Precision measurements of neutron beta decay I – Neutron lifetime –

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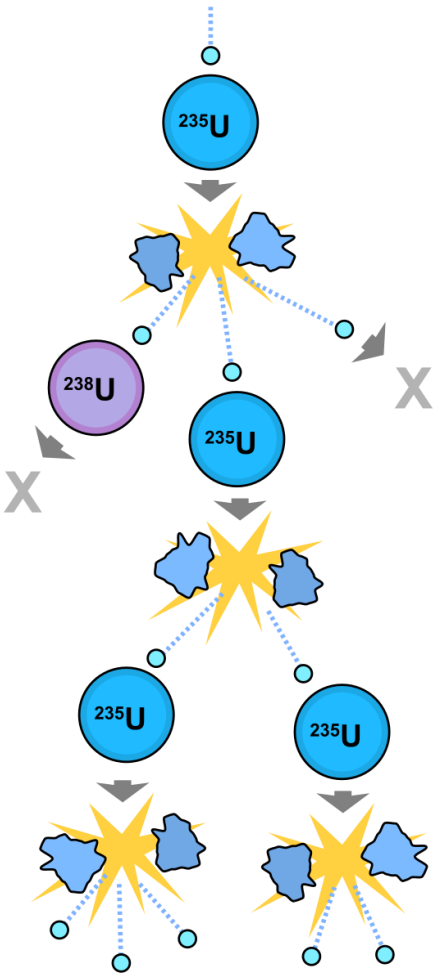
Content

- Neutron sources
  - Reactors, spallation sources
  - Neutron energies, cold and ultracold, neutron transport
- Towards neutron decay
- Measuring the neutron lifetime (partial and total width)
  - Beam experiments
  - Storage experiments
- Status and the neutron lifetime puzzle
  - Interpretations and their exclusion
- Outlook

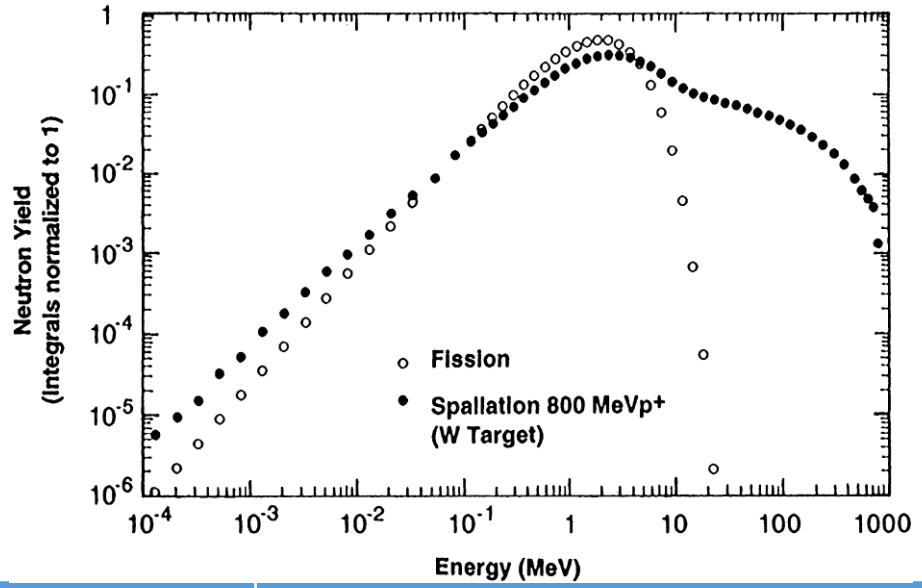
Disclaimer: I never measured the neutron lifetime myself. At least not directly.

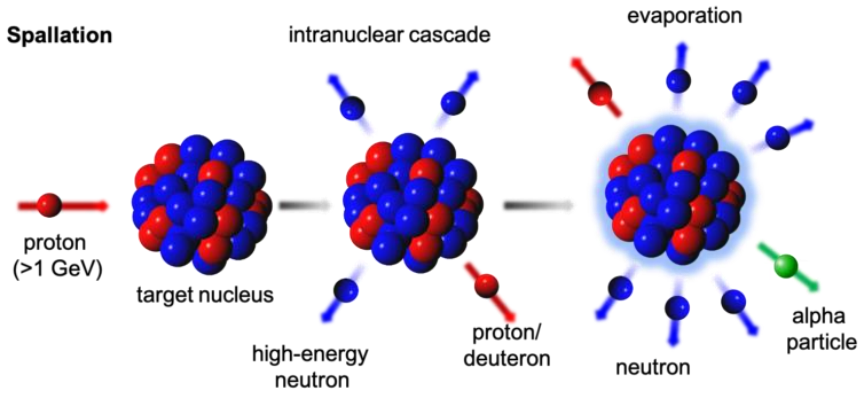
Neutron sources for slow-neutron particle physics

