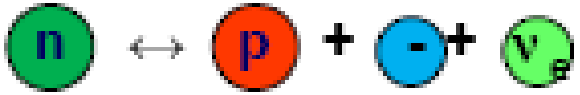
Start story of BBN at $t \sim 2\times10^{-6}$ s, when $T \sim 10^{13}$ K,
and hence characteristic energy of particles $kT \sim 1$ GeV,
comparable to mass-energy of proton and neutron:
$E_p = m_p c^2 \sim 938.3$ MeV and $E_n = m_n c^2 = 939.6$ MeV
[Note: $\Delta E = 1.3$ MeV]

Universe has cooled to point at which quarks assemble into stable protons and neutrons.

Protons and neutrons produced in almost identical numbers.

p's and n's continually interchanging with one another:

$$n \leftrightarrow p + e + \text{anti-}\nu_e$$



$$n + e^+ \leftrightarrow p + \text{anti-}\nu_e$$

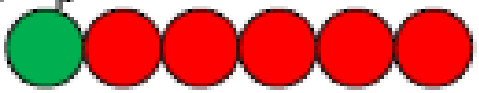
$$n + \nu_e \leftrightarrow p + e^-$$

Ratio of n's to p's, n_n/n_p, decreases as Universe cools,
due to higher mass of neutrons: $m_n = m_p + 1.3\ \text{MeV}/c^2$.

Universe expands and cools (at $t \sim 2$ s) to $T \sim 10^{10}$ K, $kT \sim 1$ MeV:

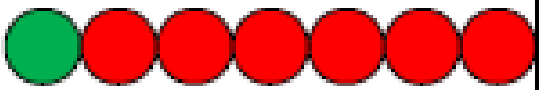
(1) comparable to mass-energy difference of proton and neutron,
(2) comparable to energy required to form e^- and e^+ via $\gamma \rightarrow e^+ + e^-$.

(1) conversion of protons to neutrons ceases.
(2) e^- and e^+ cease to be produced, most annihilate; few e^-'s remain
When conversion of protons and neutrons ceases, n_n/n_p ratio =0.22.

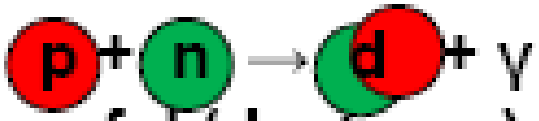


Neutrons decay with half-life 10.3 minutes … $n \rightarrow p + e^- + \text{anti-}\nu_e$

Now we wait for the Universe to cool down some more …
tick, tock, tick, tock, …
for about 4 minutes …
during which time n_n/n_p runs down to about 0.16



At $t \sim 230$ s and $T \sim 10^9$ K ($kT \sim 0.1$ MeV),
first compound nucleus can form and *survive*:



$d = {}^2H$

Binding energy of d (deuteron) is 2.2 MeV.

<u>Big Bang nucleosynthesis (BBN)</u>

Why doesn't $p + n \rightarrow d + \gamma$ $d = {}^2H$
proceed earlier at $t < 230$ s and $T > 10^9$ K ($kT > 0.1$ MeV),
since binding energy of d (deuteron) is 2.2 MeV?

Photons outnumber baryons ~ 10^9:1
so even when the "typical" photon energy is less than 2.2 MeV,
there are still more than enough 2.2 MeV photons to dissociate the d's.

Fraction of photons with $E > 2.2$ MeV falls below 10^{-9} only once $T < 10^9$ K
At higher T, energetic and abundant photons dissociate d's

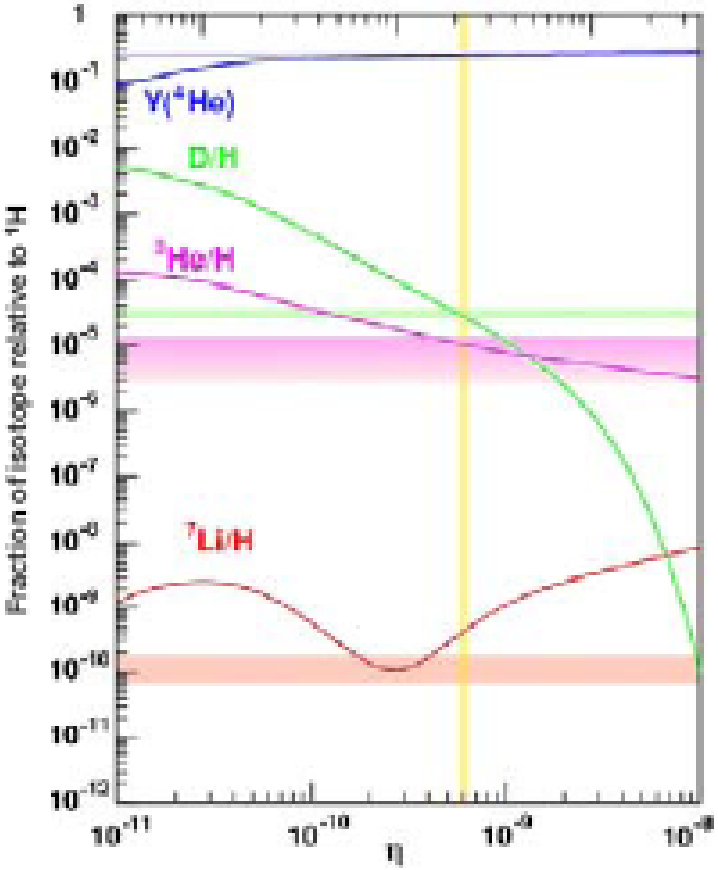
too cool (particle energies too low to tunnel through Coulomb barrier),
too few neutrons to have further nucleosynthesis.

Big Bang nucleosynthesis (BBN)

Production of ^{2}H, ^{3}He, ^{4}He and ^{7}Li calculated as a function of the baryon to photon ratio, η.

Treat η as a (the) free parameter in BBN. Obtain reasonable consensus between ^{2}H, ^{4}He and ^{7}Li and a small range of values of η. Note, however, that ^{4}He is not a very sensitive test!

Since 2003, observations of the angular power spectrum of the cosmic microwave background radiation provide a better measure of η.



How much is it 1%?

$$\eta_{10} = N_b / N_\gamma$$

Variation in neutron lifetime by 1% changes η by 17%, although the modern accuracy of estimation of this quantity amounts to ±3.3%

The "Time Scale" for Big Bang Nucleosynthesis is Given by the Neutron Lifetime

If τ_n were much smaller (seconds instead of minutes), there would be no neutrons left when the universe was cool enough for nuclei –

THE UNIVERSE BE ALL HYDROGEN

If τ_n were much larger (say hours instead of minutes), there would be no significant decrease in the number of neutrons when the neutrinos decouple ($t \approx 1$ s)-

THE UNIVERSE BE ~2/3 He, ~1/3 H

IN EITHER CASE, THE SUBSEQUENT EVOLUTION OF THE UNIVERSE WOULD BE VERY DIFFERENT !

Recombination

After $t \sim 400\,000$ yrs, $T \sim 4000$ K, $kT \sim$ few eV

kT comparable to the ionisation energy of hydrogen (13.6 eV)

(Recall: H is dominant product of BBN).

p's and (free) e^-'s can combine to form neutral H atoms

Before recombination, Universe was largely opaque to photons due to the high opacity of free electrons, which scatter photons.

[electron scattering; Thomson scattering]

After recombination, Universe becomes much more transparent as few free electrons remain.

Cosmic microwave background radiation

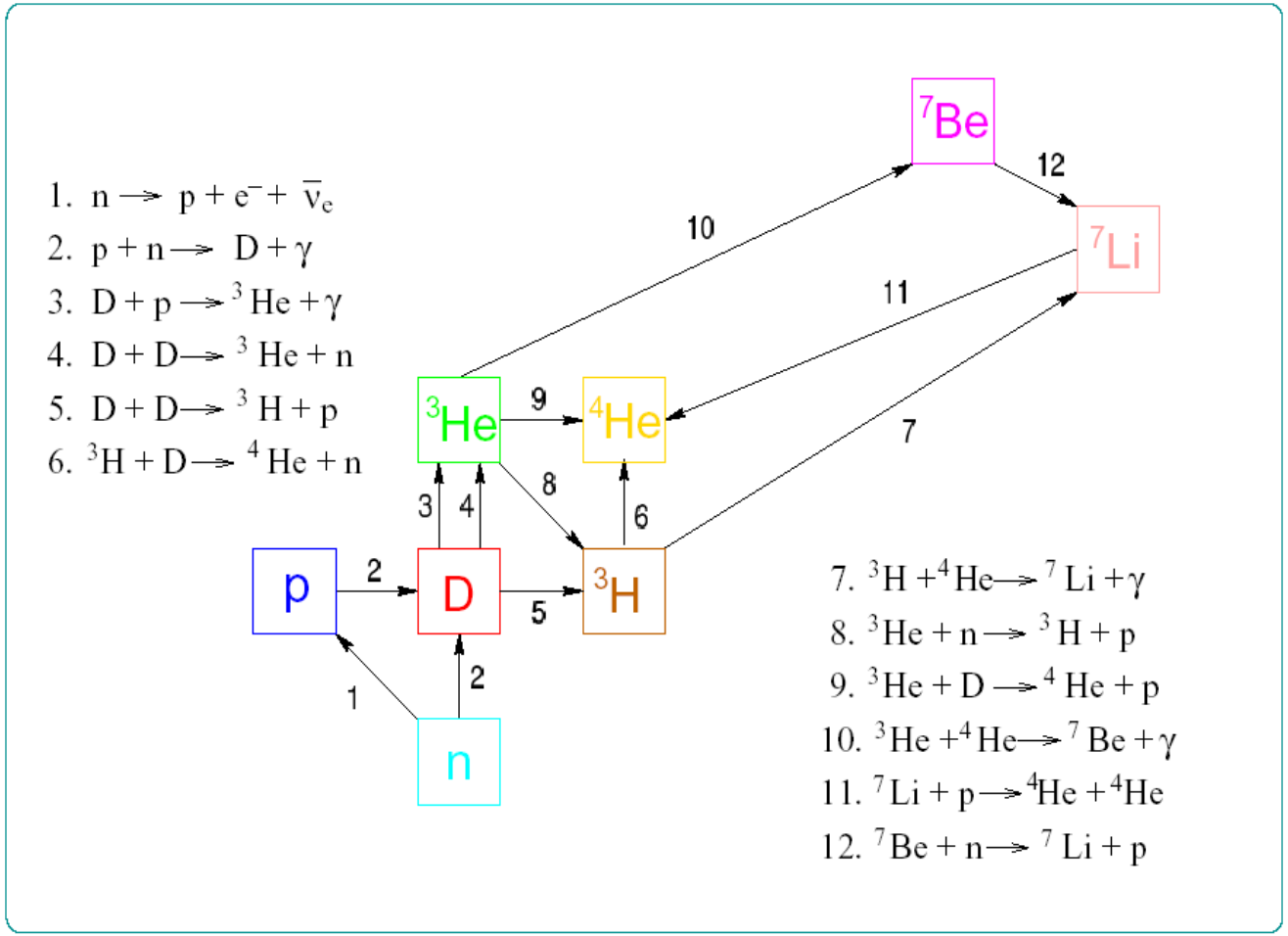
Recombination

→ more transparent Universe

→ matter and radiation no longer interact closely

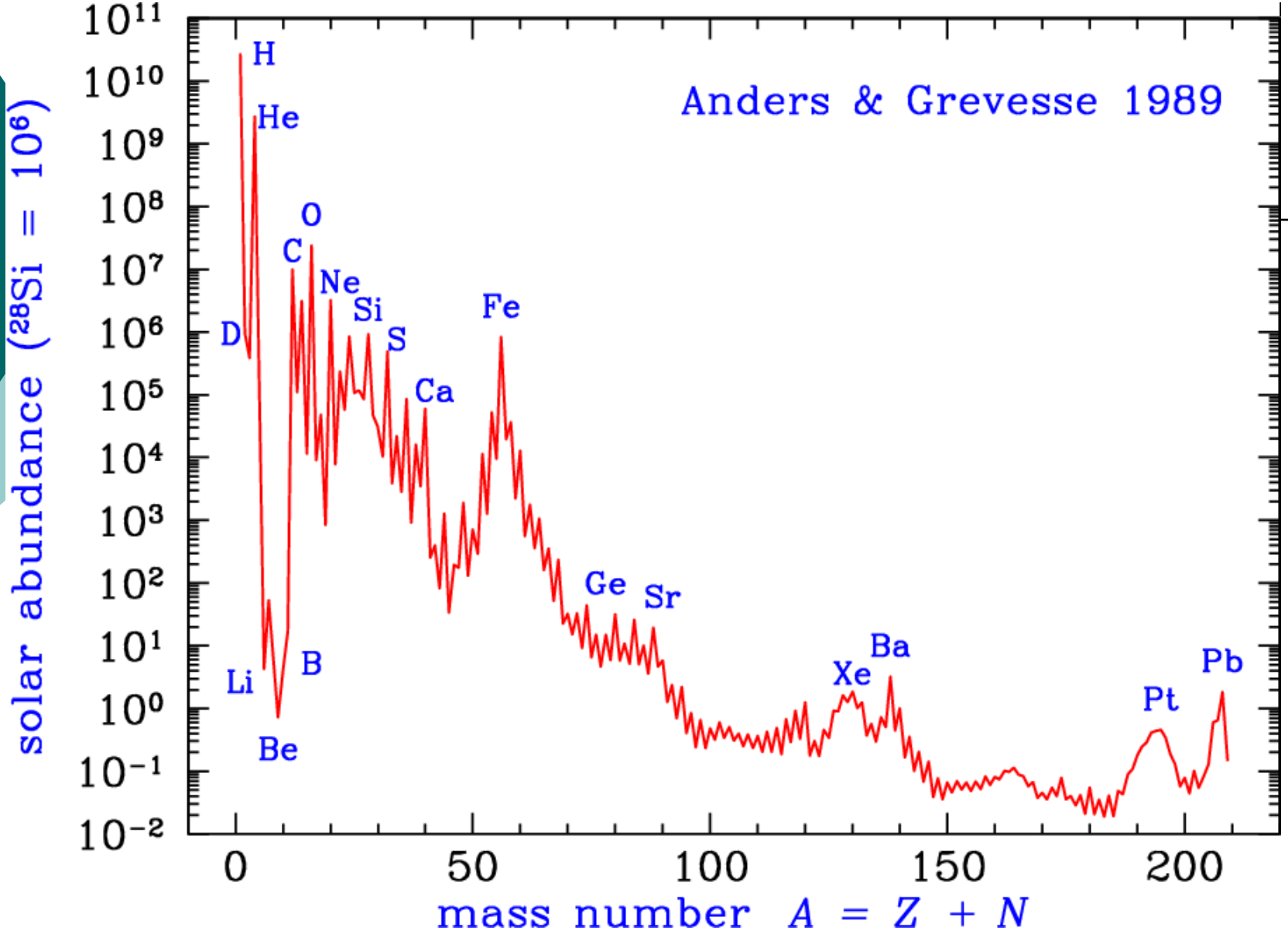
→ temperature of matter and temperature of radiation evolve separately

Photons which existed as the Universe became transparent then continued to travel through the Universe, little affected by matter.



Improved analysis of

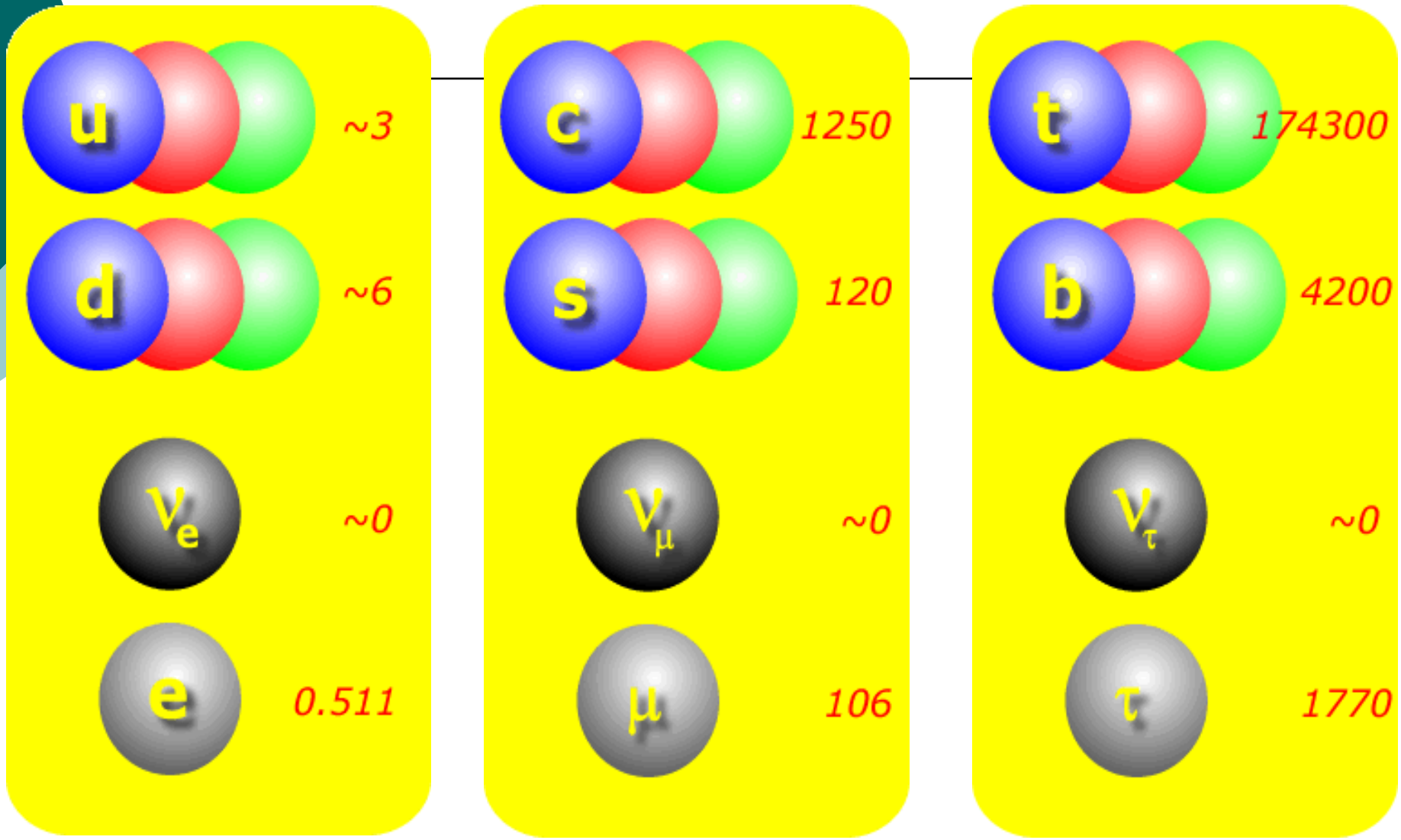
$^4He(d,\gamma)^6Li$, $^6Li(p,^3He)^4He$, $^3H(p,\gamma)^4He$, $^7Li(p,\gamma)^4He^4He$, $^7Be(n,\alpha)^4He$, $^7Li(d,n)^4He^4He$, $^7Be(d,p)^4He^4He$



Распространенность нуклидов в первичной солнечной туманности по отношению к содержанию кремния, принятого за 10^6.

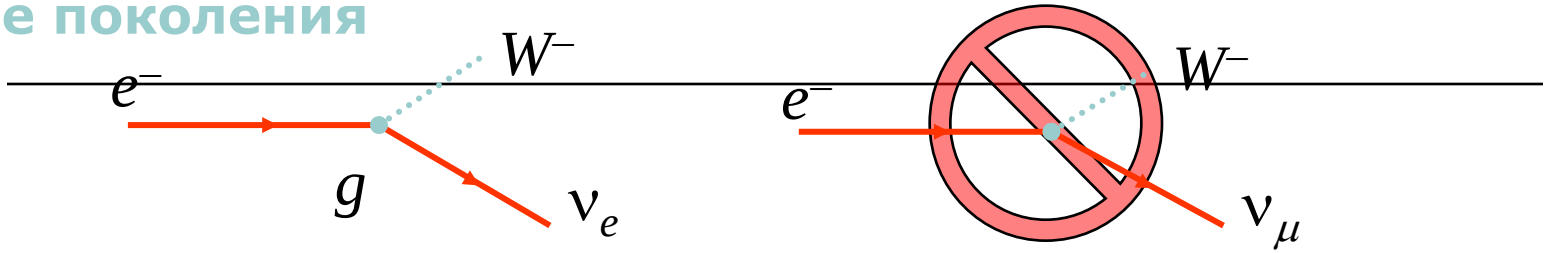
Стандартная модель

Three families: 1897-2000



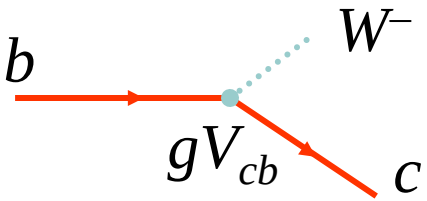
Particle masses in MeV; 1 MeV ≈ 1.8×10^{-27} gram

Лептоны могут переходить в другие лептоны только из того же поколения



- **Кварки могут переходить в другие кварки из любого поколения**

$$L_{\text{int}}^{CC} = -\frac{g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^\mu \hat{V}_{CKM}\begin{bmatrix} d_L \\ s_L \\ b_L \end{bmatrix} W_\mu^+ + h.c.$$



- **Матрица Кабиббо-Кобаяши-Маскавы (ККМ)**

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Смешивание кварков

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

Электро-слабые собств. сост.

Массовые собств. сост.

Neutron decay and Standard Model

CKM mixing matrix:

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

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

Δ=0 for Standard Model

$$|V_{ub}|^2 \sim 2 \cdot 10^{-5}$$

$$V_{ud} = \cos\theta_c$$

$$V_{us} = \sin\theta_c$$

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

$$G_V = G_F \cdot V_{ud}$$

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

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

Required experimental accuracy for τ_n and A has to be about 10^{-3} and better.

The best results for neutron lifetime

N beam:

- 886.8±1.2±3.2 (NIST, 2003)
- 889.2±4.8 (Sussex-ILL 1995)

UCN storage in material trap:

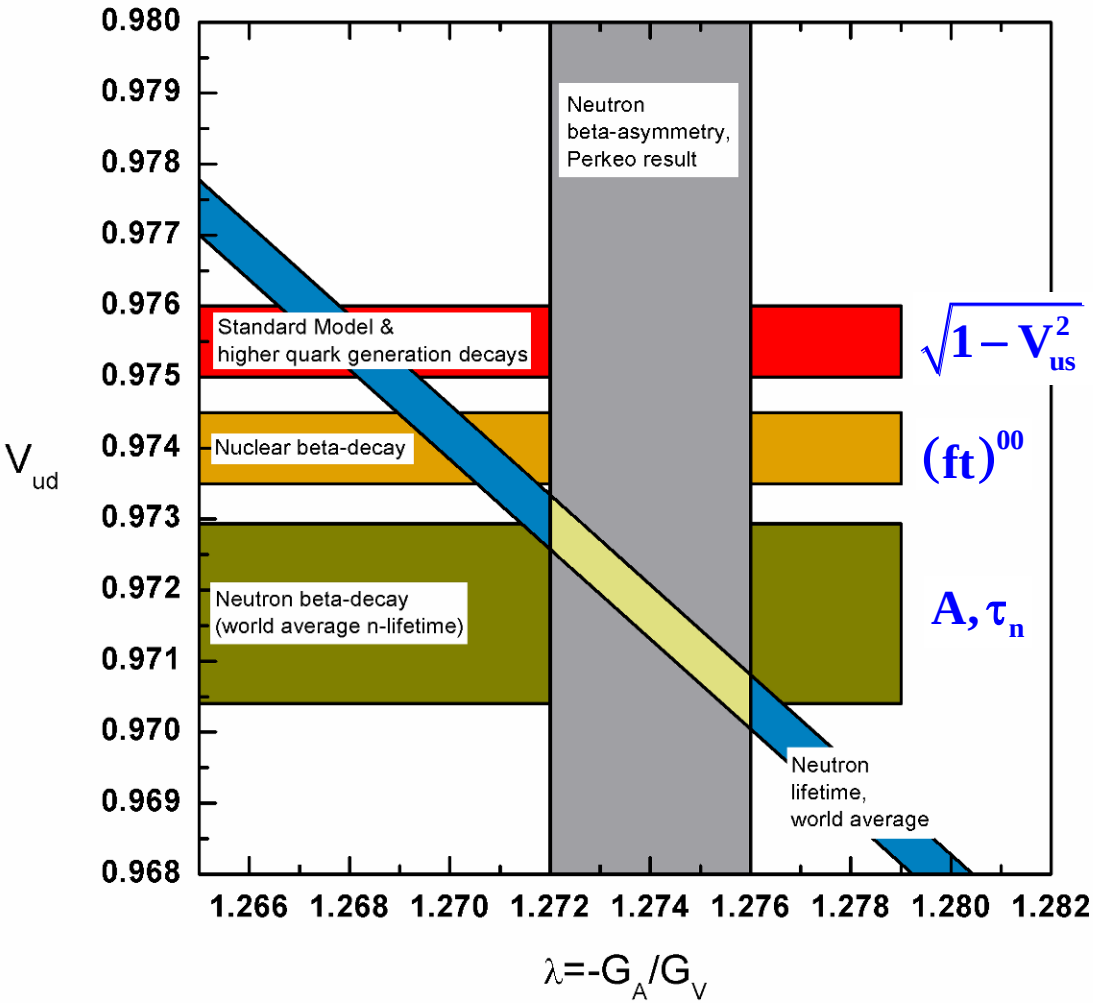
- 878.5±0.7± 0.3 (PNPI-ILL,2004)
- 885.4±0.9±0.4 (KI-ILL, 1997)
- 882.6±2.7 (KI-ILL, 1997)
- 888.4±3.1±1.1 (PNPI, 1992)
- 887.6±3.0 (ILL, 1989)

Particle data 2003
(without PNPI - ILL,2004):
τ_n = (885.7±0.8) s

$$\eta_{10} = N_b / N_\gamma$$

Variation in neutron lifetime by 1% changes η by 17%, although the modern accuracy of estimation of this quantity amounts to ±3.3%

Neutron decay and Standard Model (status in 2003)



$A=-0.1189(8)$ PERKEO 2002

$\tau_n = 885.7 \pm 0.8$ s PDG(2003)

$^{n}V_{ud} = 0.9717(13)$

$^{00}V_{ud} = 0.9738(5)$

$V_{us} = 0.2196(23)$ PDG(2003)

$V_{ub} = 0.0036(9)$ PDG(2003)

$$\boxed{\left|{}^{n}V_{ud}\right|^2 + \left|V_{us}\right|^2 + \left|V_{ub}\right|^2 = = 1 - \Delta = 0.9924(28)}$$

$$\Delta = 0.0076(28) = 2.7\sigma$$

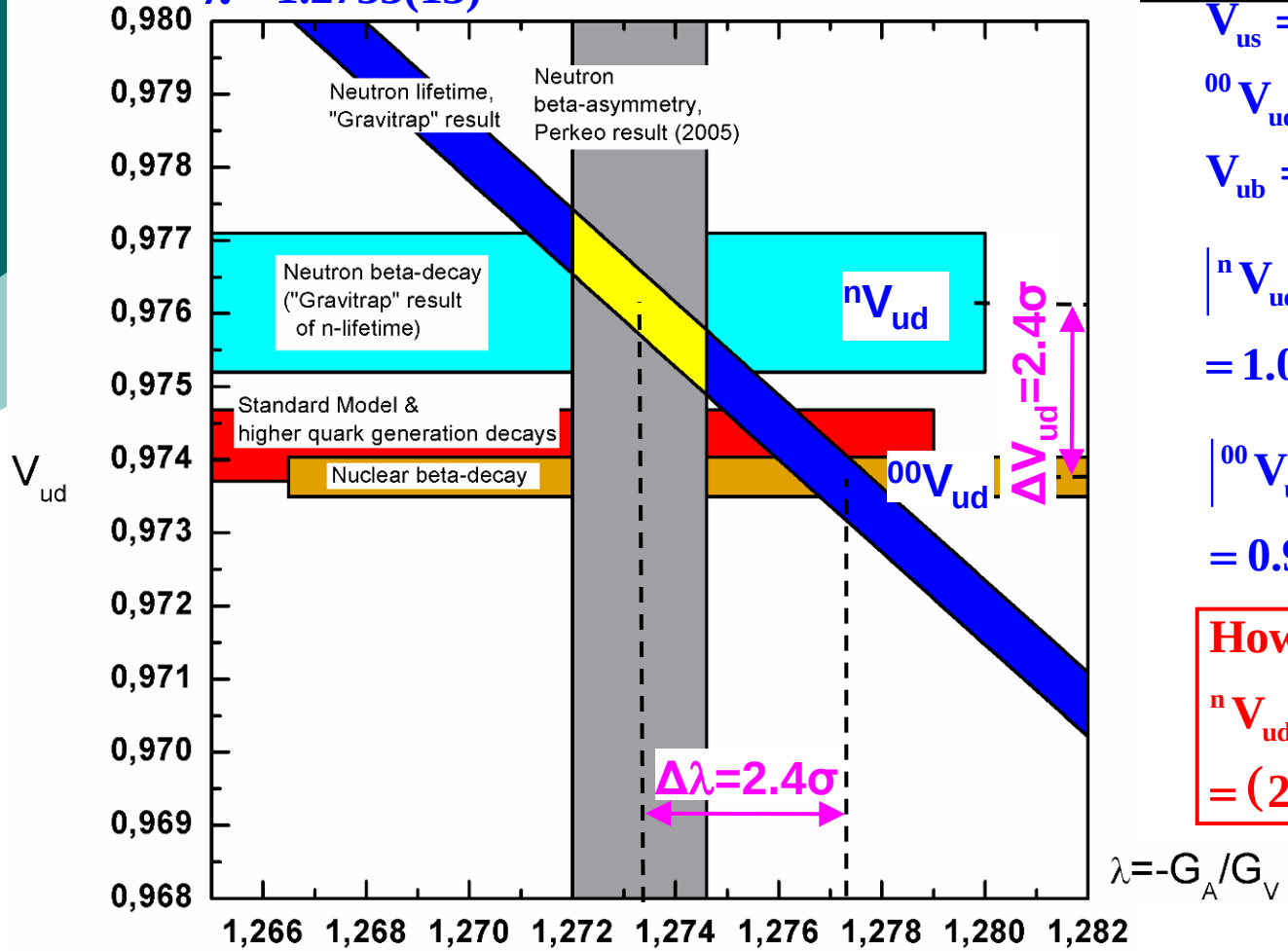
$$^{n}V_{ud} - {}^{00}V_{ud} = -0.0021(26) = = -0.8\sigma$$

Data analysis with the most precise measurements of neutron decay

$\tau_n = 878.5 \pm 0.8$ s (A.Serebrov et al. 2005)

A=-0.1187(5) (PERKEO 2005)

λ=-1.2733(13)



$^{n}V_{ud} = 0.97614(95)$

$V_{ud} = \sqrt{1 - V_{us}^2} = 0.97420(47)$

$V_{us} = 0.2257(21)$ PDG06

$^{00}V_{ud} = 0.97377(27)$ PDG06

$V_{ub} = 0.0043(3)$ PDG06

$$\left|{}^{n}V_{ud}\right|^2 + \left|V_{us}\right|^2 + \left|V_{ub}\right|^2 =$$

$$= 1.0038(28) \quad \Delta = -1.4\sigma$$

$$\left|{}^{00}V_{ud}\right|^2 + \left|V_{us}\right|^2 + \left|V_{ub}\right|^2 =$$

$$= 0.9992(15) \quad \Delta = +0.5\sigma$$

However

$$^{n}V_{ud} - {}^{00}V_{ud} =$$

$$= (2.4 \pm 1.0) \cdot 10^{-3}$$

2.4σ

The improvement of the accuracy of A-measurements (factor of 3 or more) is extremely important.

Magnetic storage - why it's interesting?

Previous neutron lifetime measurements

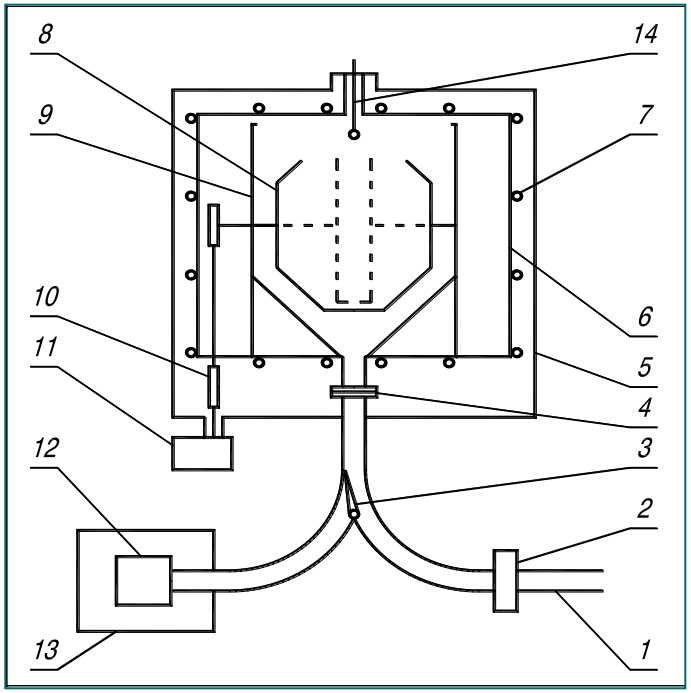
Beam measurements

Accurate absolute measurements of flux and decay products

2. UCN Storage measurement

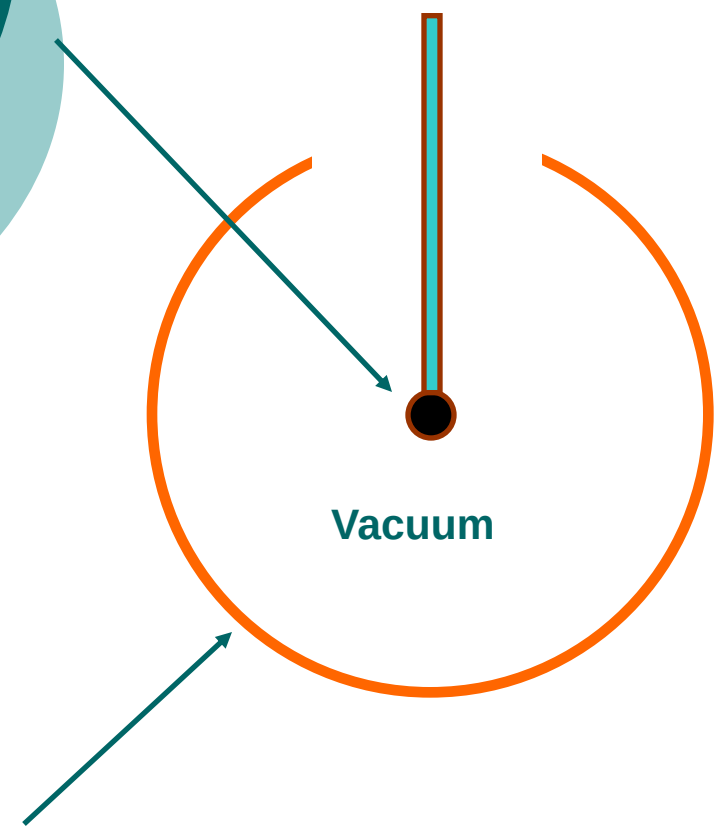
Storage losses?