Research reactors



Spallation neutron sources

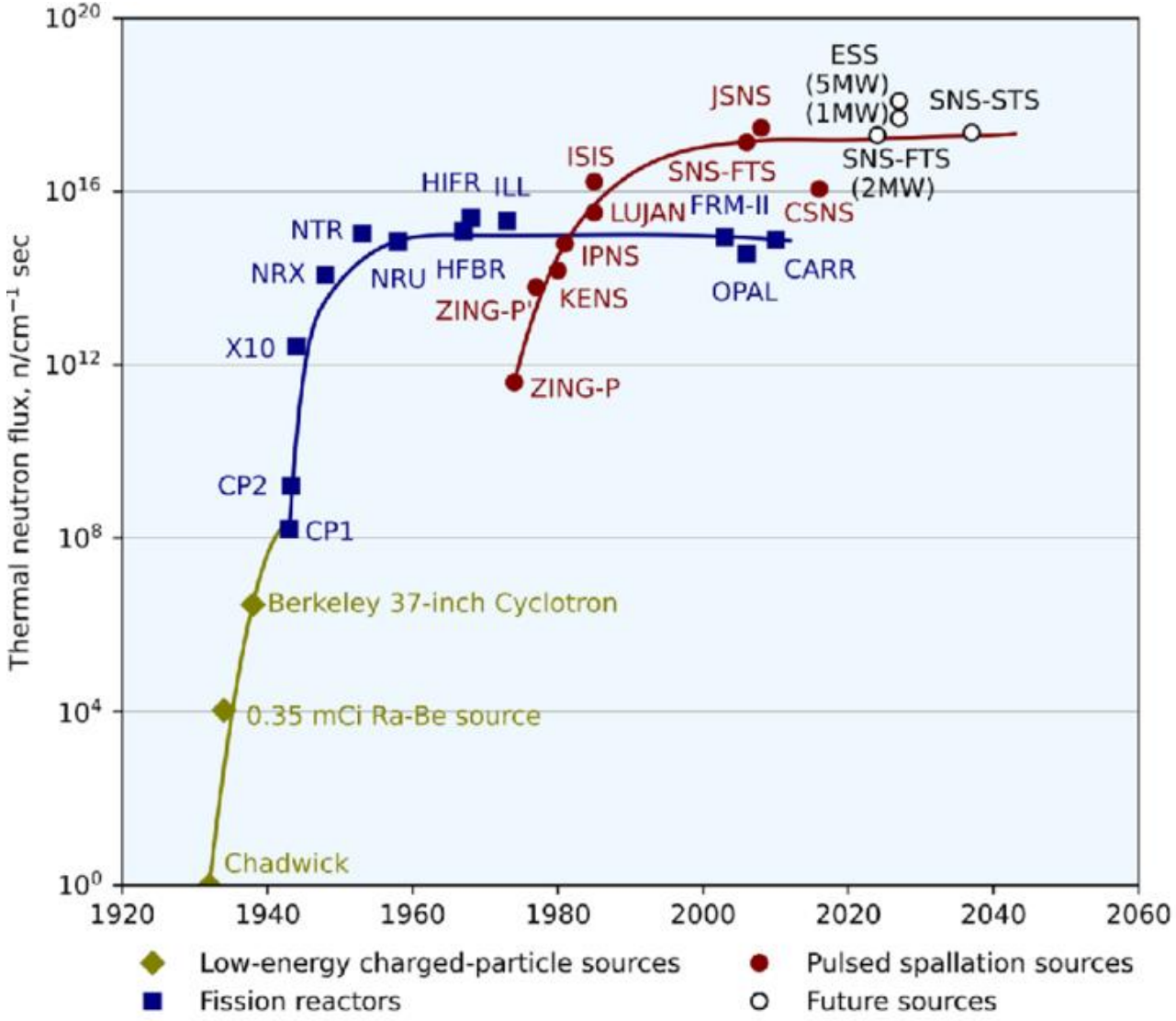




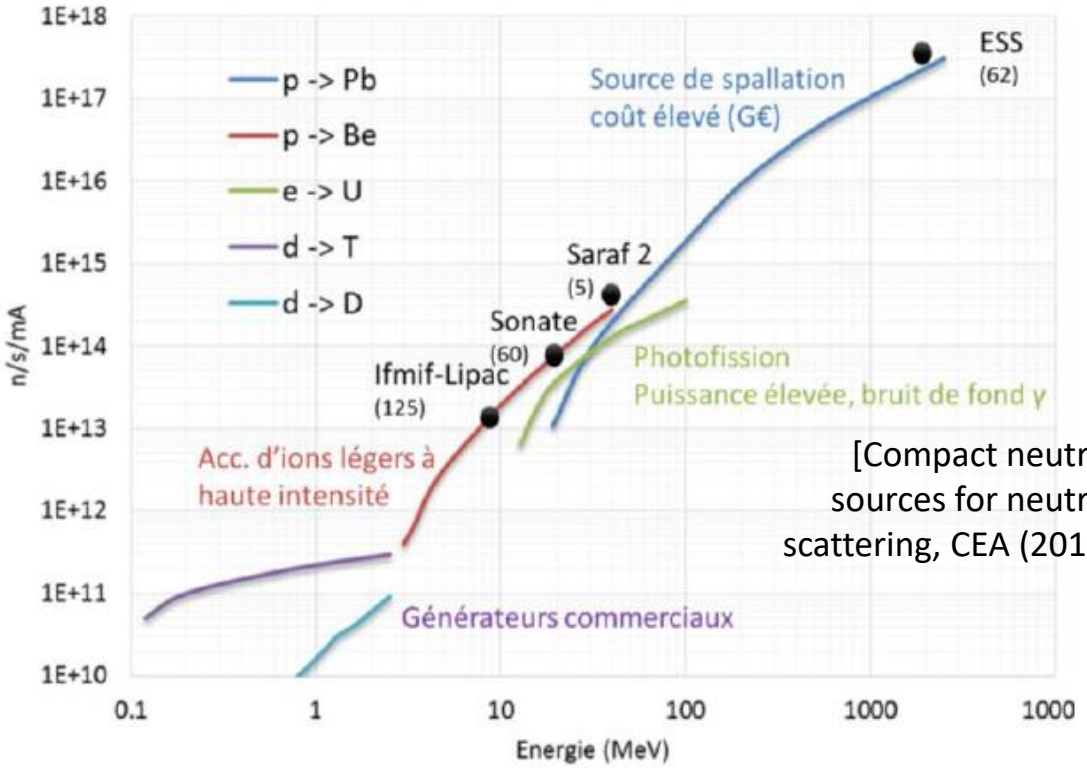
Images: [Wikipedia], [Russell, Proceedings of ICANS-XI, Tsukuba, 1990, KEK-Report Vol. 90-25, 1991, pp. 291–299.], [elena-neutron],

	Research reactor	Spallation source
Process	Fission of ^{235}U, chain reaction	Spallation of heavy nuclei by GeV protons
Neutron yield	2-3 / fission (-1 for chain reaction)	30-40 / proton
Neutron energy	Up to ~10 MeV	Up to proton energy
Heat	~180 MeV/n	~30 MeV/n
Operation	Typically continuous High time-averaged flux	Typically pulsed High peak flux

Neutron facilities



Accelerator-driven neutron sources??

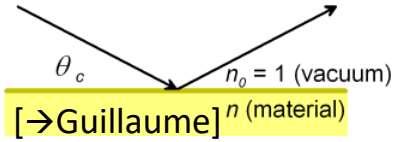


[Compact neutron sources for neutron scattering, CEA (2018)]

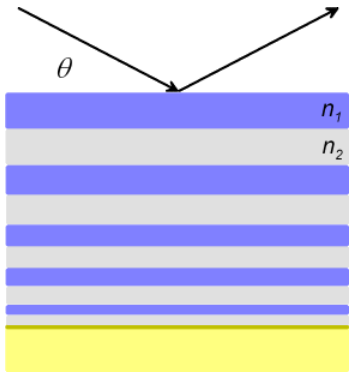
- CANS (Compact Advanced Neutron Source)
- HiCANS (High-Current Accelerator-driven Neutron Source)

Several proposals as national sources for neutron scattering, interest for statistics-limited neutron decay to be seen

Neutrons – from fast to cold to experiment

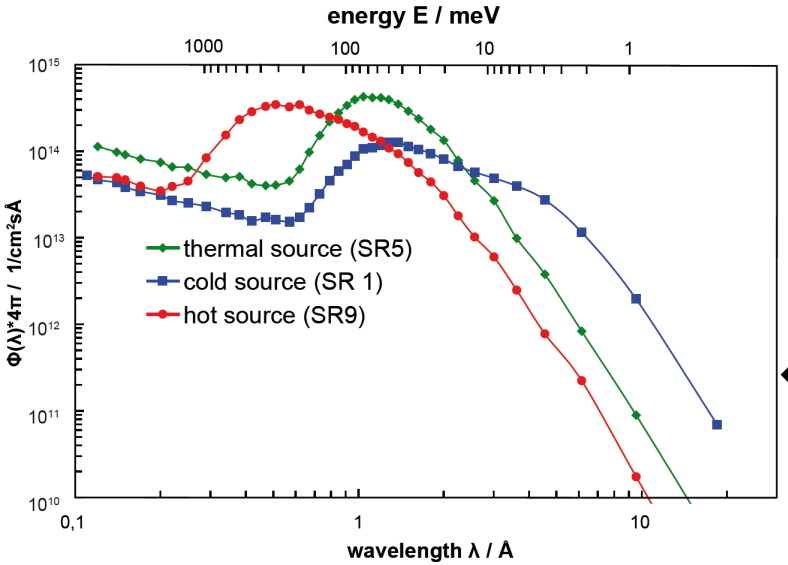


[→Guillaume]

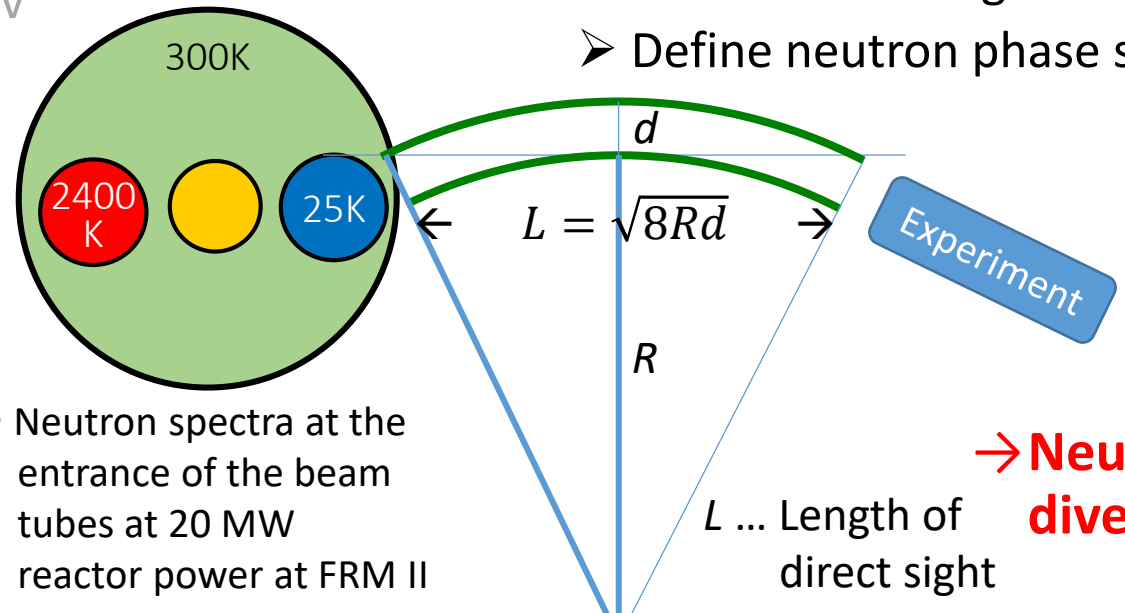


From fast to cold by moderation

Fast n:			> 1MeV
Intermediate:		1 MeV	… 1eV
Slow:		< 1eV	
> 1000 K	epithermal:	1 eV	… 100 meV
300 K	thermal:	100 meV	… 12 meV
30 K	cold:	12 meV	… 120 µeV
< 1 K	very cold:	120 µeV	… 300 neV
< 3 mK	ultra cold:	< 300neV	



← Neutron spectra at the entrance of the beam tubes at 20 MW reactor power at FRM II



From production to experiment

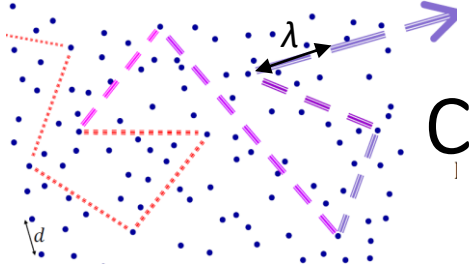
- Mirrors & SuperMirrors (m=2, 3…):

$$\theta_{c,Ni} = 1.73 \frac{\text{mrad}}{\text{Å}} \lambda, \; \theta_{c,SM} = m\, \theta_{c,Ni}$$

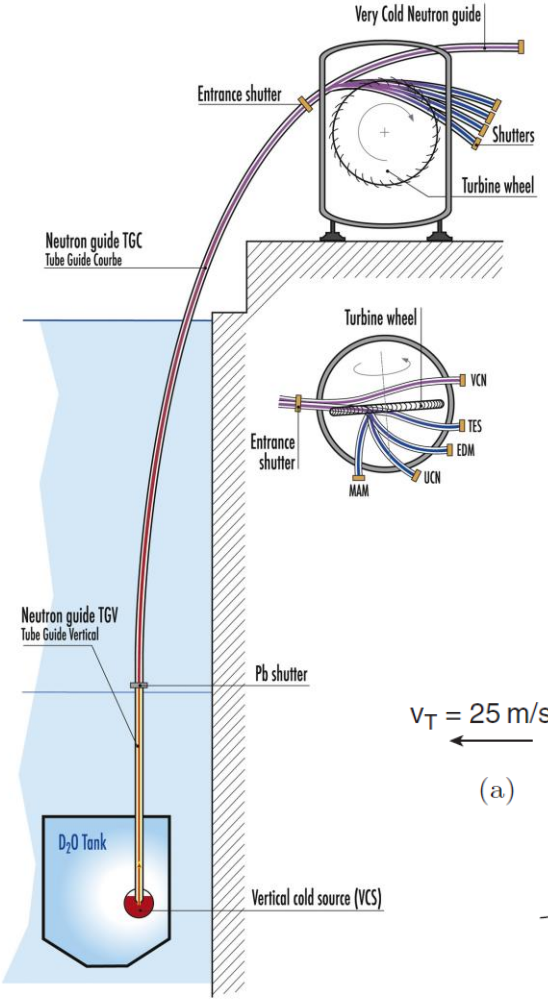
- Neutron guides:
  - ➢ Go away from source
    - → Gain space
    - → Reduce background (distance, curvature)
  - ➢ Define neutron phase space

- Typical dimensions:
  - ➢ 6×10 cm², 80 m

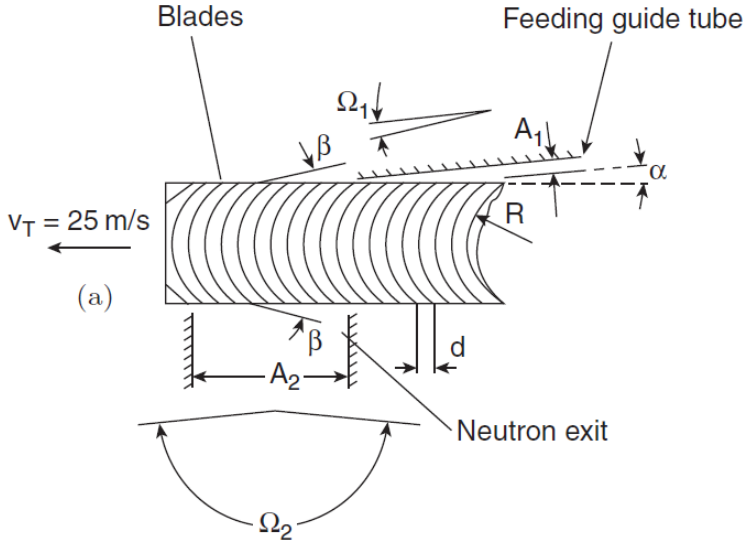
→ Neutron beams are large, divergent, inhomogeneous

Neutrons – from  cold to ultra-cold

Phase space selection or transformation



- Does not increase phase space density
- PF2@ILL:
  - 4 UCN ports
  - Stored UCN density 30/cm³
  - $3 \cdot 10^4$ UCN/cm³s



[https://www.ill.eu/users/instruments/instruments-list/pf2], [Steyerl, Nucl. Instr. Meth. 125 (I975) 461]

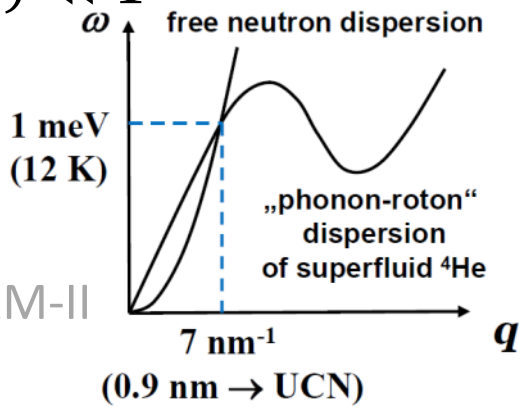
Superthermal UCN sources

[Golub & Pendlebury, Phys. Lett. A 53 (1975) 133], or thin film: [Golub & Böning, Z. Phys. B 51 (1983) 95]

- Problems with moderators:
  - $T_{\mathrm{UCN}} \ll T_{\mathrm{moderator}}$
  - Moderation inefficient for slow neutrons: see optical potential instead of individual nuclei
- Solution: "Converter" where
  - UCN can only scatter to narrow energy band with $E^* \gg kT_{\mathrm{converter}}$ and $E^* \gg E_{\mathrm{UCN}}$
  - Only neutrons with E^* can scatter to E_{UCN}
  - Neutron absorption is very small

→Upscattering of UCN suppressed by Boltzmann factor $\exp(-E^*/kT_{\mathrm{converter}}) \ll 1$

- Sources:
  - Superfluid ⁴He sources: ILL, RCNP, TRIUMF, WWR-M
  - Solid D_2 sources: LANL, PSI, Mainz, Pulstar, FRM-II



n's interactions – What is special about UCN?

- **Strong**
  - ➢Nuclear force, binding in nuclei
  - ➢Neutron detection: ^{3}He(n,p)t, Gd(n,γ)
  - ➢Neutron optical potential $V = \frac{2\pi\hbar}{m_n} bN$

$$\boldsymbol{V = \mathfrak{O}(100)\ \mathrm{neV}}$$

- **Weak**
  - ➢Decay $n \to p + e + \bar{\nu}_e$
  - ➢Spin rotation in non-magnetic materials
  - ➢Parity violation in hadronic interactions: $p(n_{\mathrm{pol}}, \gamma)d$

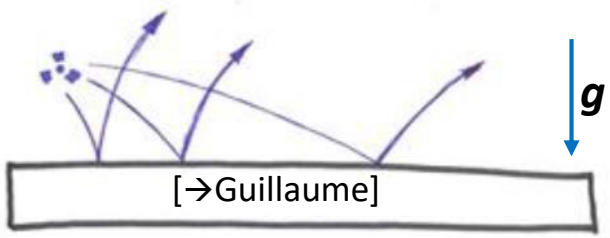
- **Electromagnetic**
  - ➢Magnetic moment $\mu_n = -60\ \mathrm{neV/T}$
  - ➢Magnetic scattering
  - ➢Magnetic potential $V = -\boldsymbol{\mu_n B}$

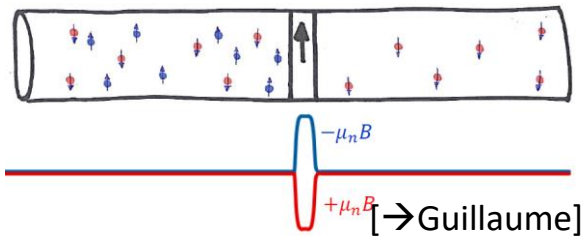
$$\boldsymbol{V = 60 \frac{\mathrm{neV}}{\mathrm{T}}\ B}$$

- **Gravitational**
  - ➢Free fall
  - ➢Gravitational potential $V = mgh$

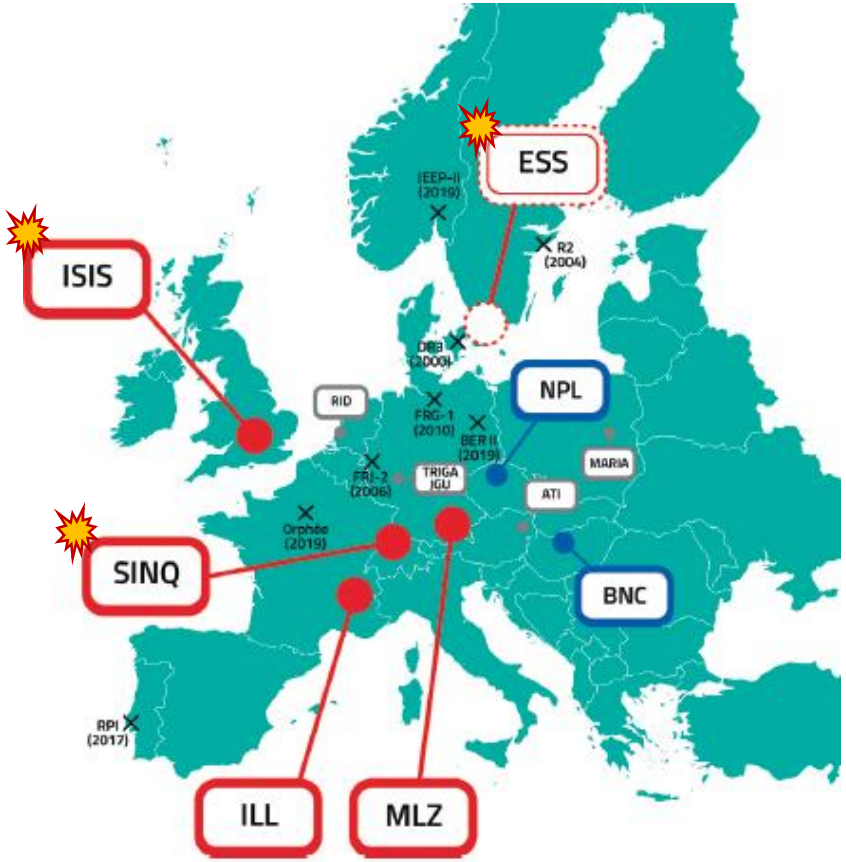
$$\boldsymbol{V = 102 \frac{\mathrm{neV}}{\mathrm{m}}\ h}$$