Scheme of “Gravitrap”, the gravitational UCN storage system



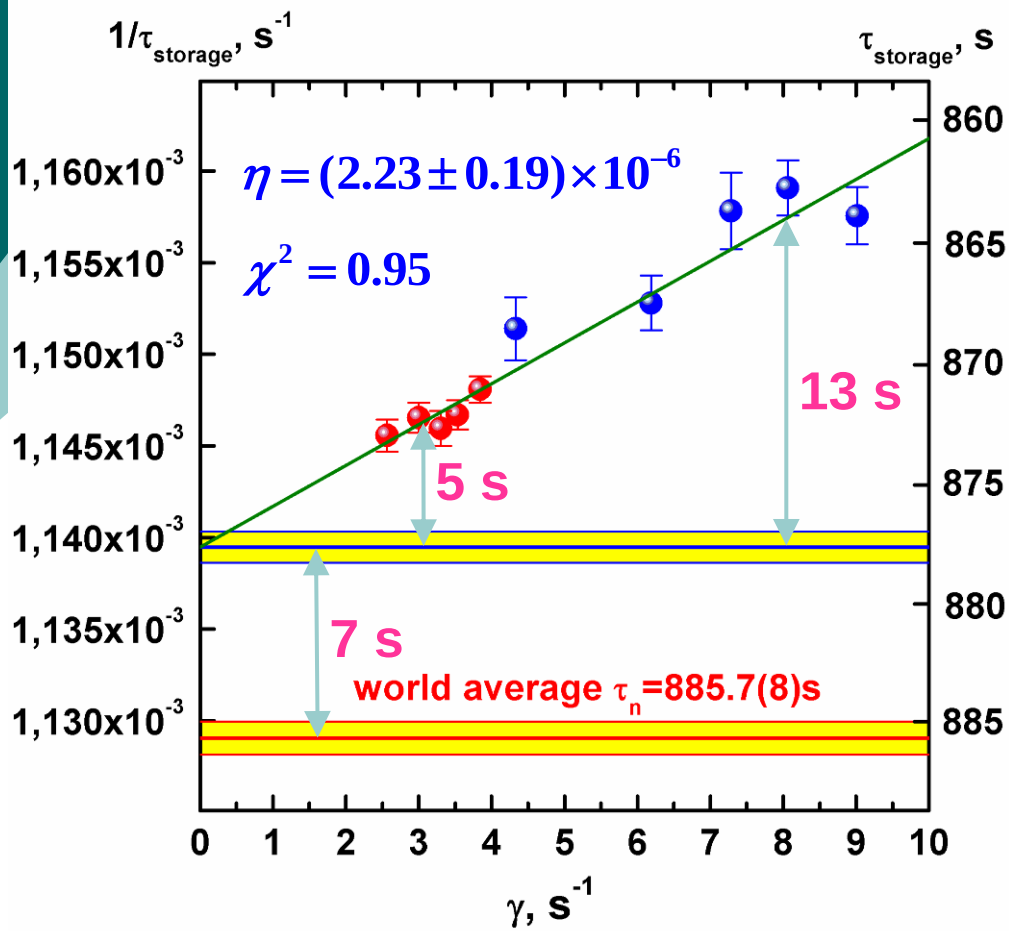
-
- 1 – neutron guide from UCN Turbine;
- 2 – UCN inlet valve;
- 3 – beam distribution flap valve;
- 4 – aluminium foil (now removed);
- 5 – “dirty” vacuum volume;
- 6 – “clean” (UHV) vacuum volume;

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

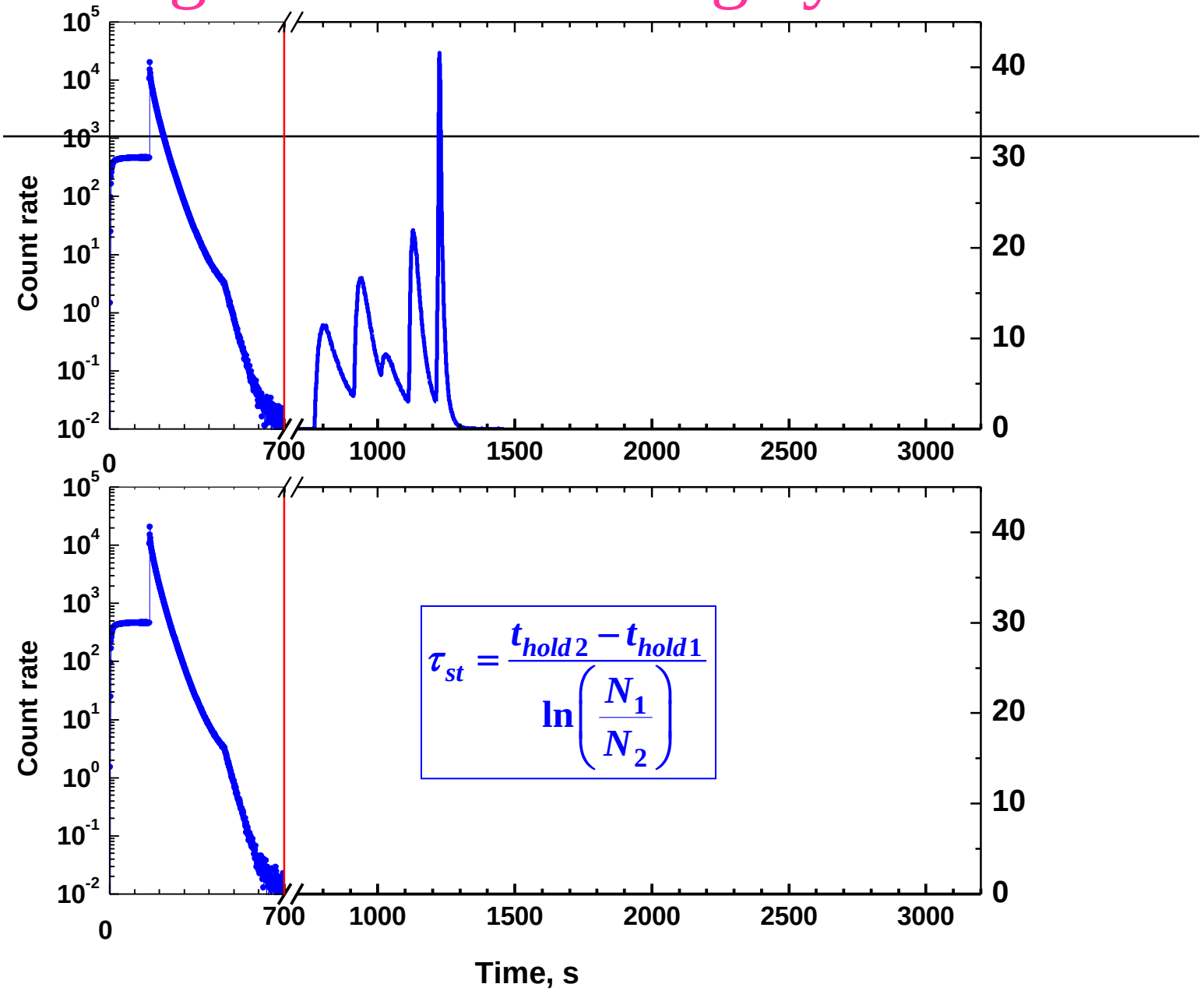
Extrapolation to n- lifetime
(joint energy and size extrapolation)



- The result of joint (size and energy) extrapolation: $\tau_n^{J} = 877.60 \pm 0.65\ s$
- The result of energy extrapolation: $\tau_n^{E} = 875.55 \pm 1.60\ s$
- The result of size extrapolation: $\tau_n^{S} = 878.07 \pm 0.73\ s$
- Size extrapolation has rather weak dependence on μ(E) and we take it as the most reliable.

The most close extrapolation to neutron lifetime (5 s only) is reached in this experiment!

Time diagram of measuring cycle



$$\tau_{st} = \frac{t_{hold\,2} - t_{hold\,1}}{\ln\left(\frac{N_1}{N_2}\right)}$$

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

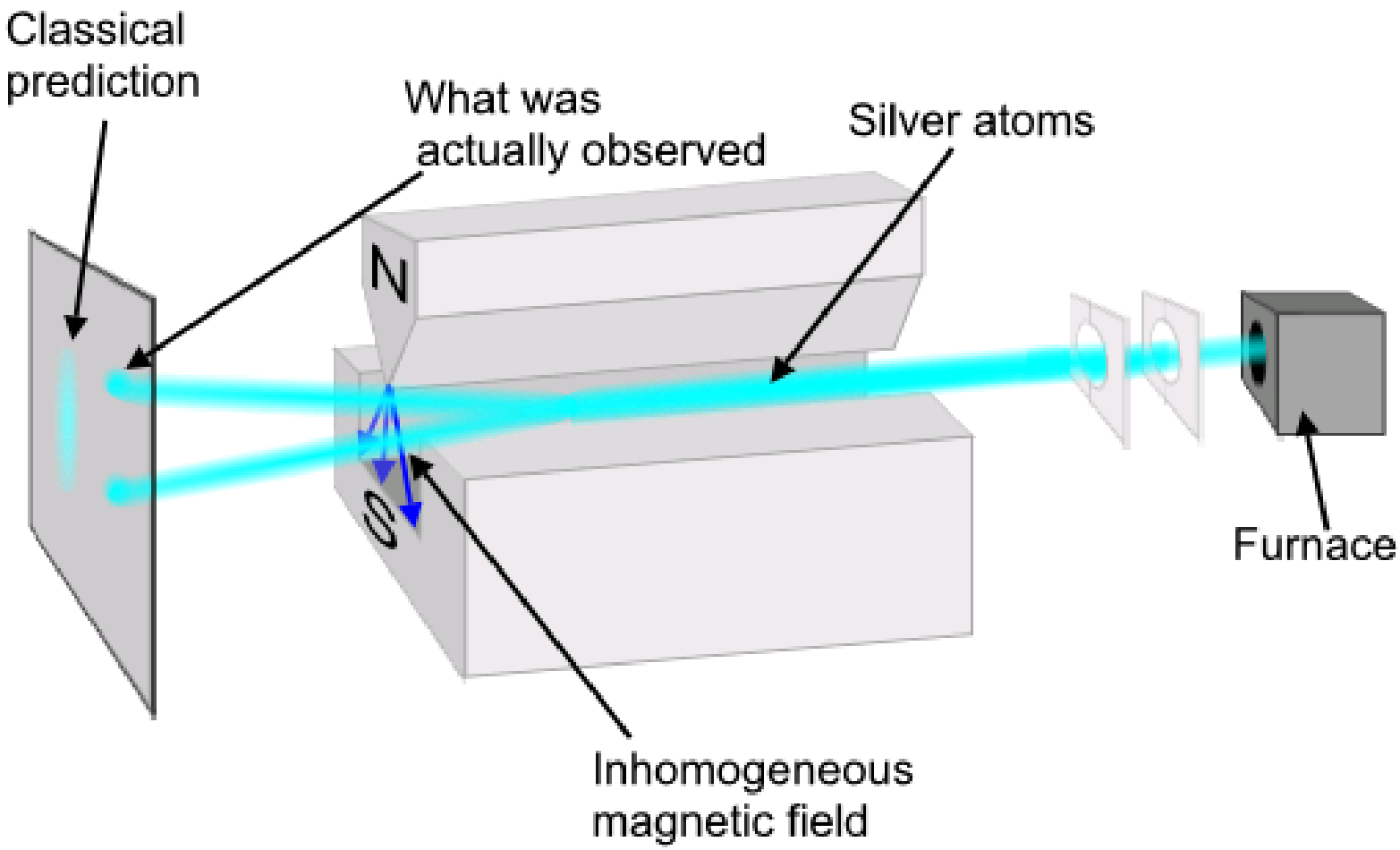
For magnetic moment of neutron $U = 60 neV \cdot T^{-1}$

Nuclear potential of Be $250 neV$

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

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

Atomic Magnetic moment in inhomogeneos magnetic field. 1922 – Stern and Gerlach



PROCEEDINGS OF THE

International Conference

Nuclear Physics

and the

Physics of Fundamental Particles

Report Edited by

Jay Orear
A. H. Rosenfeld
R. A. Schluter

September 17 to 22, 1951

IV B. NEUTRONS AND FISSION

Speaker: M. Paul

Topic: Magnetic Lens for Focusing Neutral Particles

Focusing occurs when the particles are subject to a force which is proportional to the displacement r from an axis passing through the source of particles, where the force is directed toward the axis. For particles with magnetic moment μ this can be achieved by use of a magnetic field which is subject to the equation

$$\mu \frac{dH}{dr} = \text{const. } x\ r\ .$$

An appropriate field is given by:

$$H_x = C(x^2 - y^2); \quad H_y = 2Cxy; \quad H_z = 0\ .$$

A good approximation to the required field is obtained by employing three pairs of magnetic poles distributed symmetrically about the z-axis. Focusing occurs for particles emitted within an angle θ with respect to the z-axis, where

$$\theta = (\mu H/kT)^{\frac{1}{2}}.$$

kT is the particle energy. For neutrons, choosing H = 20,000 gauss and T = 10^{0} K, one obtains θ = 1/60 radians. This is believed to be practicle for neutron focusing.

Probability of depolarization

- Precession of magnetic moment

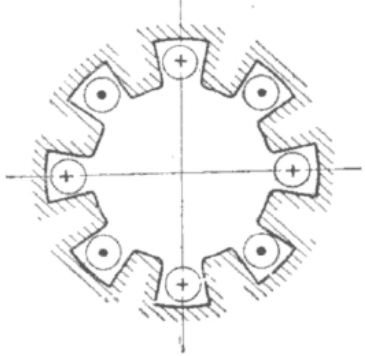
$$\frac{d\vec{\mu}}{dt} = \gamma_n \vec{\mu} \times \vec{B}$$

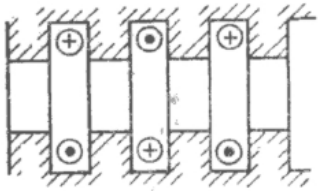
$$\gamma_n = 1.83 \cdot 10^8 \, s^{-1} T^{-1}$$

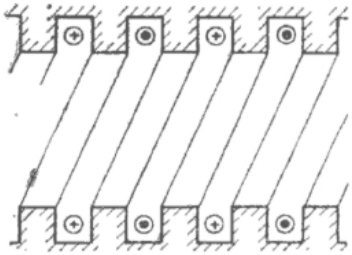
- Adiabatic condition

$$\gamma_n B >> \left(dB/dt\right)/B = v \cdot \nabla |B| / B$$

- (v -- is the velocity of neutron)
- For case of strong field
- (B = 1T), ∇B = 1T/mm and velocity v = 3.4 m/s one can receive next relation for adiabatic condition:
- $1.83 \cdot 10^8 >> 3.4 \cdot 10^3$.

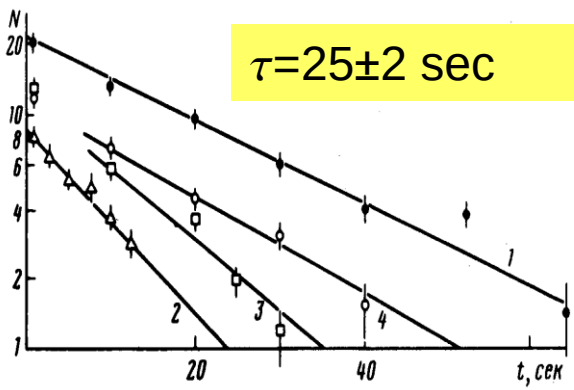






Vladimirskii, V.V. Magnetic mirrors, channels and bottles neutrons. Sov. Phys. JETP 12, 740-746, (1961)

“UCN storage in the vessel with magnetic wall.”
JETP Letters 23(3), 1976
Y.Y.Kosvintsev, Y.A.Kushnir, V.I.Morozov



τ=25±2 sec

Рис. 2. Зависимость числа УХН, оставшихся в сосуде, от времени хранения: *1* – торец сердечника покрыт медной фольгой, электромагнит отключен, *2* – торец сердечника покрыт полиэтиленом, электромагнит отключен, *3* – торец покрыт полиэтиленом, электромагнит включен, *4* – торец покрыт полиэтиленом, электромагнит включен, соленоид ведущего поля включен

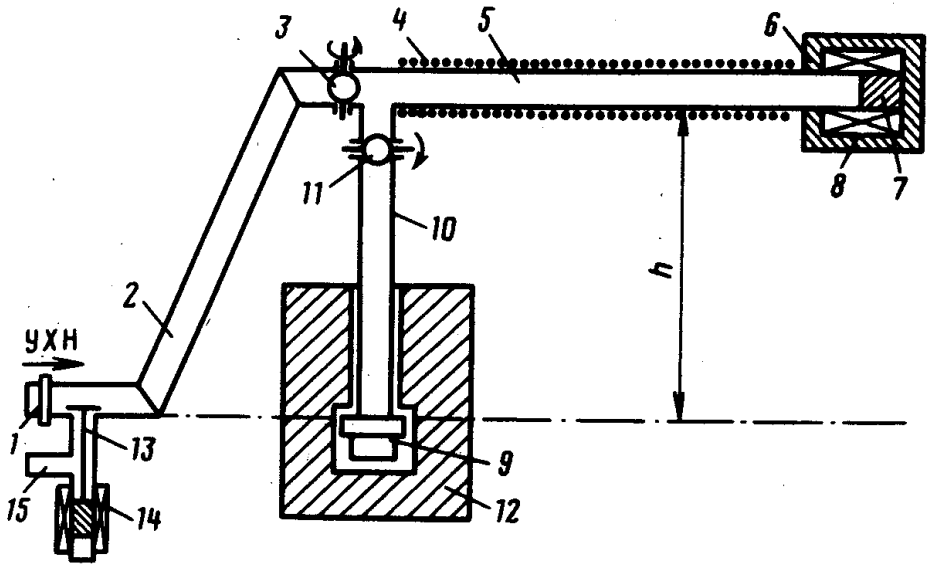


Рис. 1. Схема эксперимента по хранению УХН в сосуде с магнитной "ст... ко": *1* – выходной патрубок установки для извлечения УХН, *2* – наклонный нейтроновод, *3* – впускная заслонка, *4* – соленоид ведущего поля, *5* – сосуд для хранения УХН; *6* – панцирь электромагнита, *7* – сердечник электромагнита,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