- ***Kinetic energy***
  - ➢$\lambda\, v = 3956\ \text{Å}\ \frac{\mathrm{m}}{\mathrm{s}}, \quad E = 5.22\ \frac{\mathrm{neV}}{(\mathrm{m/s})^2} v^2$
  - ➢Cold: $v \sim 1\ \mathrm{km/s}$, $E(1\ \mathrm{km/s}) = 5\ \mathrm{meV}$
  - ➢UCN: $v \sim 5 \frac{\mathrm{m}}{\mathrm{s}}$, $\boldsymbol{E = 130\ \mathrm{neV} \left(\frac{v}{5\ \mathrm{m/s}}\right)^2}$ → **Confinable by 3 interactions**





Neutron facilities



… with slow neutrons beams for particle physics:

(green … planned or in progress)

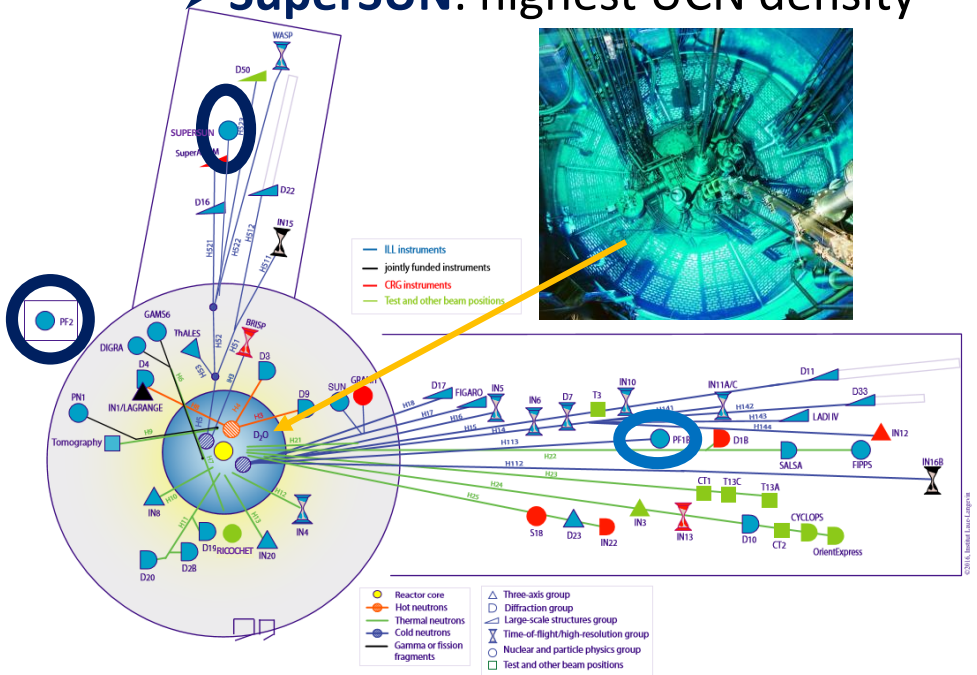
- Europe
  - **Reactors:** ILL (cold, UCN), FRM II (cold, UCN), Mainz (UCN)
  - **Spallation:** PSI (*continuous*, UCN), ESS (??)
- America
  - **Reactors:** NIST (cold), PULSTAR (UCN)
  - **Spallation:** LANL (UCN), SNS (cold, UCN-EDM), TRIUMF (UCN)
- Japan
  - **Spallation:** RCNP (UCN), JPARC (cold, UCN)

Maps from: LENS report, Neutron science in Europe (2022).

European facilities

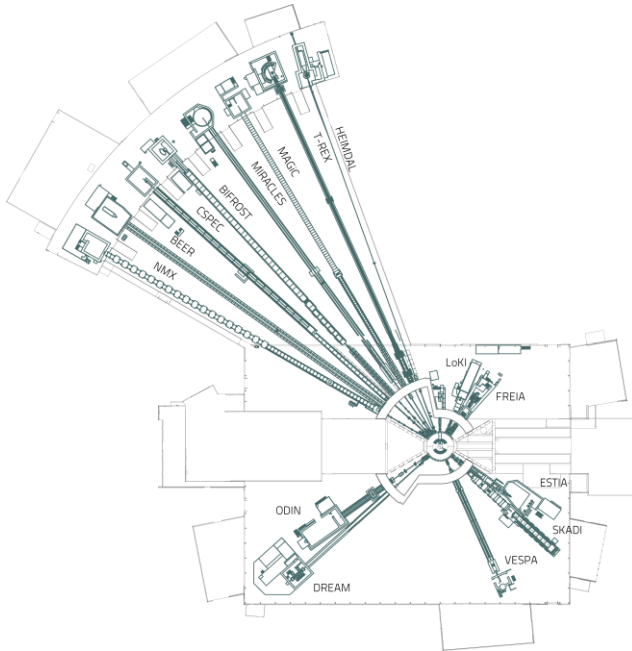
ILL – High flux reactor (Grenoble, F)

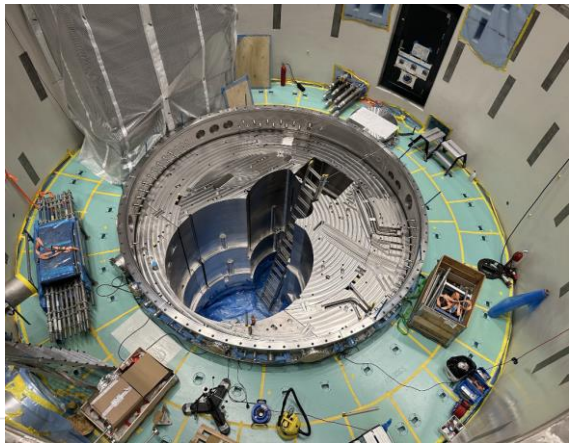
- 58 MW_{th}, 2 cold sources, 1 hot source
- 40 Instruments, 800 exps/a, 1400 visitors/a
  - **PF1B**: most intense cold neutron beam for particle physics, highest neutron polarization
  - **PF2**: most intense UCN beams
  - **SuperSUN**: highest UCN density



ESS – Long-pulse spallation source (Lund, S)

- 2-5 MW, 14 Hz, 3 ms, 1 cold source, POT 2025
- 15 instruments in construction
  - Proposal **ANNI**: most intense pulsed cold neutron beam facility (see lecture II)
  - Studies for **UCN/VCN** sources ongoing
  - No such instrument before 2030ies ☹





For particle physics opportunities at the ESS, including neutrinos, see: **Physics Reports 1023 (2023) 1–84.**

Facilities for particle physics with neutrons

Cold

Facility	Pulsed	Capture flux density [10^9 n/cm²/s]
PF1B (ILL)	No	20
MEPHISTO (FRM II)	No	18(sim)
NG-C (NIST)	No	8.3
FnPB (SNS)	Yes	3.8/(1.4 MW)
FP12 (LANSCE)	Yes	0.1
NOP (J-PARC)	Yes	1.2/MW(sim)
ANNI (ESS)	Yes	50(sim)

Taken from: Theroine et al, ESS Instrument Construction Proposal ANNI, (2015)

UCN

Source	Converter	Density in storage vol UCN cm^{-3}	Useful current 10^4 UCN s^{-1}	Source storage time (s)
Available now:				
LANL area B [78]	SD_2	52	10	40
ILL turbine [75]	liq. D_2	>40	100	< 1 sec
ILL LHe [79]	LHe	>55	0.14	67
RCNP [81]	LHe	26	1	81
PSI [82]	SD_2	23	4.2	90
Mainz [83]	SD_2	18	0.12	Few sec
ILL SuperSUN Phase 1	LHe	commissioning in progress		
Planned (date)		Target parameters:		
PULSTAR [84] (2014+)(2023+)	SD_2	>30	>10	Few sec
FRM II [85] (2015+)(2023+)	SD_2	5000	3000	N/A
TRIUMF [86] (2016)(2023+)	LHe	1500*	100*	150
WWR-M [87] (2016)(2023+)	LHe	12000	7000	10

* polarized UCN

Updated from: Young et al, J. Phys. G: Nucl. Part. Phys. 41 (2014) 114007

- **Warning**: **What counts is what arrives in the experiment**.
  This depends on many more factors (spectrum, divergence, area or volume, transport, design of experiment, …)

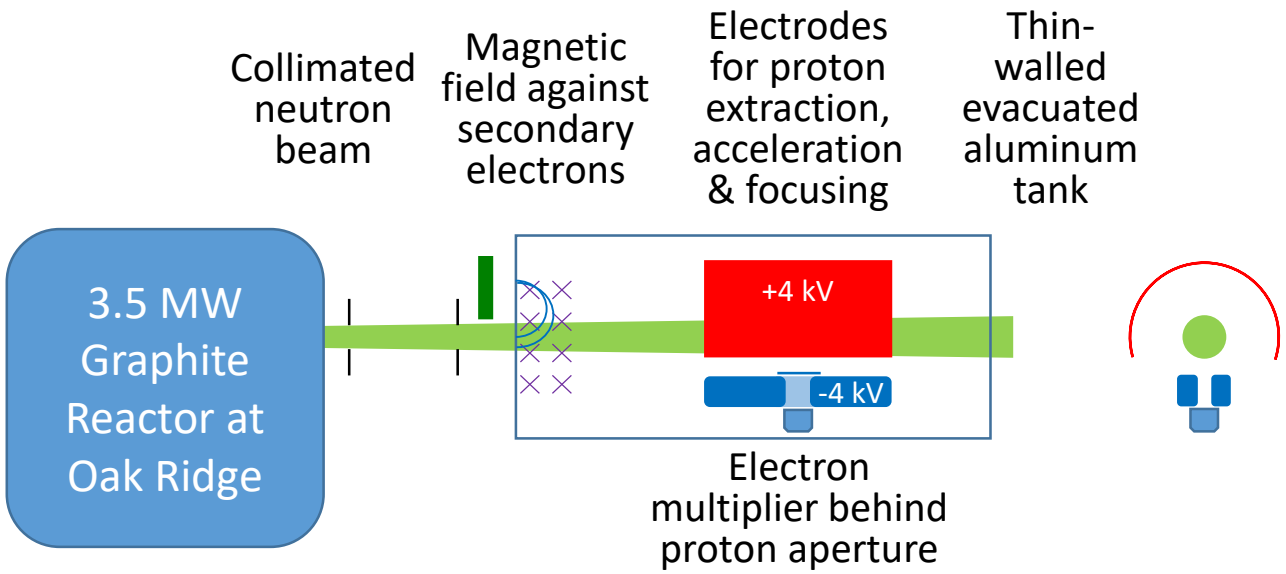
Towards neutron decay

- **Rutherford 1920:** E. Rutherford, Bakerian Lecture: Nuclear constitution of atoms, Proc. R. Soc. A 97 (1920) 374
  - Atomic nuclei composed of H nuclei and electrons. An electron can be bound very closely to a H nucleus (much more tightly than in an H atom), forming a neutral doublet.
  - These "atoms" [today: neutron] would be *difficult to detect*, may be *impossible to contain in a vessel*, can readily *enter atoms and unite with nuclei*, or be disintegrated by its intense field
- These free "atoms" could not decay spontaneously because of binding energy:
  - $m_{\text{"atom"}} < m_p + m_e$
- **Chadwick 1932, 1933:** J. Chadwick, Possible Existence of a Neutron, Nature 129 (1932) 312
  J. Chadwick, Bakerian Lecture. The Neutron, Proc. R. Soc. A 142 (1933) 1-25
  - Discovery of the neutron
  - Neutron mass smaller than that of hydrogen atom – consistent with Rutherford model
  - Good reasons to consider neutron as elementary particle: binding energy [at the time] larger than mass of electron, spin considerations, hydrogen atom should transform into neutron
- **Curie & Joliot 1934** I. Curie & F. Joliot, Mass of the neutron, Nature 133 (1934) 721
  - Neutron mass estimate heavier than H atom, energy release $n \to p + e$ from mass $2.1 \cdot 10^6$eV
- **Chadwick & Goldhaber 1934** J. Chadwick & M. Goldhaber, A "Nuclear Photo-effect": Disintegration of the Diplon by γ rays, Nature 134 (1934) 237
  J. Chadwick & M. Goldhaber, The Nuclear Photoelectric Effect, Proc. R. Soc. A 151 (1935) 479
  - First precision measurement of m_n from $D + \gamma \to p + n$ and measurement of proton energy
  - Neutron "definitively" heavier than H atom → free neutrons decay $\boldsymbol{n \to p + e + \nu}$ unless $m_\nu \sim m_e$

Discovery of neutron decay

- **Snell & Miller, 1948**

A. H. Snell & L. C. Miller, On the Radioactive Decay of the Neutron, in: Proc. Am. Phys. Soc., Phys. Rev. 74 (1948) 1201, p 1217



Thin ^{10}B neutron shutter	Thin foil to close proton aperture	Acceleration voltage	Rate [1/min]
Open	Out	On	300
Open	In	On	~200
Closed	In	On	Same
Open	Out	Off	~200
Closed	Out	Off	Same

Scheme (not to scale) according to description in Snell &Miller (1948). See also Snell et al, Phys. Rev. 78 (190) 310

- Experimental factors:
  - Proton collection and counting efficiency (10%)
  - Number of neutrons in the sample ($4 \cdot 10^4$)
- Results:
  - Estimate $\tau_{1/2} = 30$ min
  - "…much safer however to say that neutron half-life must exceed 15 minutes"
- Next step: Search coincidences

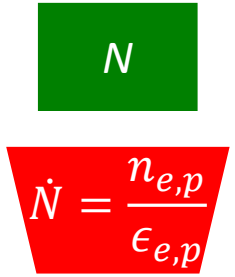
Shows common challenges of beam lifetime measurements:

- Accurate knowledge of number of neutrons
- Accurate knowledge of detection efficiency of decay products
- Backgrounds

Measurement of the neutron lifetime

Beam method

- Measure specific activity of neutron beam: "Counting the dead"

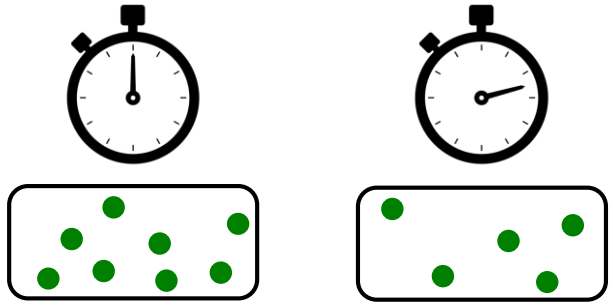


$$\tau = -\frac{N}{\dot{N}}$$

- Two absolute measurements:
  - Total number of neutrons
  - Total rate of decay products (protons or electrons – corrected for all losses)
- τBeam = specifically decay branch into electrons or protons
  → **Partial decay width**

UCN Storage method

- Measure number of stored neutrons in function of time: "Counting the survivors"



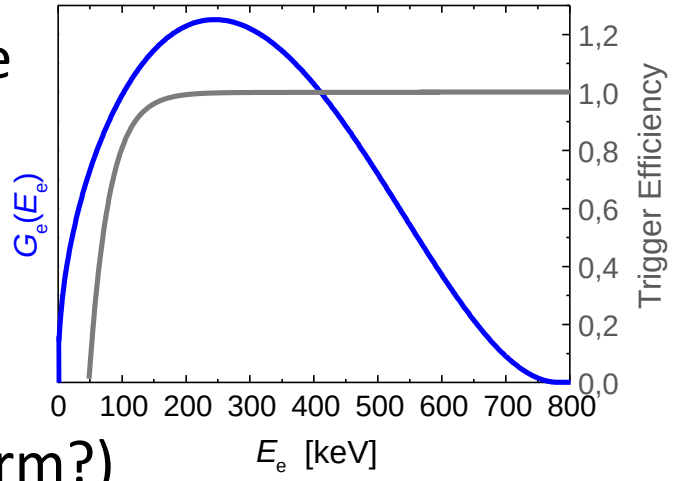
$$N(t) = N_0 \exp\left(-\frac{t}{\tau}\right)$$

- Relative measurement but:
  - Quantify or exclude all other loss channels
- τBottle = all decay branches (and other types of neutron disappearance)
  → **Total decay width**

Counting the dead: $n \rightarrow pe\nu$, $m_n - m_p - m_e = 782$ keV

E_e: 0 … 782 keV

+ Directly detectable



– Threshold effects

– Detector non-linearity, real spectrum (Fierz term?)