Ю.Г.Абов,
Письма Ж

Y.G.Abov, V.V.Vasil'ev, V.V.Vladirski, I.B.Rozhnin
JETP Letters, 44(8), 369, (1986)

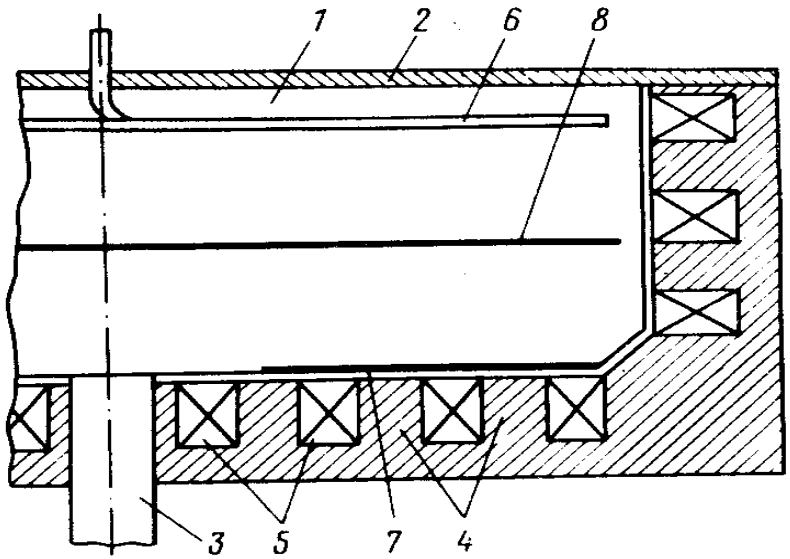


Рис. 1

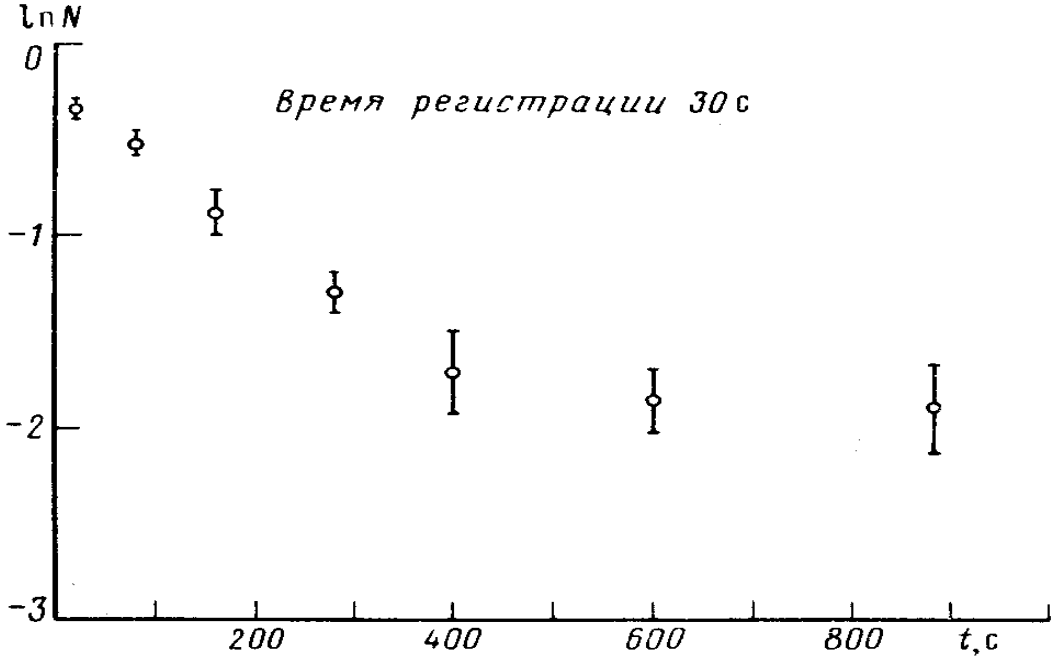


Рис. 2

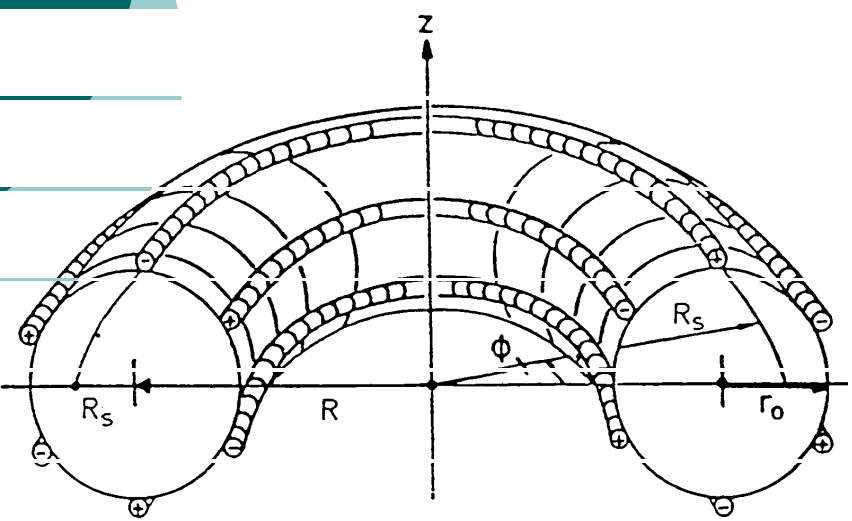
Рис. 1. Магн... еры, 3 – патрубок для инжекц... магнита, 6 – корректирующа... титель

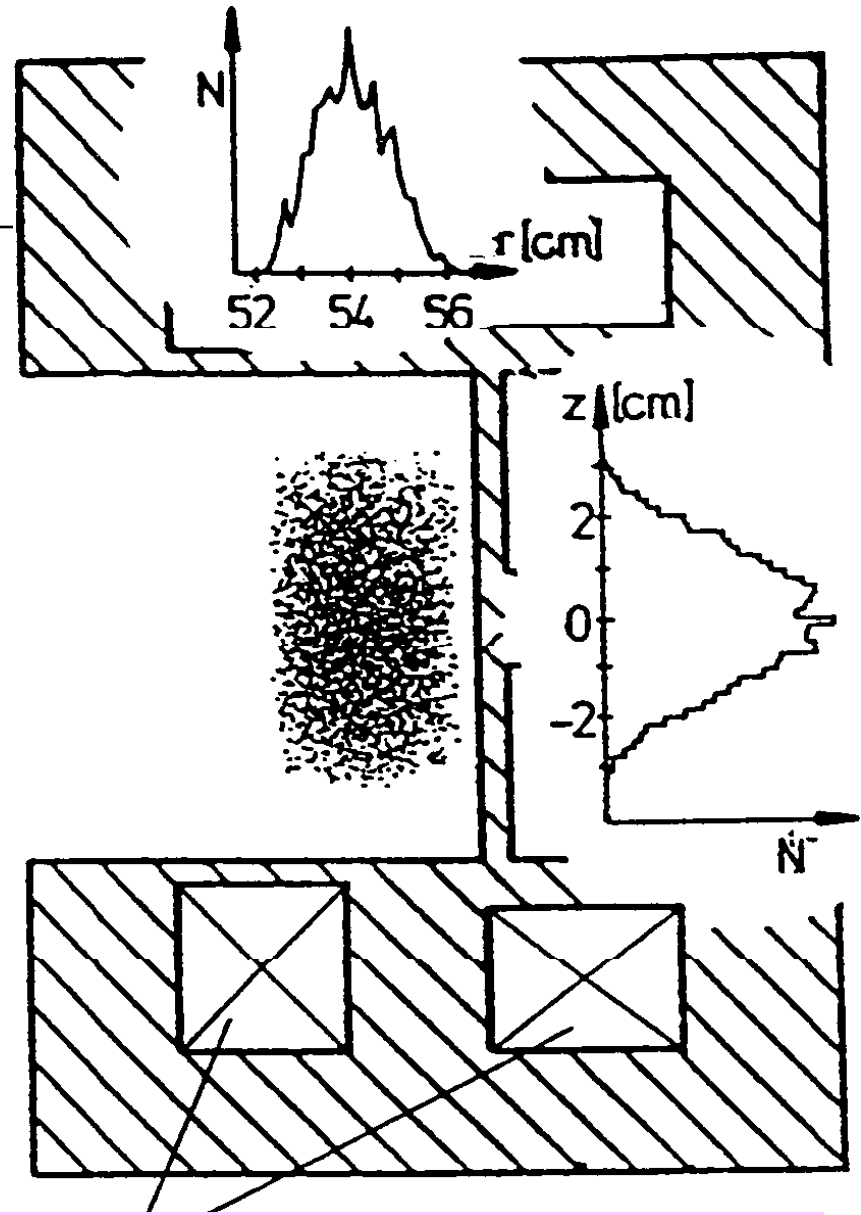
Main problem of the current systems is too large electric power (about 100 kWt)

Рис. 2. Зависимость количества нейтронов, оставшихся в ловушке после времени выдержки t и зареги-

Main result:
It was shown firstly that it's possible to obtain **τ > 700 sec** in the magneto-gravitational trap.

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



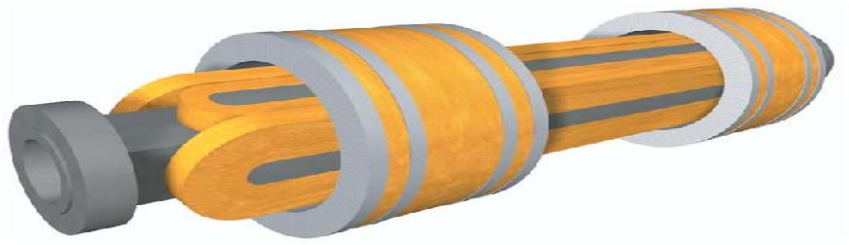


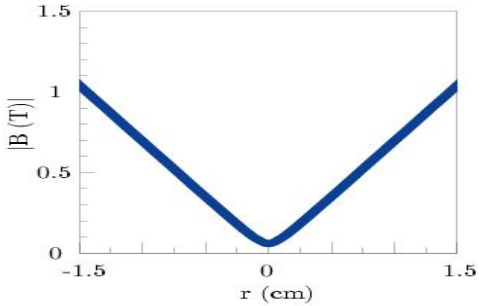
Sextupole torus. Rs orbit of circulating neutrons.

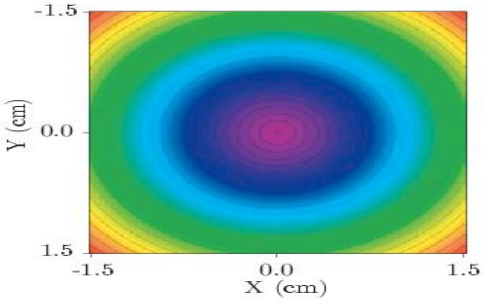
$\tau = 877 \pm 10$ s

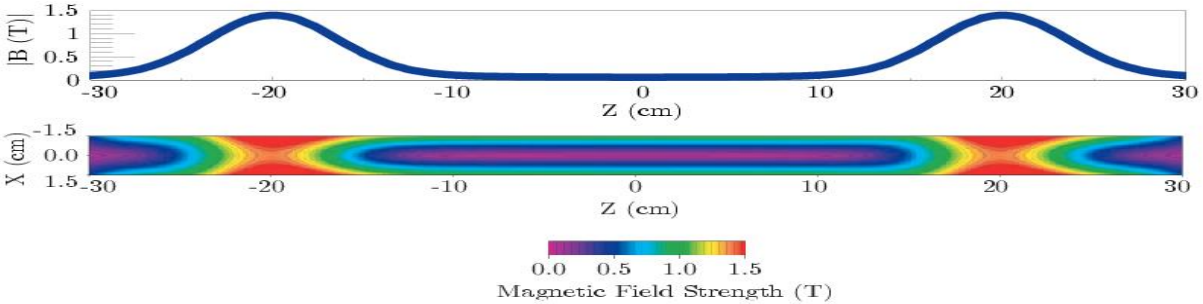
The achieved usable field of **3.5 T** permits the confinement of neutrons in the velocity range of 5 – 20 m/s corresponding to a kinetic energy up to 2 * 10-6 *eV.*

Ioffe-Type Magnetic Trap



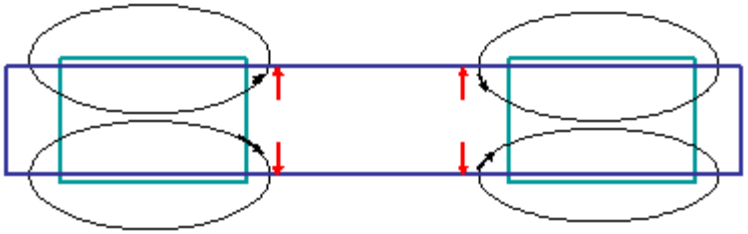




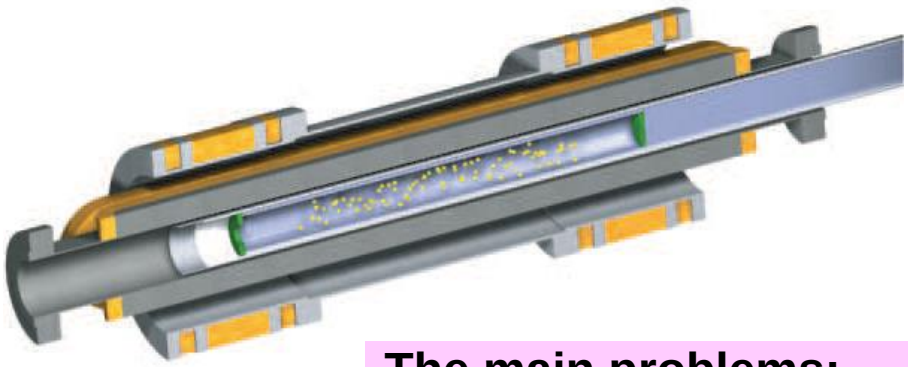


NIST

P. R. Huffman



P.R. Huffman, C.R. Brome, J. S. Butterworth, K. J. Coakle, M. S. Dewey, S.N. Dzhosyuk, R. Golub, G. L. Greene, K. Habicht, S.K. Lamoreaux, C.E.H. Mattoni, D.N. McKinsey, F. E. Wietfeldt, & J.M. Doyle
Nature **403**, 62, 2000



The main problems:

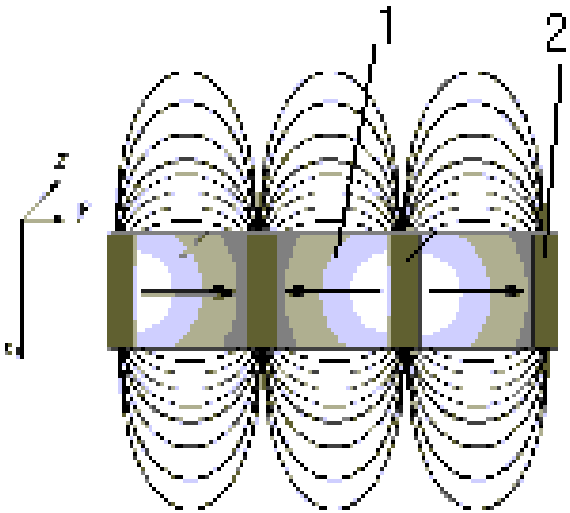
1. Filling and empting. If one use superconducting system, then he can't switch on field too fast.