– (Back)scattering by detector and materials

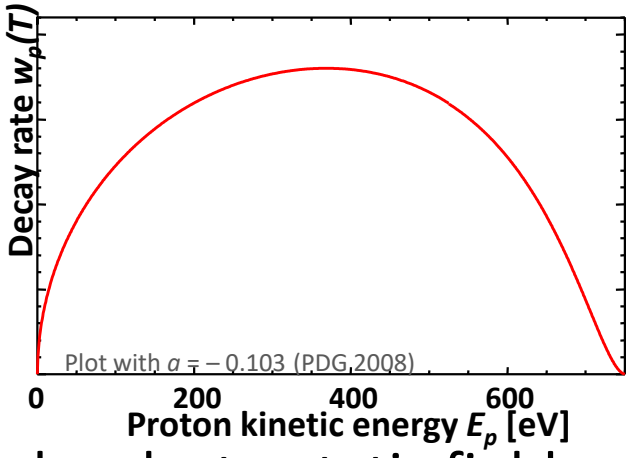
• Lowly ionizing → Background from gammas and electrons

E_p: 0 … 751 eV

– Acceleration required

+ Threshold effects suppressed:

$$E_{\mathrm{det}} = E_p + V$$



+ Extraction & focusing by electrostatic field

– Sensitivity to stray fields, charges

– Scattering by rest gas, losses in dead layers

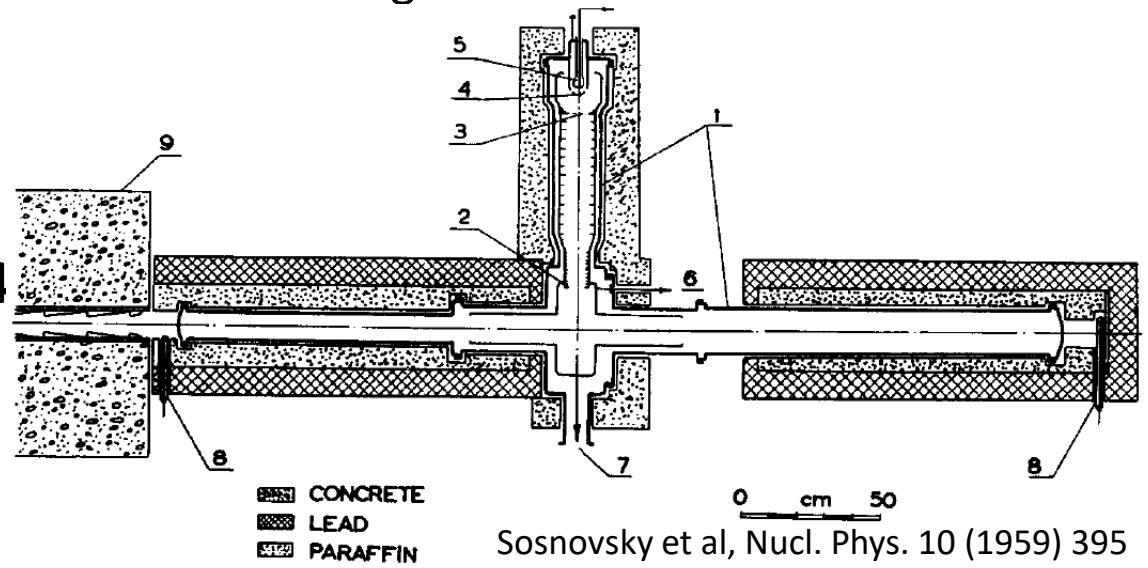
• Highly ionizing → Background from ions

N / $n_{e,p}$: Source volume & Detector solid angle

Accurate detector collimation

Neutron beams are large, divergent, inhomogeneous

→Convolution of neutron density distribution with detector solid angle needed

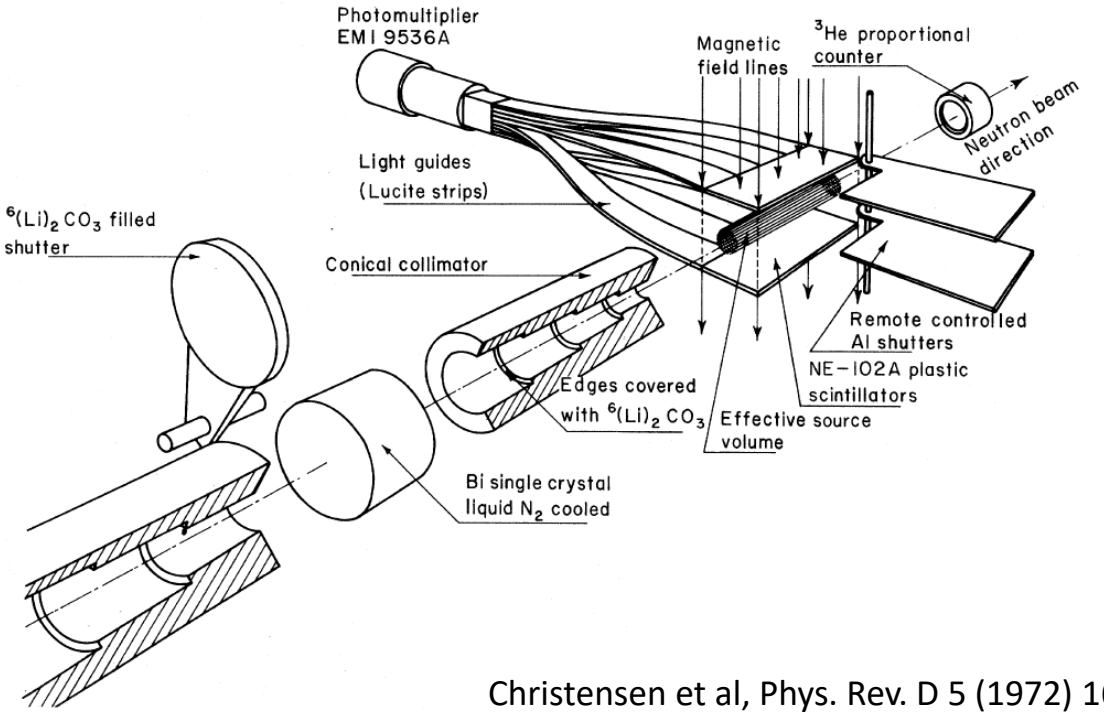


Sosnovsky et al, Nucl. Phys. 10 (1959) 395
Bondarenko et al, JETP Lett. 28 (1978) 303

- Proton detection by thin-window proportional counter.
- Beam profile was measured in 900 squares of 3×3 mm^2.
- Adding of barrier voltage to stop decay protons for background measurement.

4π detection

- **Magnetic field**



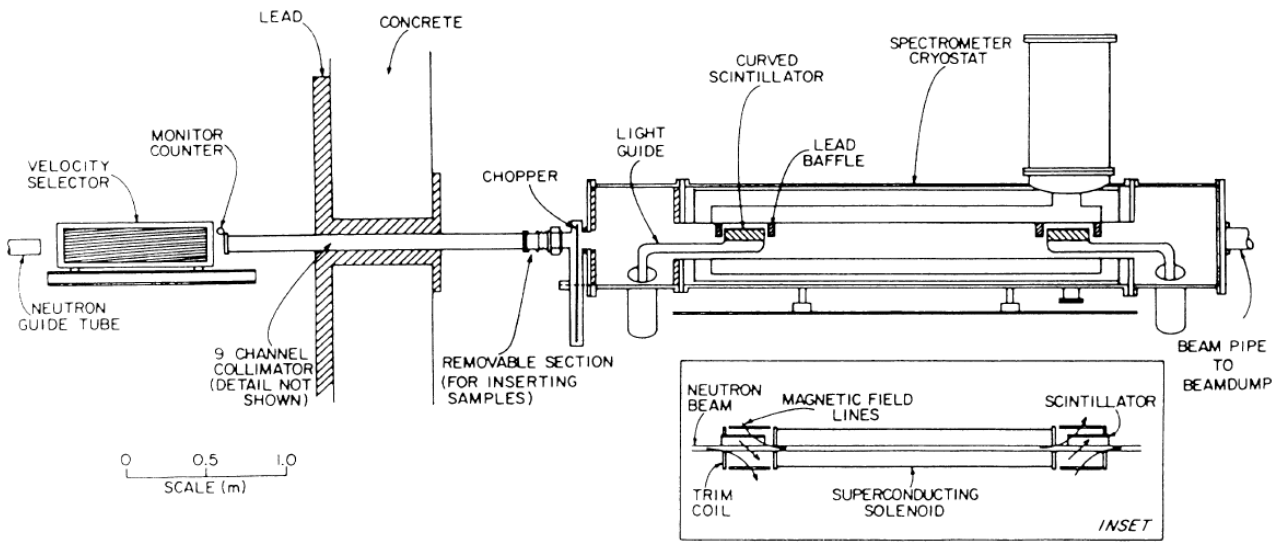
Christensen et al, Phys. Rev. D 5 (1972) 1628

- Transversal homogeneous field of 0.7 T.
- Electron detection in plastic scintillators.
- Backscattered electrons detected in opposite scintillator (collection of full energy).