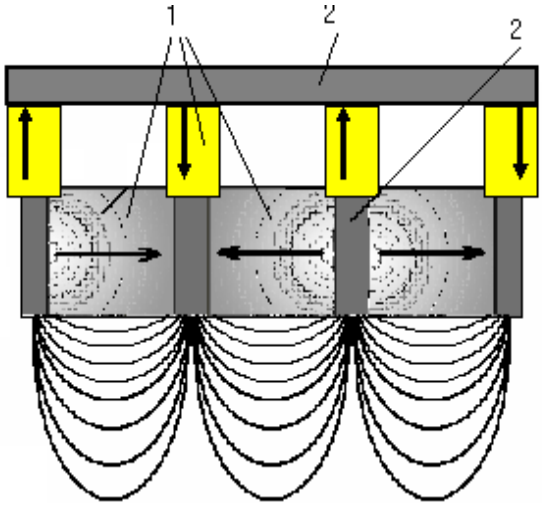
2. Huge setup and small storage volume

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

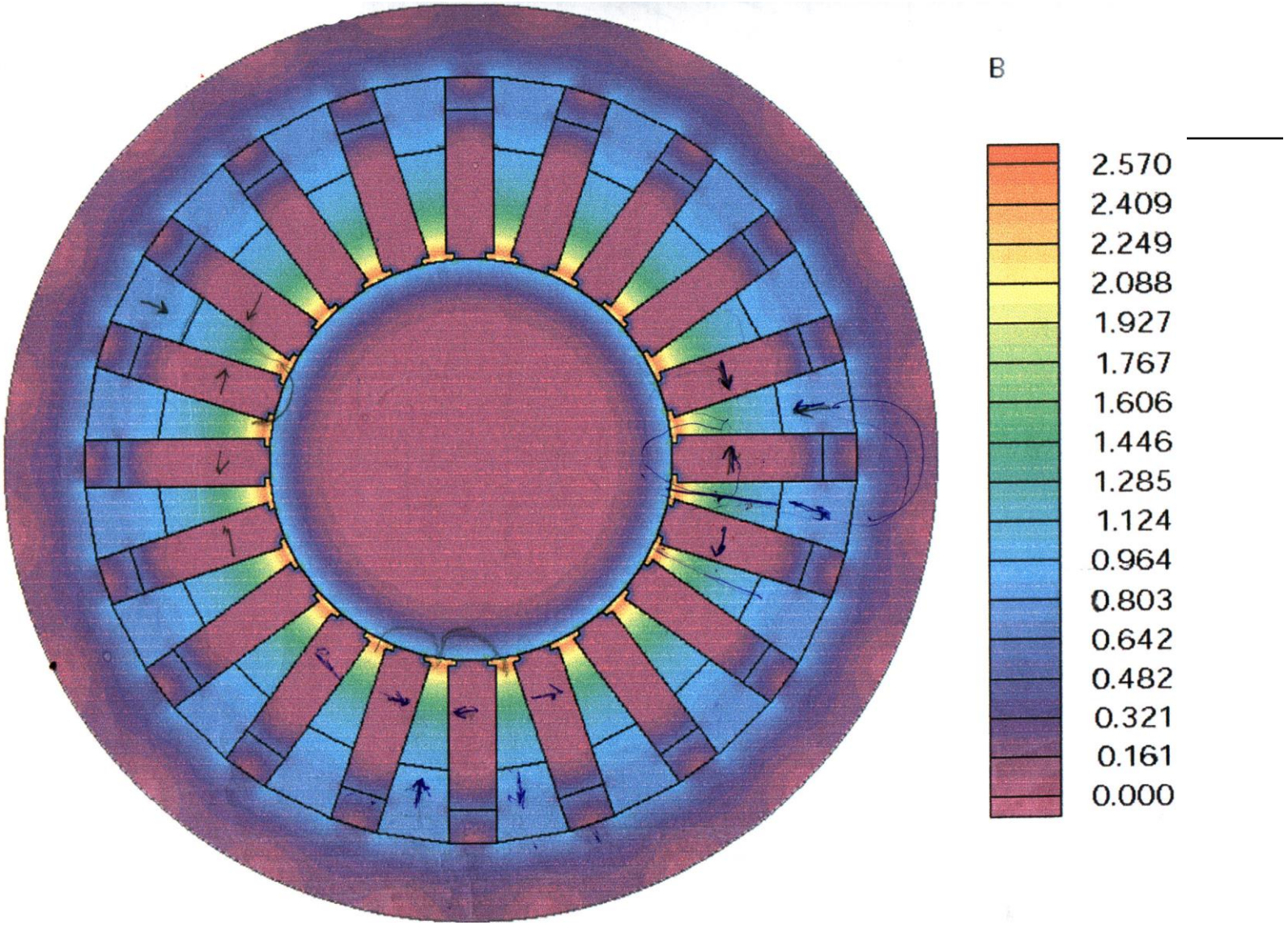
$$\tau = 750^{+330}_{-200}\ \text{s.}$$

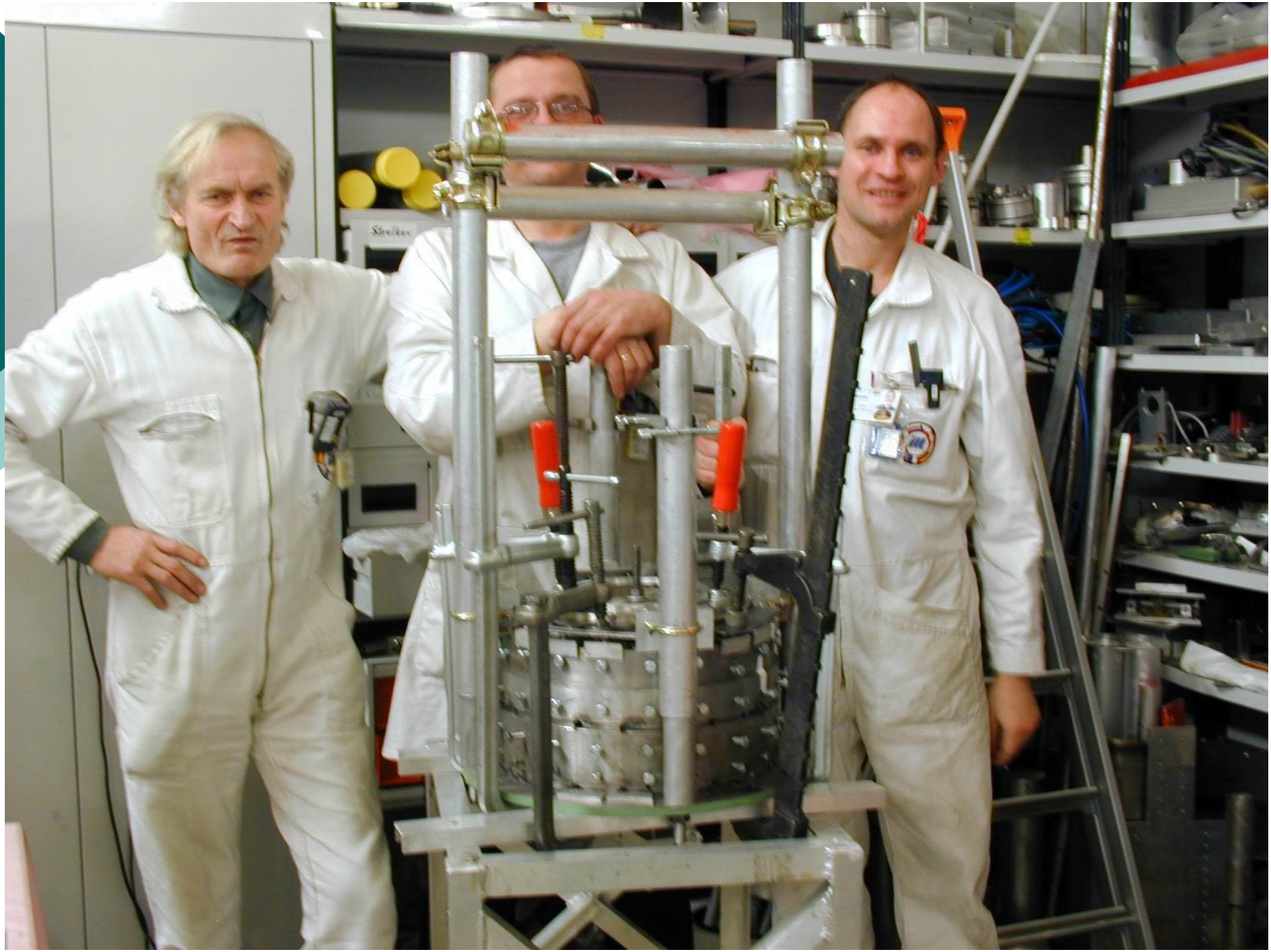
Magnetic wall



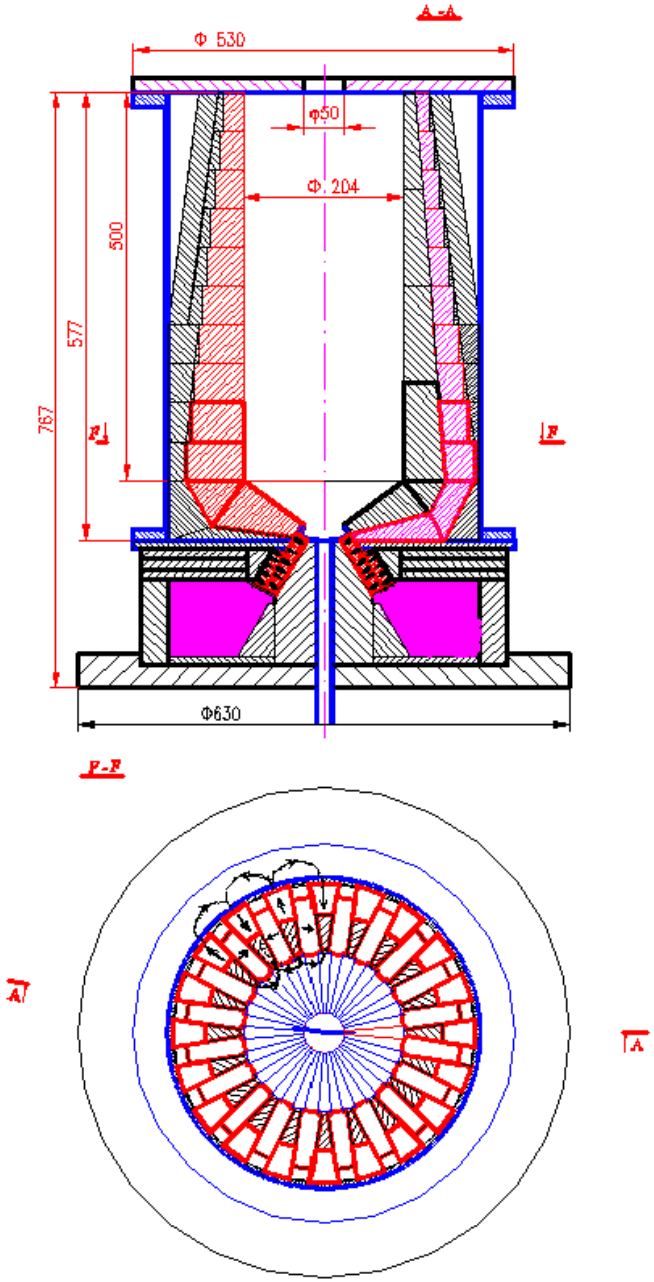


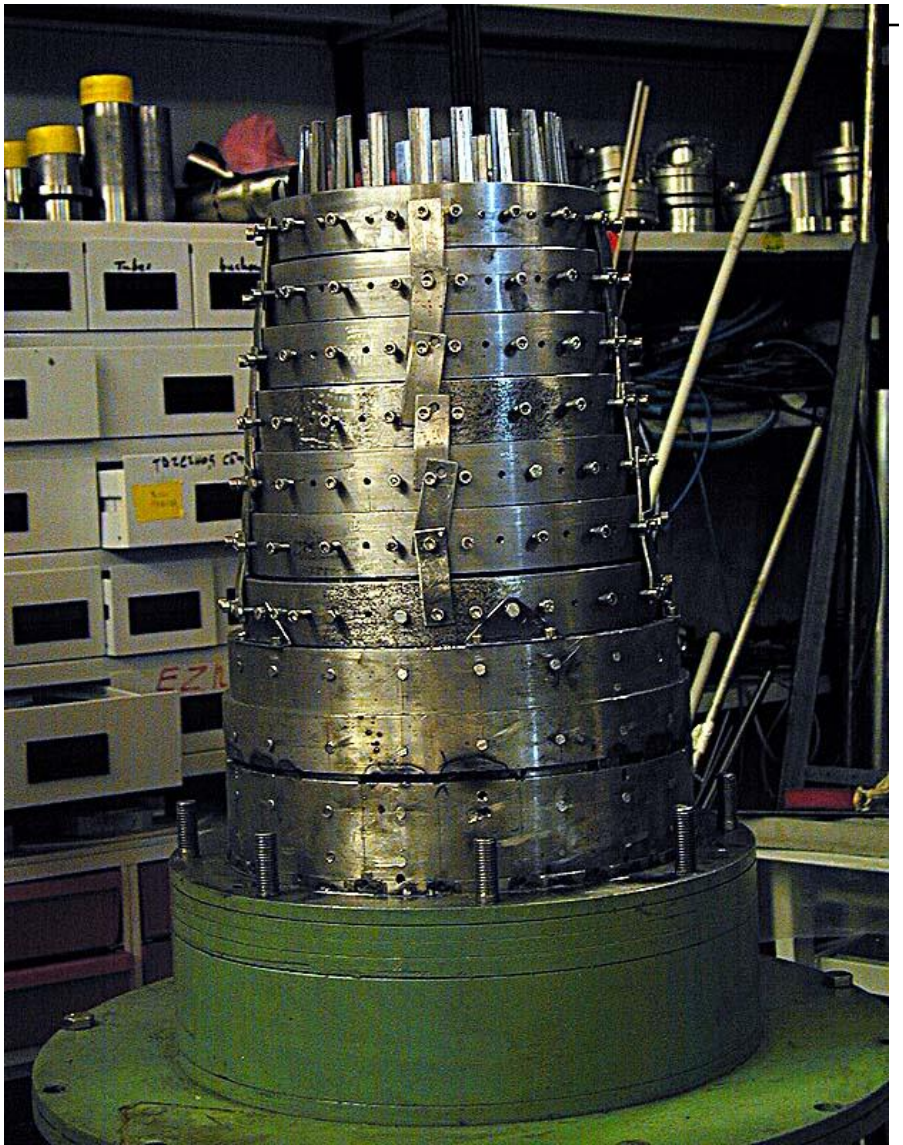
1 – permanent magnet
2 – magnetic field guide

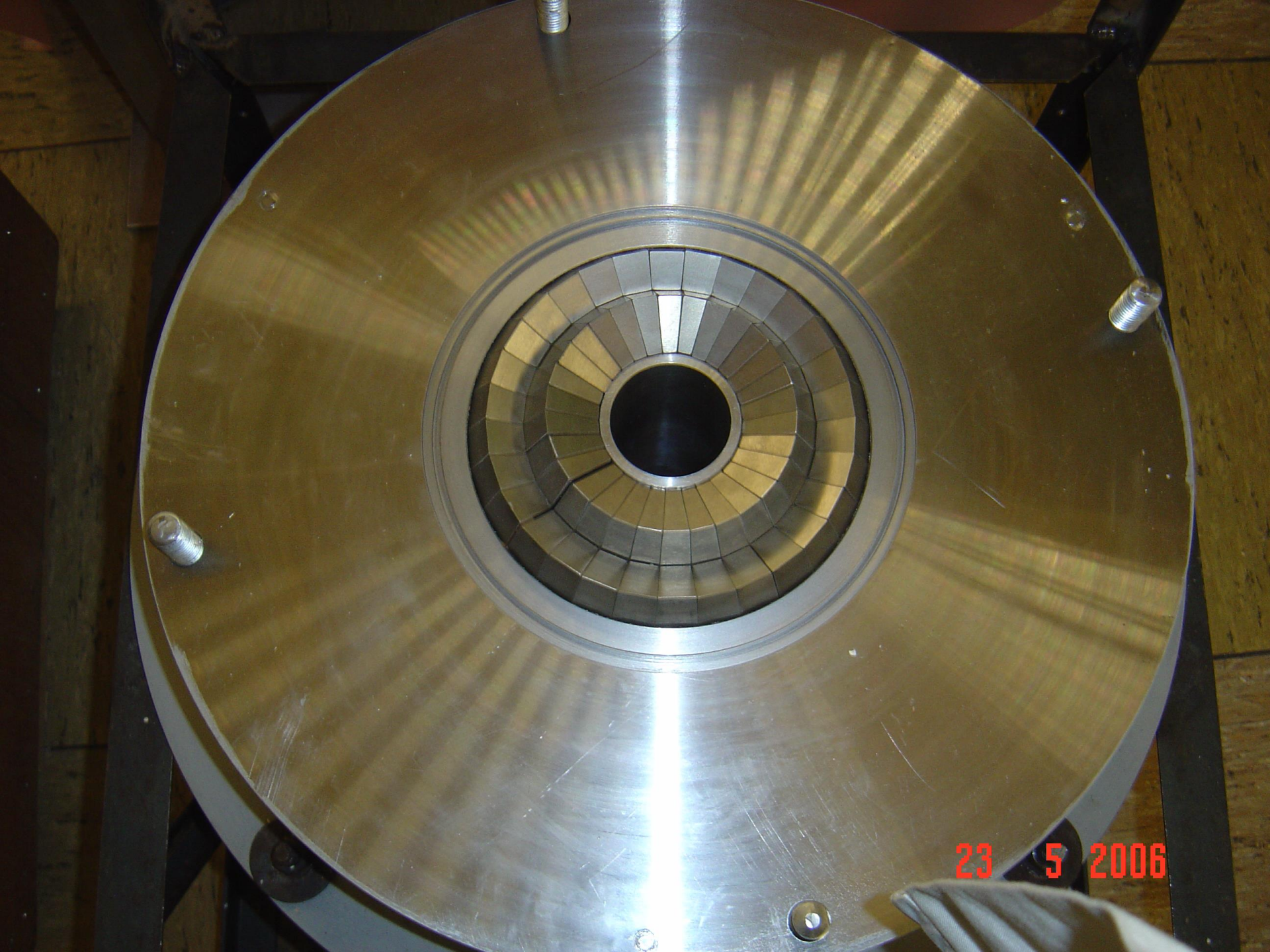

B
2.570
2.409
2.249
2.088
1.927
1.767
1.606
1.446
1.285
1.124
0.964
0.803
0.642
0.482
0.321
0.161
0.000

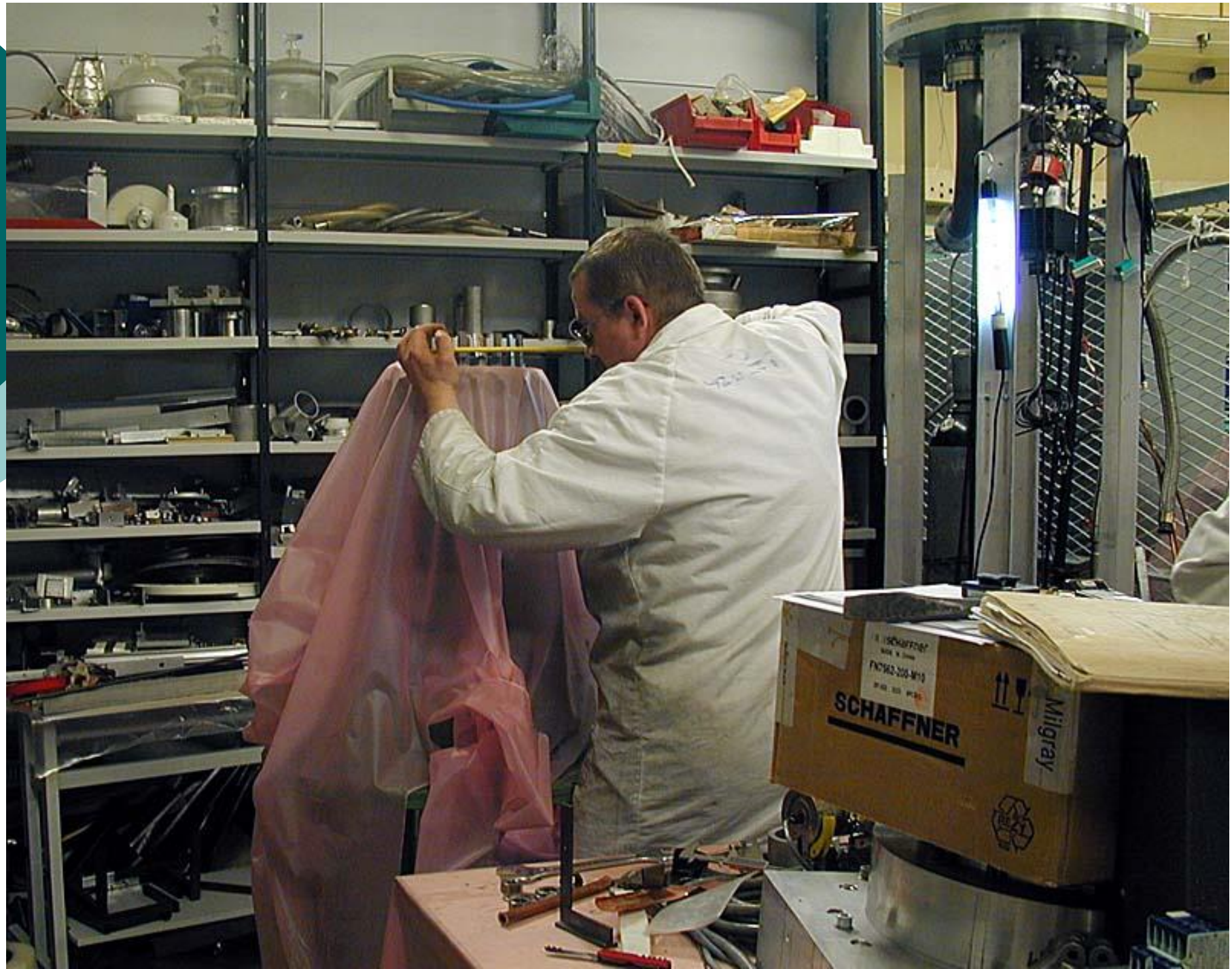


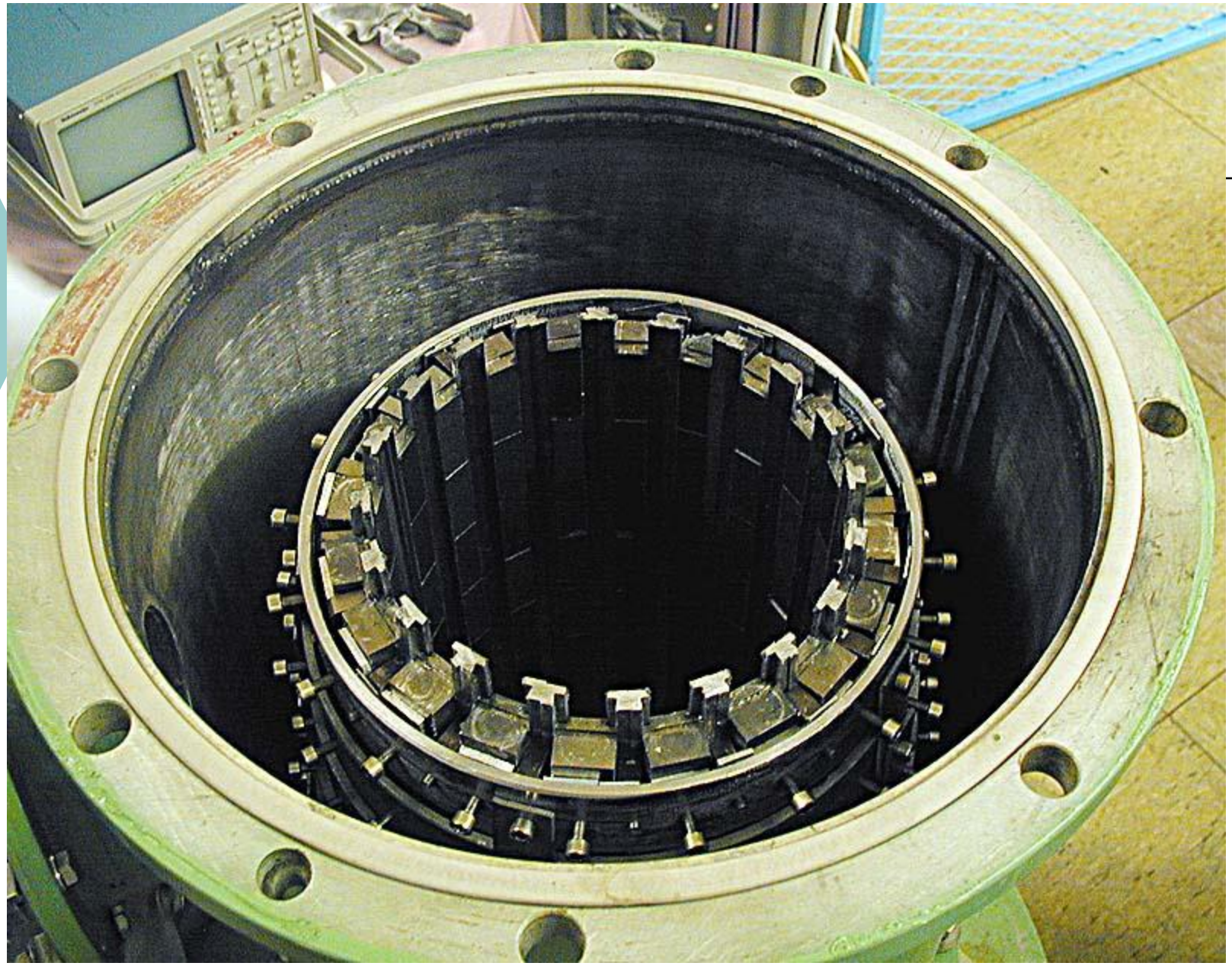
2004

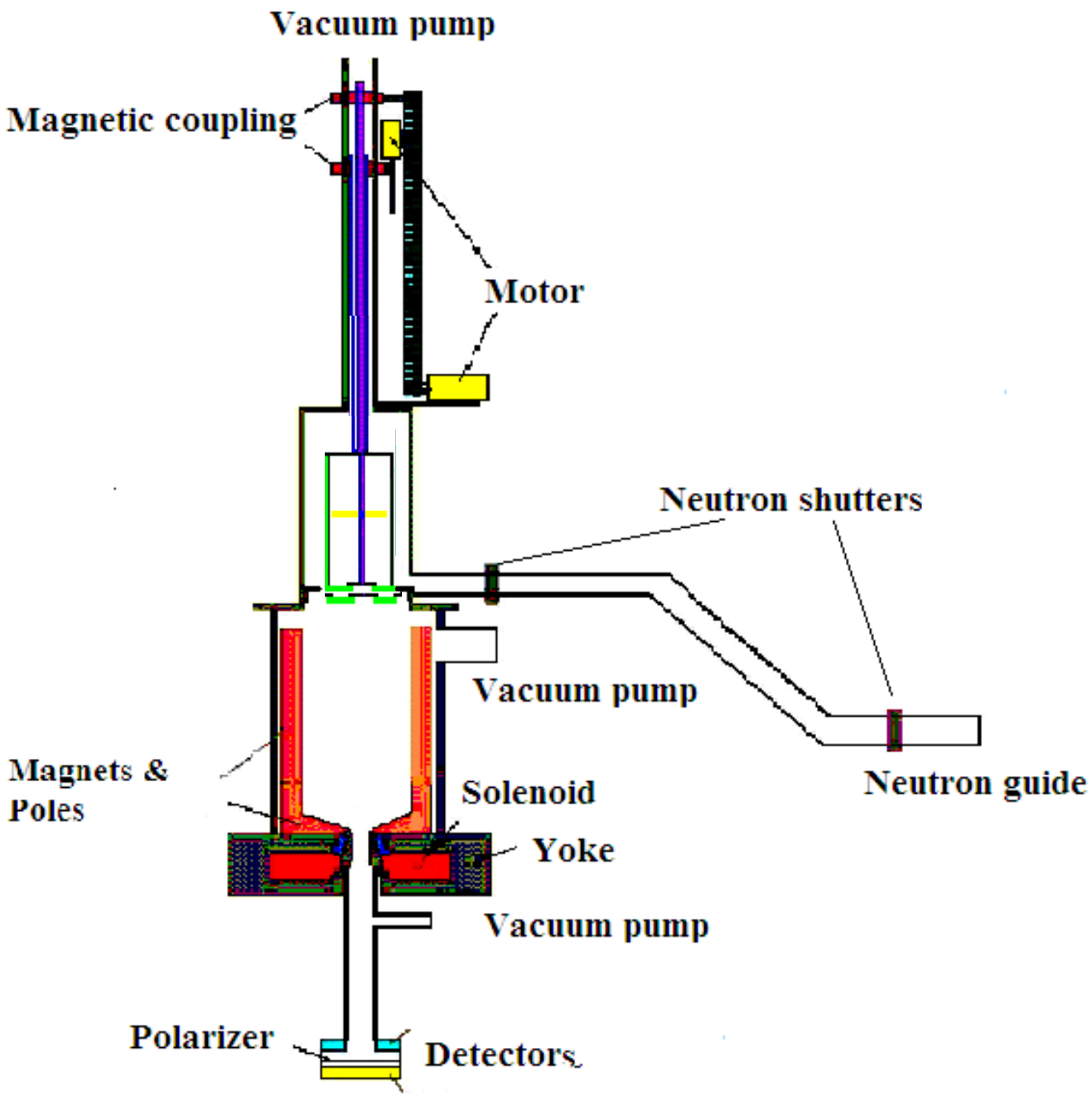


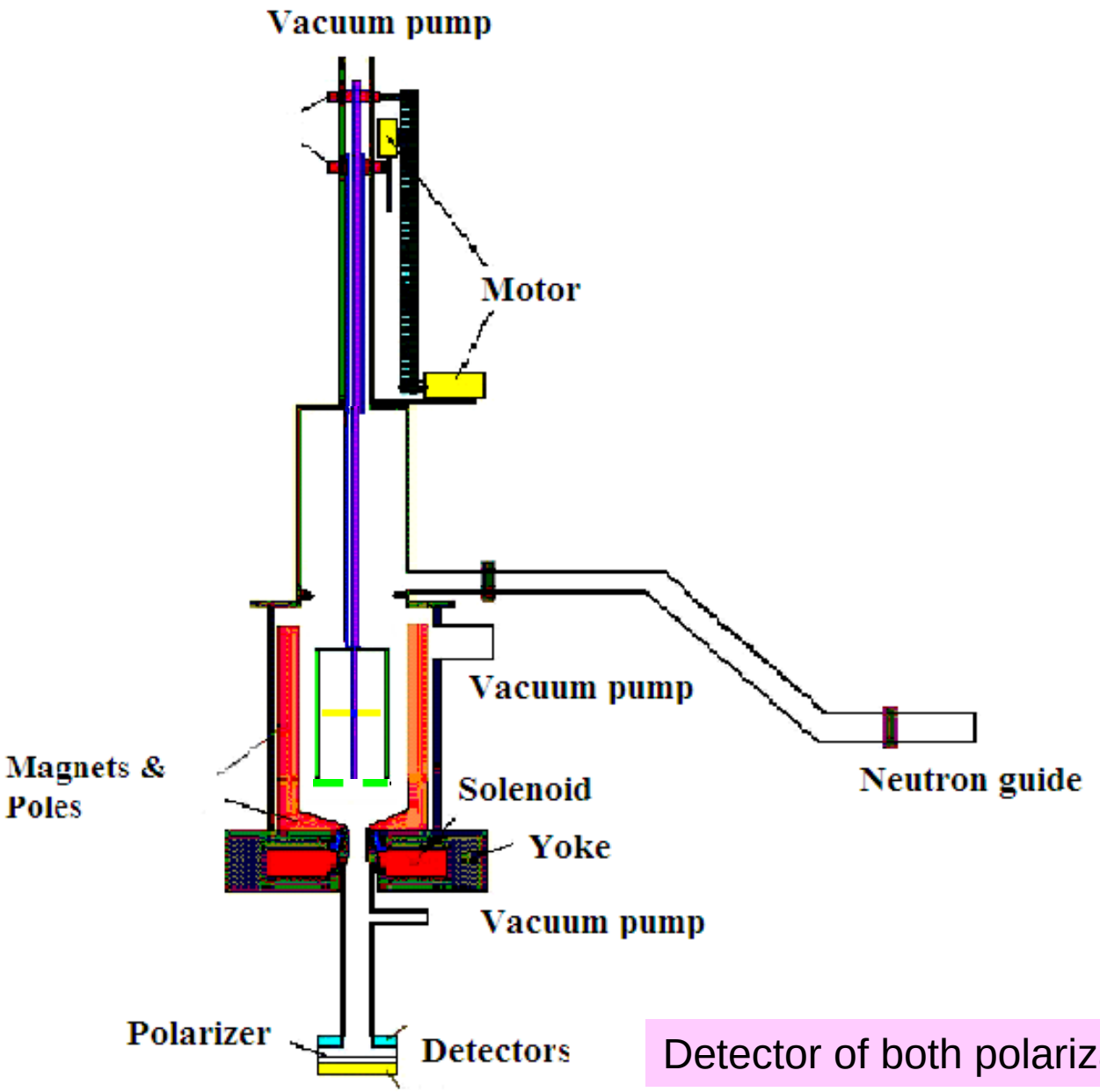



23 5 2006

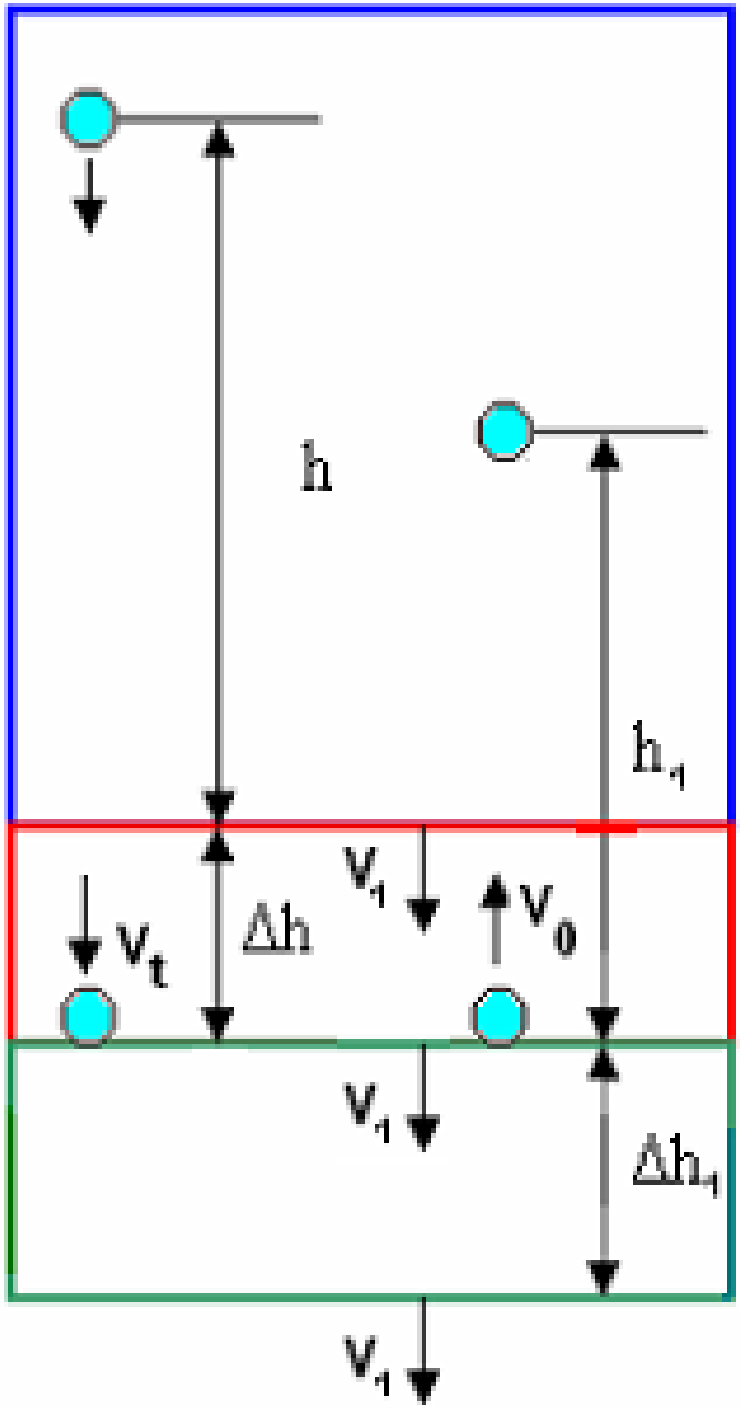

SCHAFFNER
Milgray




Vacuum pump
Magnetic coupling
Motor
Neutron shutters
Vacuum pump
Magnets &
Poles
Solenoid
Neutron guide
Yoke
Vacuum pump
Polarizer
Detectors