N / $n_{e,p}$: Source volume & Det solid angle

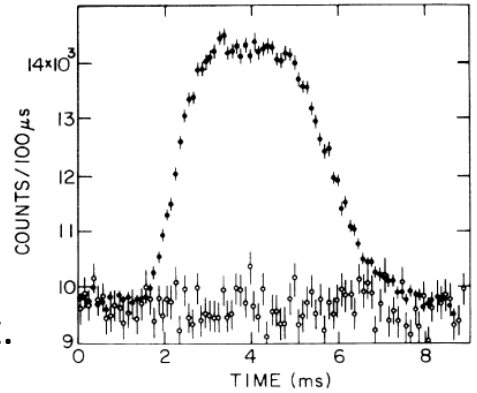
4π detection

- **Magnetic field, pulsed beam**



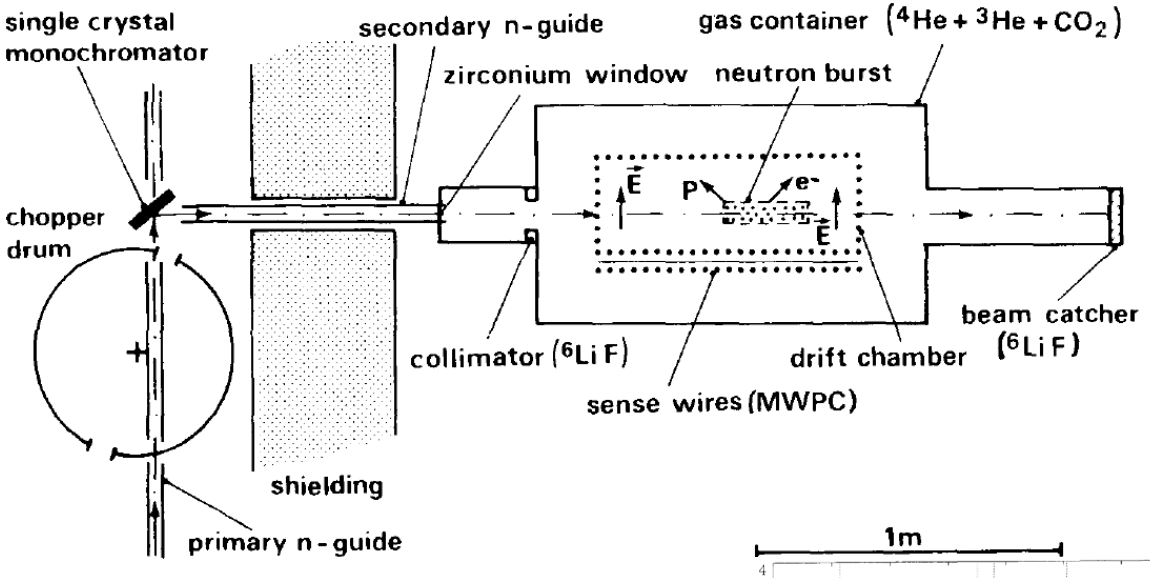
Last et al, Phys. Rev. Lett. 60 (1988) 995

- Longitudinal field of 1.7 T upwards bent at both ends.
- Electron and backscatter detection by plastic scintillators.
- Pulsed beam for full containment.



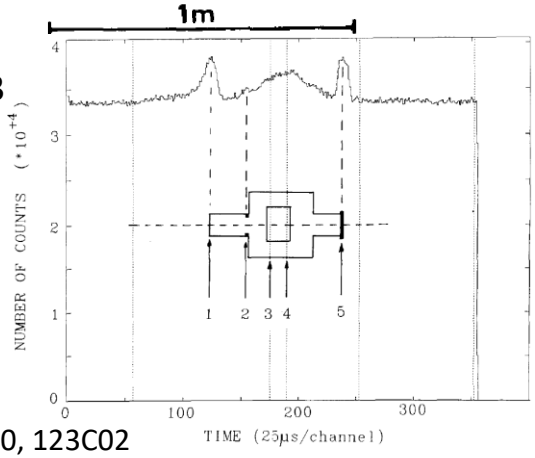
4π detection

- **Drift chamber for electrons, pulsed beam**



Kossakowski et al, Nucl. Phys. A 503 (1989) 473

- Electron threshold of a few eV.
- Pulsed beam for full containment.
- Simultaneous measurement of neutron density by $^3He(n,p)t$ with same geometry and dead time.



Same concept: Hirota et al, Prog. Theor. Exp. Phys. 2020, 123C02

N / $n_{e,p}$: Neutron counting

Continuous beams $\tau = -N/\dot{N}$

Observe neutrons traversing active volume

- Number of neutrons in volume: $N = \varrho_n V$
- Neutron with velocity v stays for time $\frac{L}{v}$

$$\varrho_n = \int \frac{1}{v} \frac{d\Phi}{dv} dv$$ particle flux $\Phi = \int \frac{d\Phi}{dv} dv$

- Neutron capture cross section:

$$\sigma(v) = \frac{\sigma_{th} v_{th}}{v}$$ capture flux $\Phi_c = \int \frac{v_{th}}{v} \frac{d\Phi}{dv} dv$

($v_{th} = 2200$ m/s) density & Φ_c: $\varrho_n = \Phi_c / v_{th}$

$1/v$ law: valid with relative error < 10^{-4} except for strong absorbers or absorbers with low-lying capture resonances

- Capture rate in **thin** foil (areal atom density ϱ_{foil})

$$R = a\varrho_{foil} \int \sigma(v) \frac{d\Phi(v)}{dv} dv$$

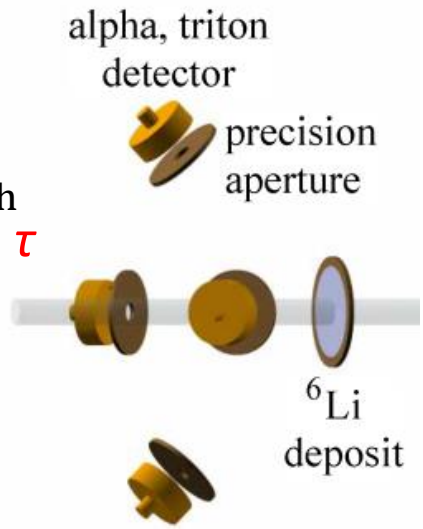
$$R = a\varrho_{foil}\sigma_{th} v_{th} \varrho_n = a\varrho_{foil}\sigma_{th}\Phi_c$$

Examples

- Activation (Na, Mg, Au), separate readout
- Low-efficiency proportional counters
- ^{6}LiF deposit

Example importance of **thin**:
Deposit with 0.4% absorption for v_{th} resulted in correction of +5.2(8) s to τ because of deviation from $1/v$ for deposit of this thickness.

NIST beam lifetime (next slides):
Nico et al, Phys. Rev. C 71 (2005) 055502



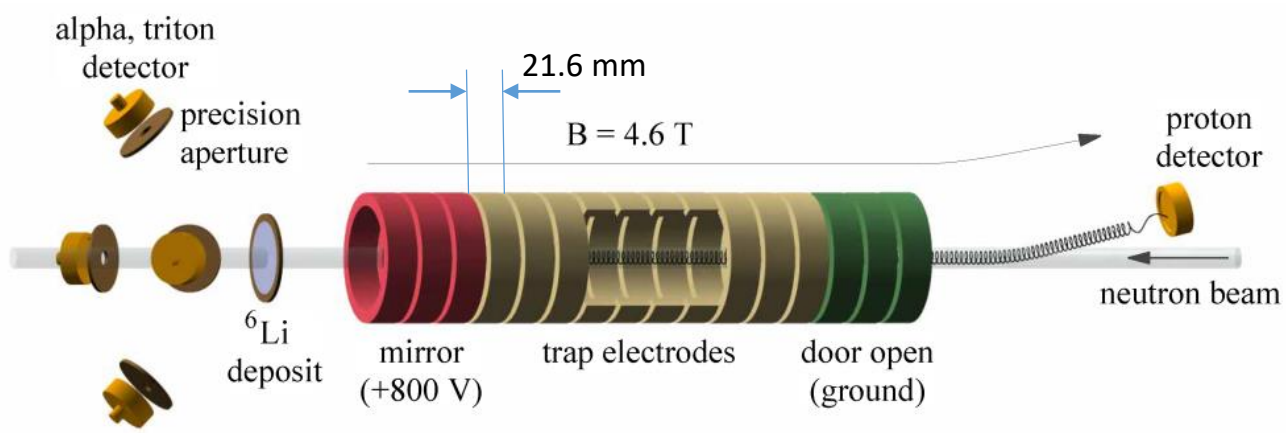
Remark pulsed beams

Observe neutrons in a pulse for a given time, independent on their respective velocity.

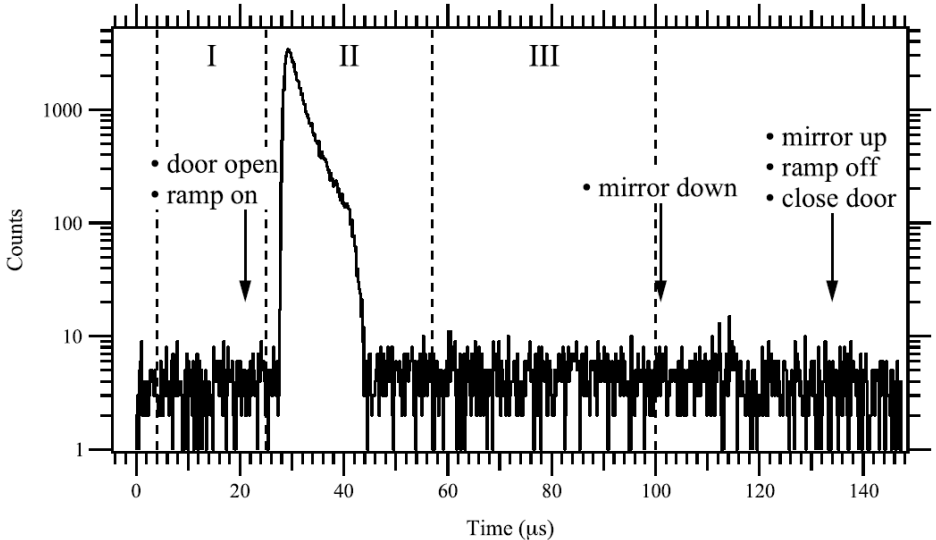
- Need number of neutrons in pulse, not capture flux.