Detector of both polarization



$$h + \Delta h = \frac{gt^2}{2} \qquad t = \sqrt{\frac{2(h+\Delta h)}{g}}$$

$$\Delta h = \mathrm{v}_1 t \qquad \mathrm{v}_1 = \frac{\Delta h}{t} = \frac{\Delta h\sqrt{g}}{\sqrt{2(h+\Delta h)}}$$

$$\mathrm{v}_t = \sqrt{2g(h+\Delta h)}$$

$$\mathrm{v}_0 = \mathrm{v}_t - 2\mathrm{v}_1 = \sqrt{2g(h+\Delta h)} - 2\frac{\Delta h\sqrt{g}}{\sqrt{2(h+\Delta h)}} = \sqrt{2g}\,\frac{h}{\sqrt{h+\Delta h}}$$

$$h_1 = \frac{\mathrm{v}_0^{\,2}}{2g} = h\frac{h}{h+\Delta h}$$

$$t_1 = \sqrt{\frac{2h_1}{g}} = \sqrt{\frac{2h^2}{h+\Delta h}}$$

$$\Delta h_1 = \mathrm{v}_1 t_1 = \mathrm{v}_1\sqrt{\frac{2h^2}{(h+\Delta h)g}} = \frac{\Delta h\sqrt{g}}{\sqrt{2(h+\Delta h)}}\sqrt{\frac{2h^2}{(h+\Delta h)g}} = \Delta h\frac{h}{h+\Delta h}$$

$$h_2 = h_1 + \Delta h_1 = h\frac{h}{h+\Delta h} + \Delta h\frac{h}{h+\Delta h} = h$$


2 5 2005

Experimental advantages

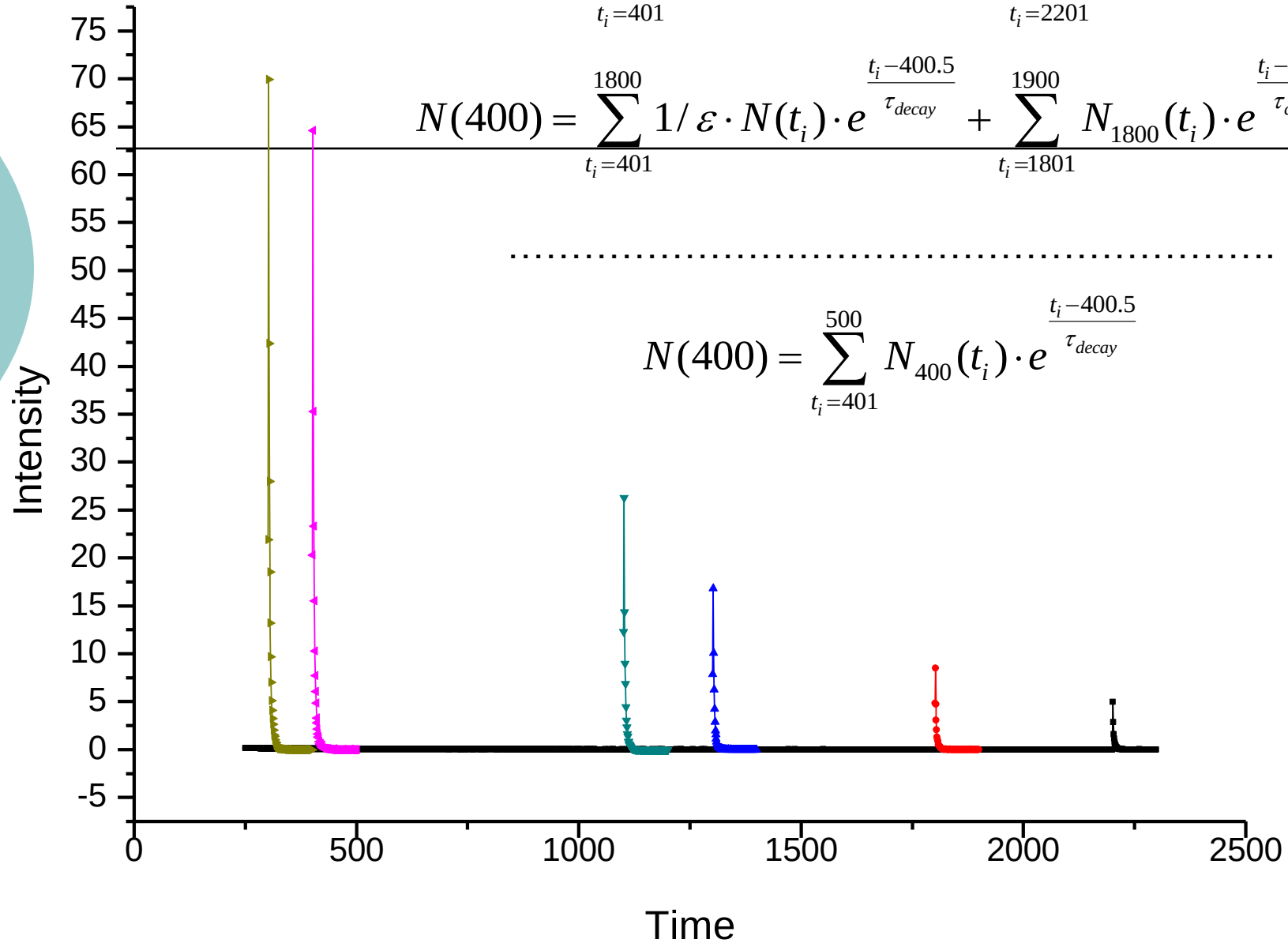
- **To control the depolarization of UCN we cover the inner trap walls with thin lay of fomblin that reflects depolarized UCN. In this case the depolarized UCN penetrate the magnetic barrier inside the solenoid and are measured by the UCN detector installed below the solenoid. Hence this detector may be used as monitor for depolarization losses during neutron storage.**
- **Monitor of trap filling**
- **Preliminary neutron spectrum preparation**
- **Absence of neutrons heating at the moment of magnetic shutter switching on.**
- **Possibility to divide fast and spin-flipped neutrons**

$$N(400) = \sum_{t_i=401}^{2200} 1/\varepsilon \cdot N(t_i) \cdot e^{\frac{t_i - 400.5}{\tau_{decay}}} + \sum_{t_i=2201}^{2300} N_{2200}(t_i) \cdot e^{\frac{t_i - 400.5}{\tau_{decay}}}$$

$$N(400) = \sum_{t_i=401}^{1800} 1/\varepsilon \cdot N(t_i) \cdot e^{\frac{t_i - 400.5}{\tau_{decay}}} + \sum_{t_i=1801}^{1900} N_{1800}(t_i) \cdot e^{\frac{t_i - 400.5}{\tau_{decay}}}$$

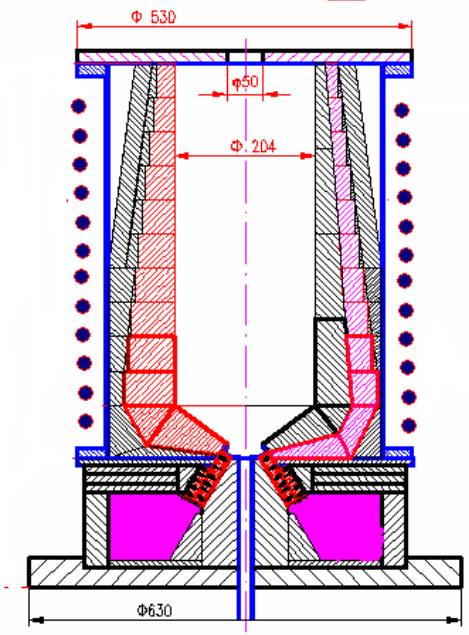
.....

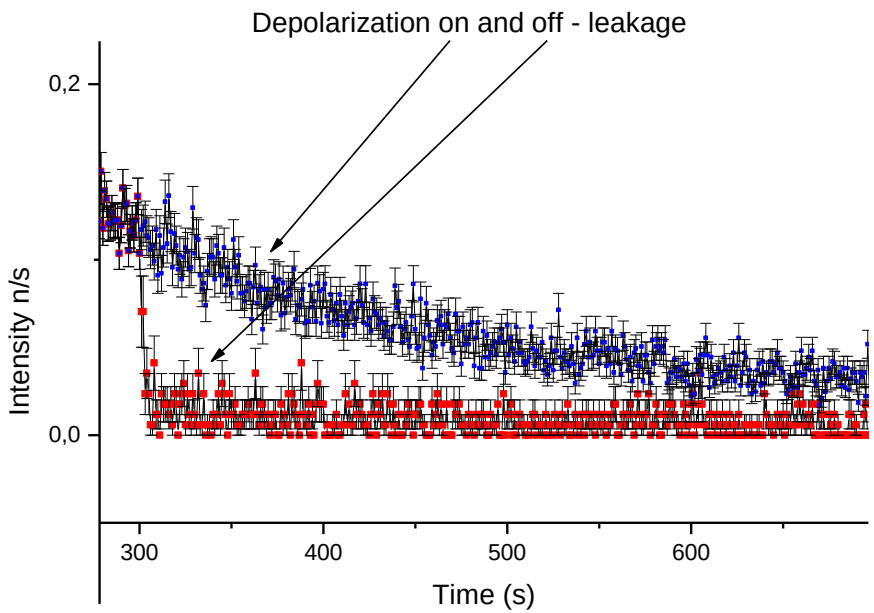
$$N(400) = \sum_{t_i=401}^{500} N_{400}(t_i) \cdot e^{\frac{t_i - 400.5}{\tau_{decay}}}$$

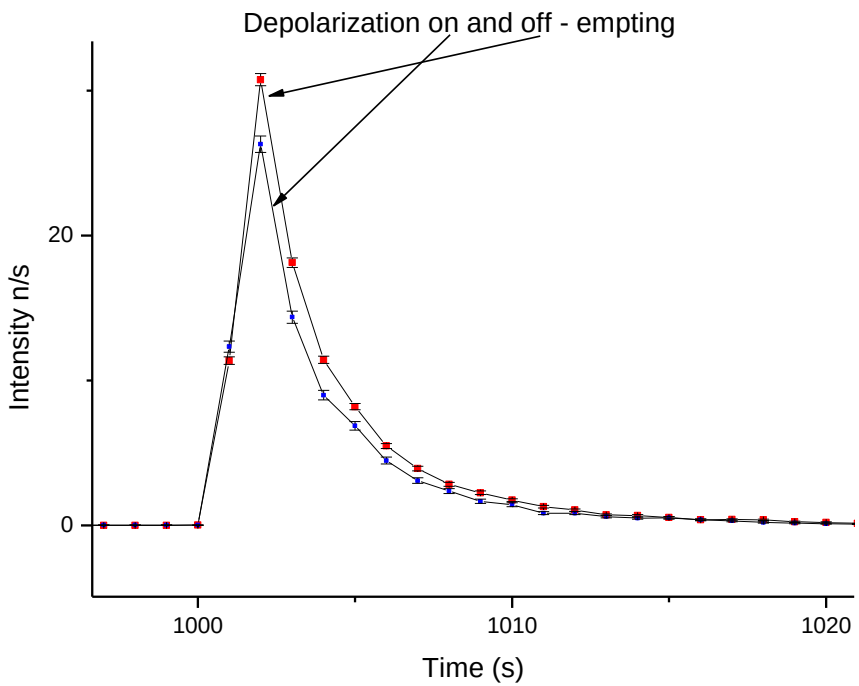


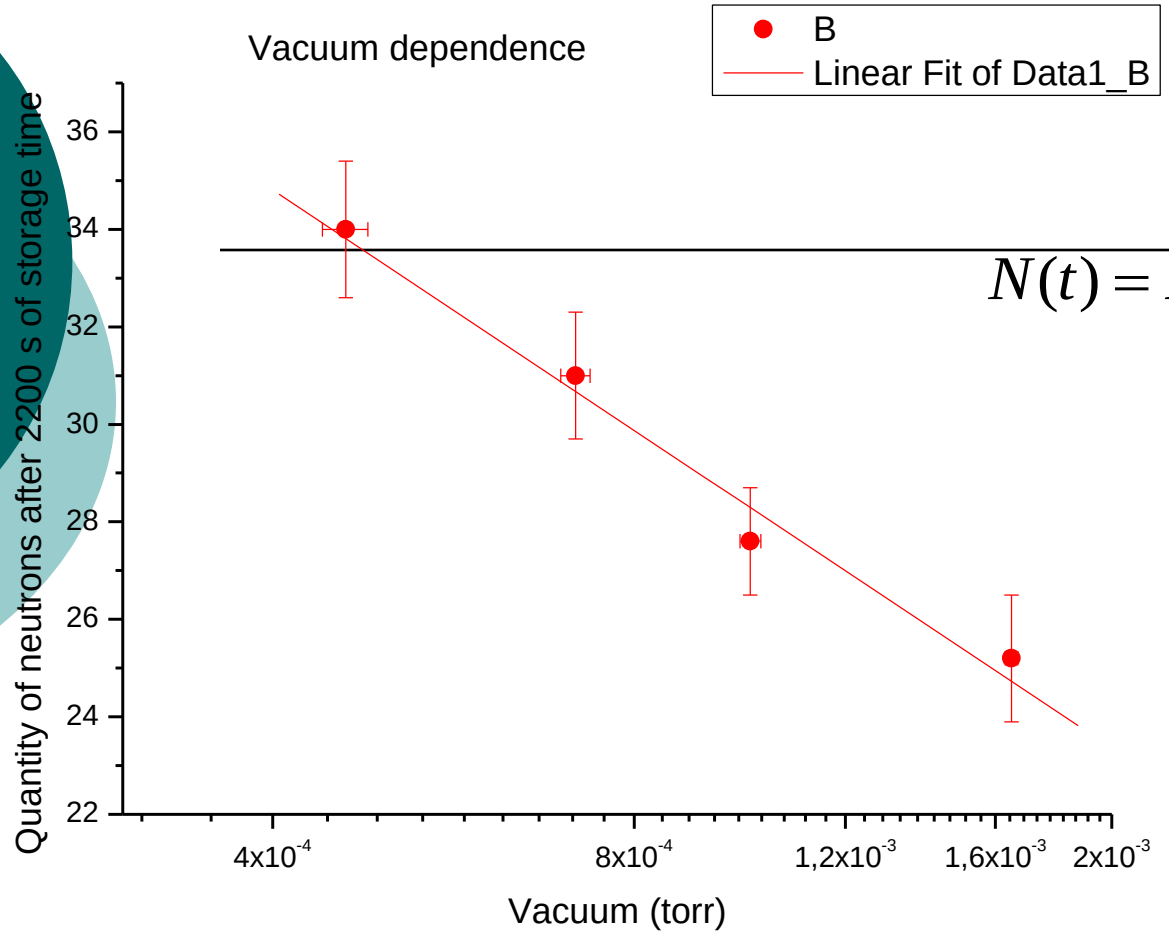
$$\varepsilon = \frac{\sum_{t_i=301}^{1000} (N_1(t_i) - N_2(t_i)) \cdot e^{\frac{t_i - 300.5}{\tau_{decay}}}}{\sum_{t_i=1001}^{1100} (N_2(t_i) - N_1(t_i)) \cdot e^{\frac{t_i - 300.5}{\tau_{decay}}}}$$

ε = 0.90±0.02









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

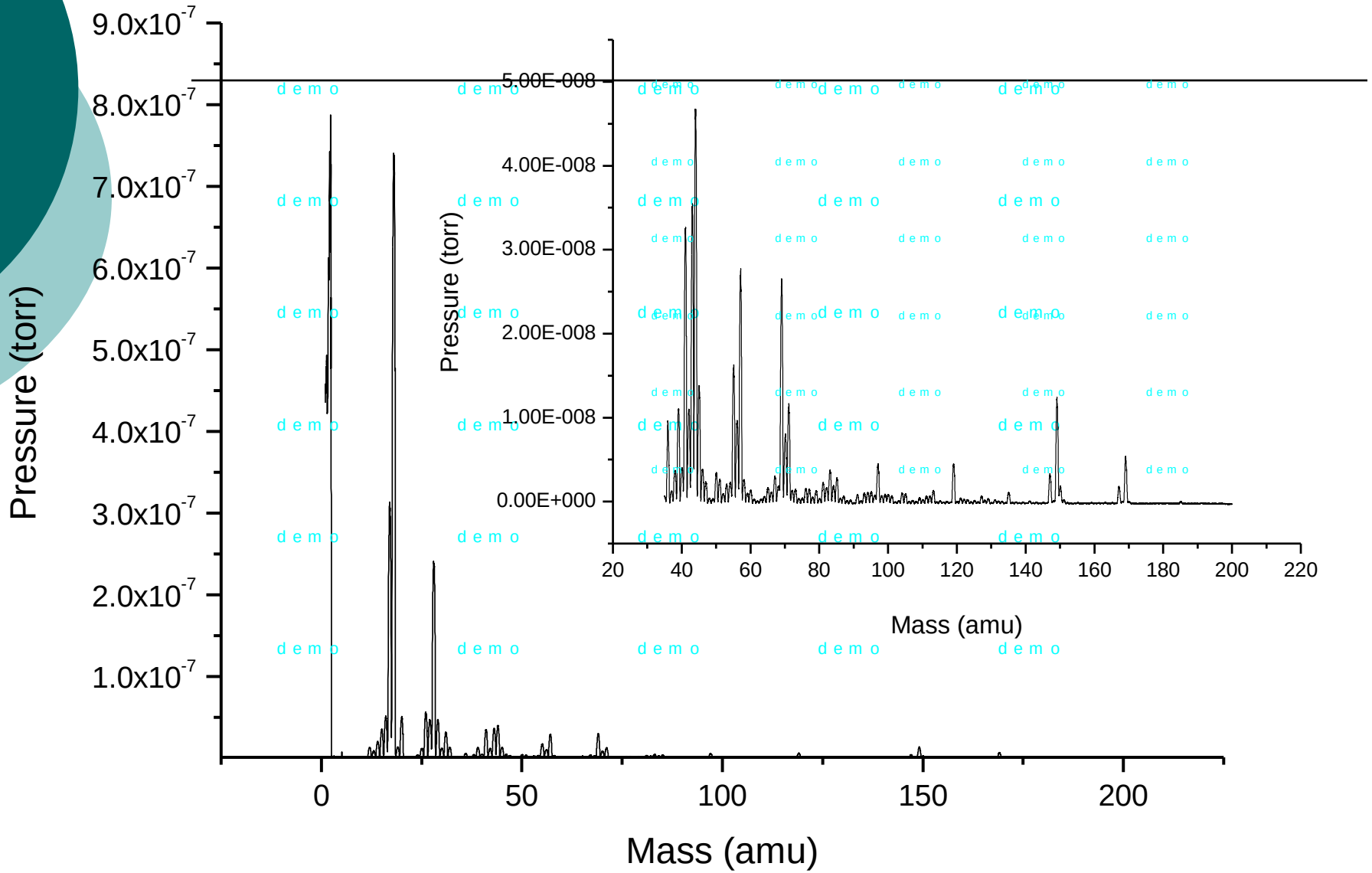
$$\lambda_p = \frac{\ln\left(\frac{N_1(t)}{N0_1}\right) - \ln\left(\frac{N(t)}{N0}\right)}{t(p - p_1)}$$

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

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

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

Mass spectrum of the rest gases in the trap (vacuum $1.2 \cdot 10^{-6}$ torr)



The best results for neutron lifetime

N beam:

- 886.8±1.2±3.2 (NIST, 2003)
- 889.2±4.8 (Sussex-ILL 1995)

880 ± 3 →

UCN storage in material trap:

- 878.5±0.7± 0.3 (PNPI-ILL,2004)
- 885.4±0.9±0.4 (KI-ILL, 1997)
- 882.6±2.7 (KI-ILL, 1997)
- 888.4±3.1±1.1 (PNPI, 1992)
- 887.6±3.0 (ILL, 1989)

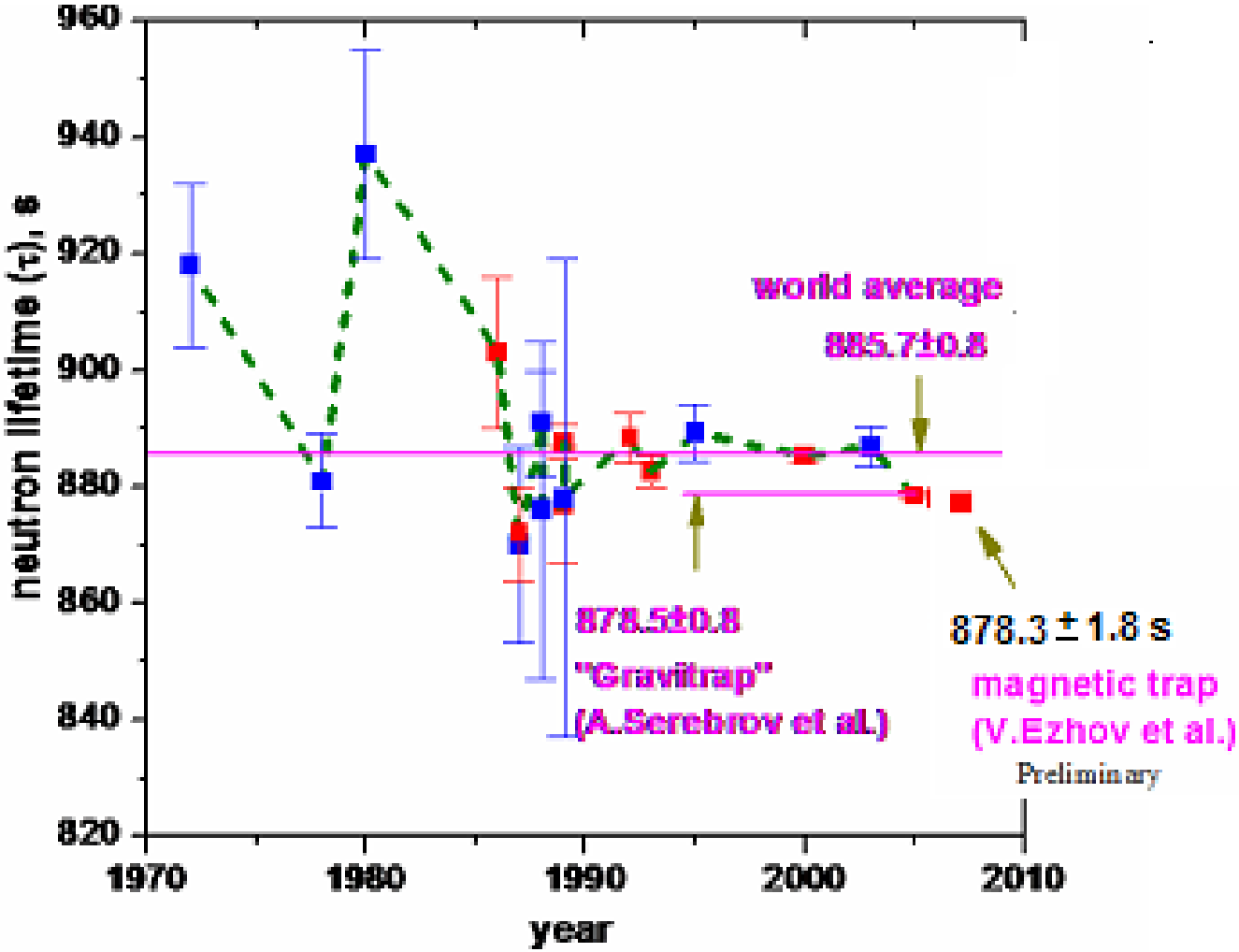
Particle data 2003
(without PNPI - ILL,2004):
τn = (885.7±0.8) s

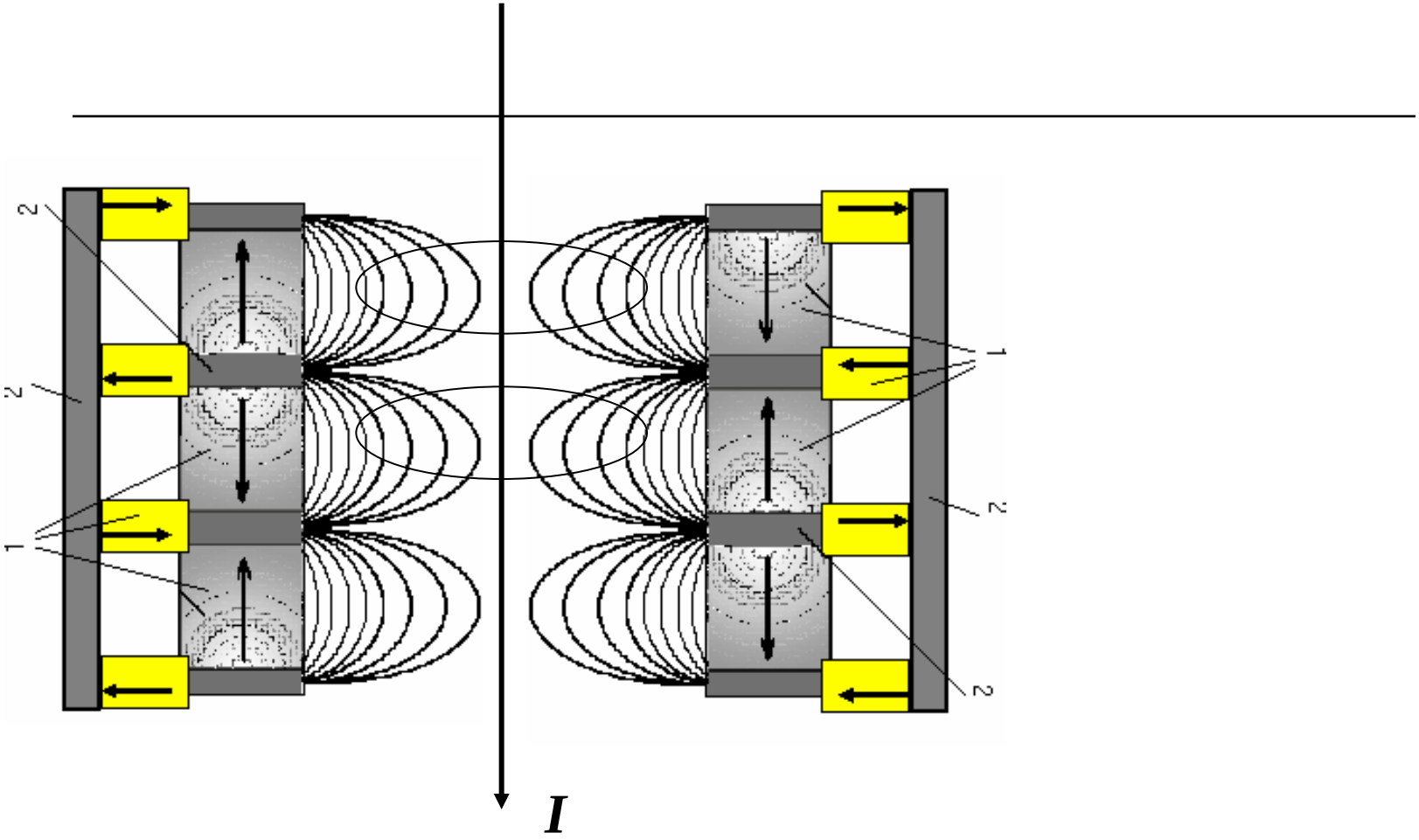
Magnetic trap
(2007)
878.0 ± 1.9 s.

Preliminary

Neutron lifetime measurements (history of experimental results)

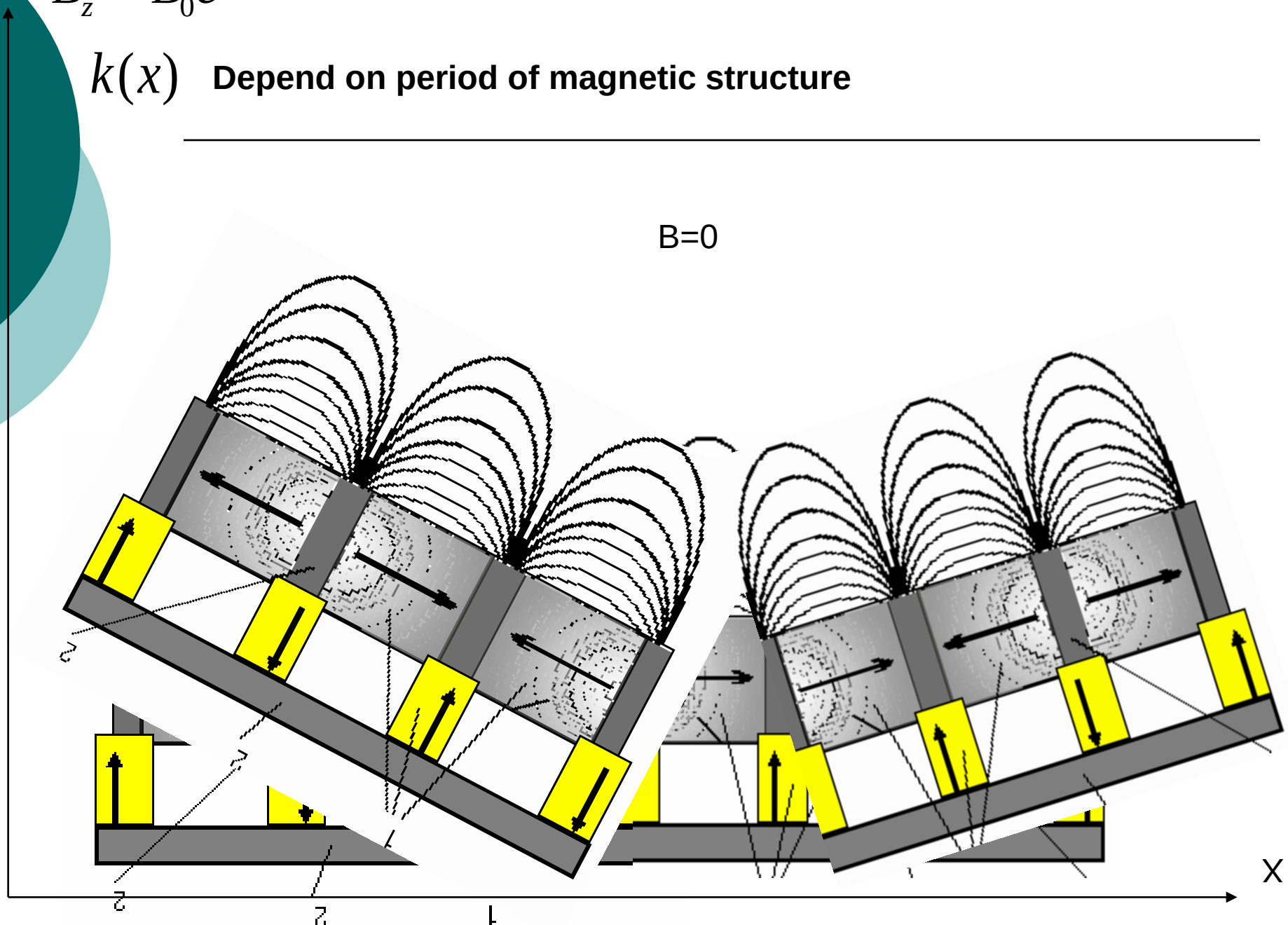
Lifetime τ[s]	Ref./Year
$878.5^{+4.0}_{-1.6}$	V. Ezhov et al. 2006
878.5 ± 0.8	A. Serebrov et al. 2004
886.8 ± 3.42	M.S. Dewey et al. 2003
885.4 ± 0.95	S. Arzumanov et al. 2000
889.2 ± 4.8	J. Byrne et al. 1995
882.6 ± 2.7	W. Mampe et al. 1993
888.4 ± 3.1 ± 1.1	V. Nesvizhevski et al. 1992
876 ± 27 ± 14	R. Kosakowski 1989
887.6 ± 3.0	W. Mampe et al. 1989
877 ± 10	W. Paul et al. 1989
876 ± 10 ± 19	J. Last et al. 1988
891 ± 9	P. Spivac et al. 1988
872 ± 8	A. Serebrov et al. 1987
870 ± 17	M. Arnold et al. 1987
903 ± 13	Y.Y. Kosvintsev et al. 1986
875 ± 95	Y.Y. Kosvintsev et al. 1980
937 ± 18	J. Byrne et al. 1980
881 ± 8	L. Bondarenko et al. 1978
918 ± 14	C.J. Christensen et al. 1972

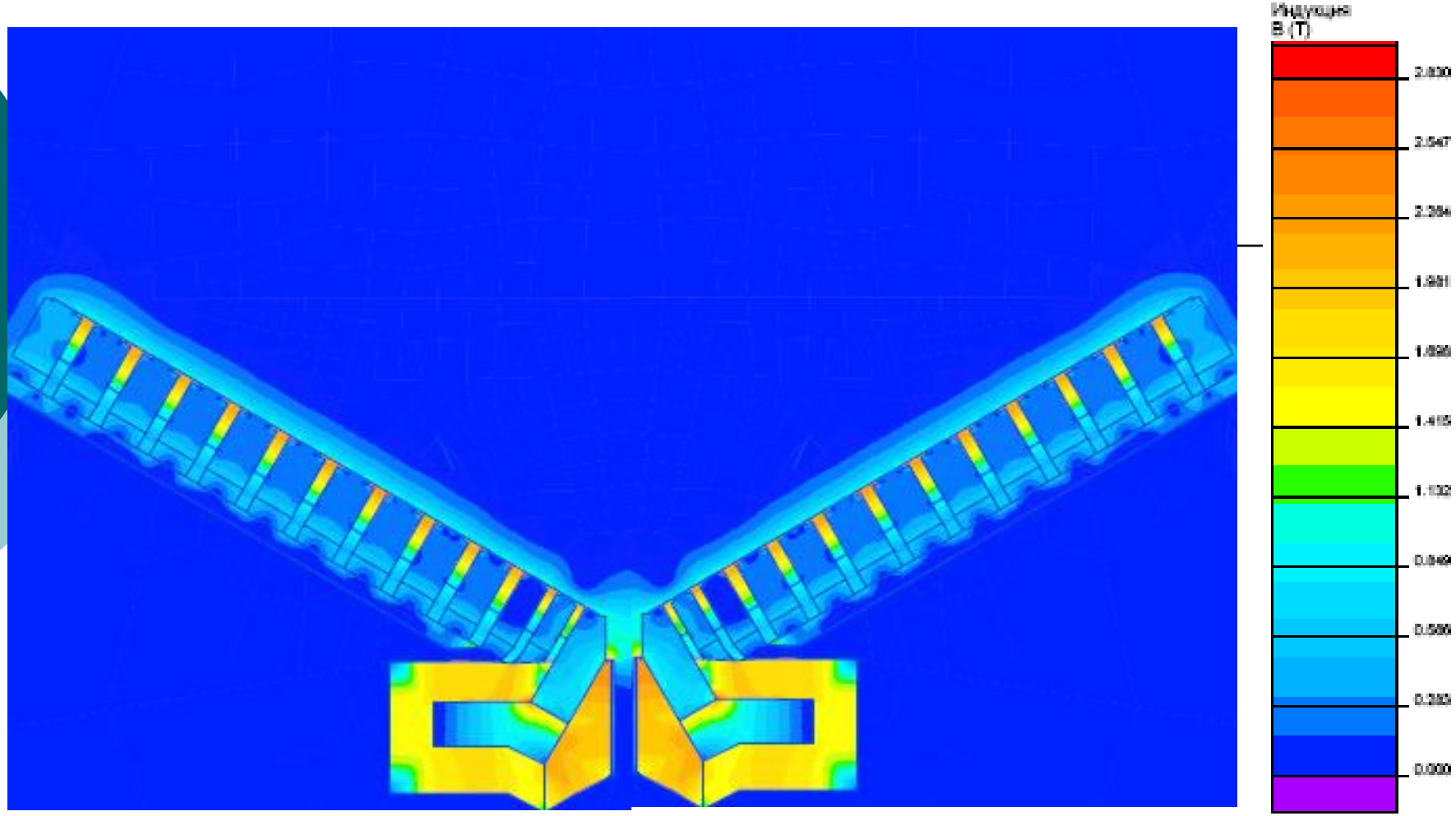



2
2
1
1
2
2
I

$$\vec{B}_z = \vec{B}_0 e^{-kz}$$

$k(x)$ **Depend on period of magnetic structure**




Индукция
B (T)
2.830
2.547
2.264
1.981
1.698
1.415
1.132
0.849
0.566
0.283
0.000