: NIST beam lifetime

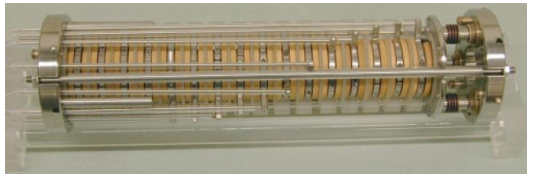
Byrne et al, Phys. Rev. Lett. 65 (1990) 289
Byrne et al, EPL 33 (1996) 187
Dewey et al, Phys. Rev. Lett. 91 (2003) 152302
Nico et al, Phys. Rev. C 71 (2005) 055502
Yue et al, Phys. Rev. Lett. 111 (2013) 222501



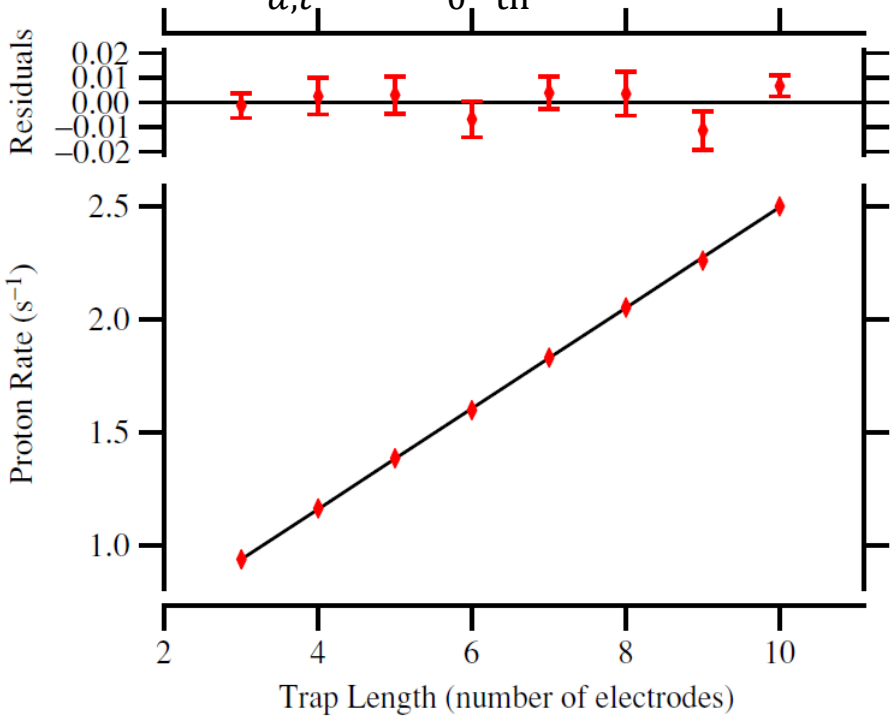
- Longitudinal magnetic field 4.6 T → Proton cyclotron radius < 1 mm
- Penning trap for protons of variable length → Get rid of end effects
- Cycles of accumulation (100 ms) and counting (76 µs)



- ➢ improved S/BG
- ➢ BG measurement after emptying the trap



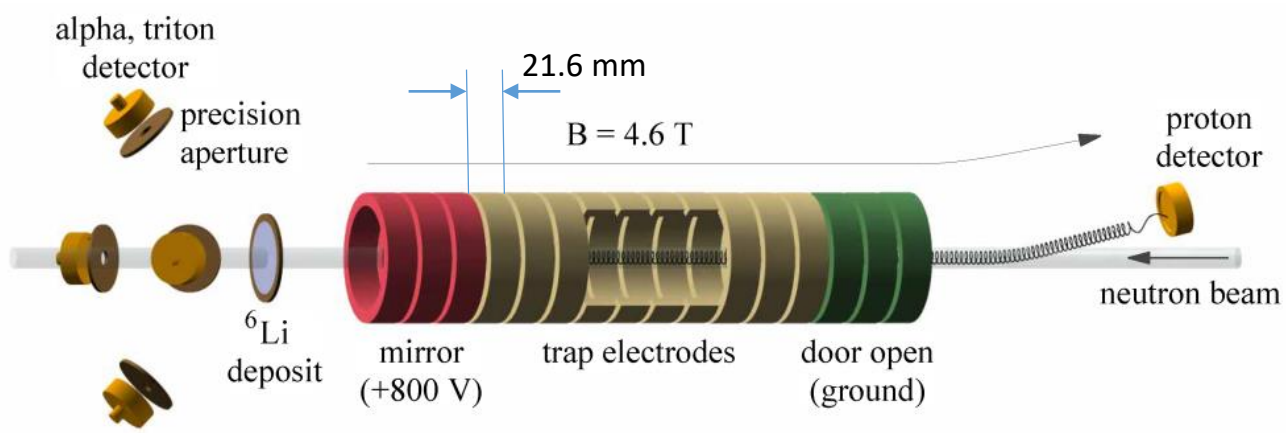
$$\frac{N_p}{N_{\alpha,t}} = \frac{1}{\tau}\frac{\epsilon_p}{\epsilon_0 v_{\mathrm{th}}}(nl + L_{\mathrm{end}})$$



L_{end} depends on trap length (magnetic field, beam divergence). Correction by **MC simulation** for each trap length. Correspond to –5.3(8) s correction on τ.

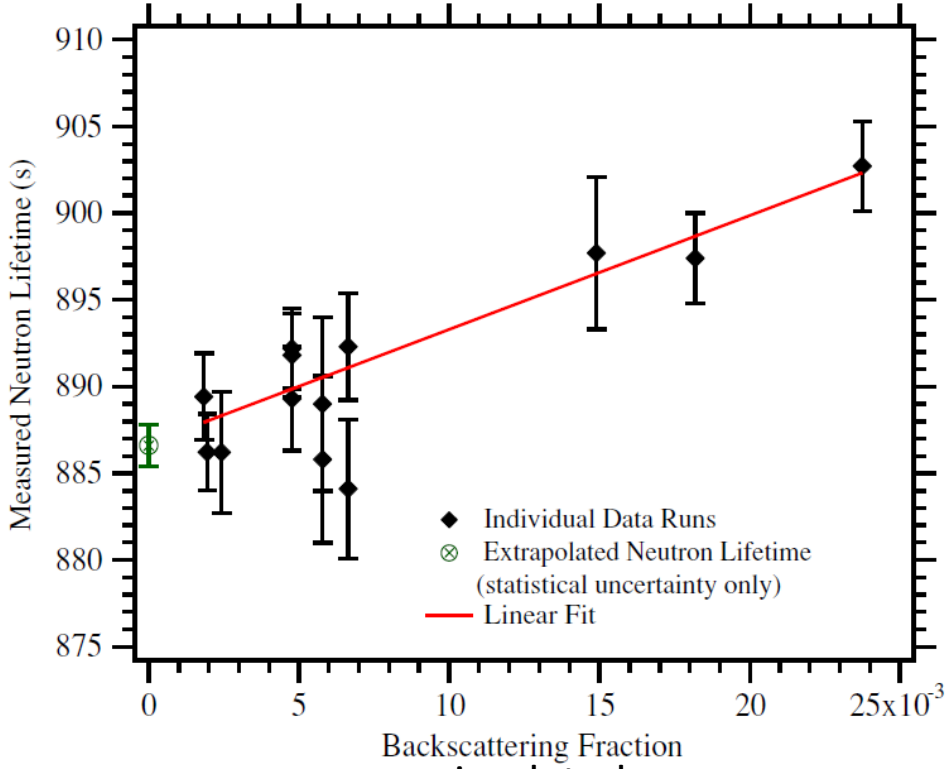
: NIST beam lifetime

Byrne et al, Phys. Rev. Lett. 65 (1990) 289
Byrne et al, EPL 33 (1996) 187
Dewey et al, Phys. Rev. Lett. 91 (2003) 152302
Nico et al, Phys. Rev. C 71 (2005) 055502
Yue et al, Phys. Rev. Lett. 111 (2013) 222501



- Proton acceleration to 25-35 kV
- Detection with Si surface barrier detectors and passive ion-implanted planar detectors
- Measurements with different detectors (dead layers) and acceleration potentials to correct for losses:
  - **Monte Carlo simulation** of fraction of lost $f_{\mathrm{Lost},i}$ and of backscattered $f_{\mathrm{Bsc},i}$ protons for each configuration i
  - Correction of measured life times $\tau_{\mathrm{measured},i}$ for $f_{\mathrm{Lost},i}$
  - **Extrapolation** to 0 backscattering fraction $f_{\mathrm{Bsc},i}$

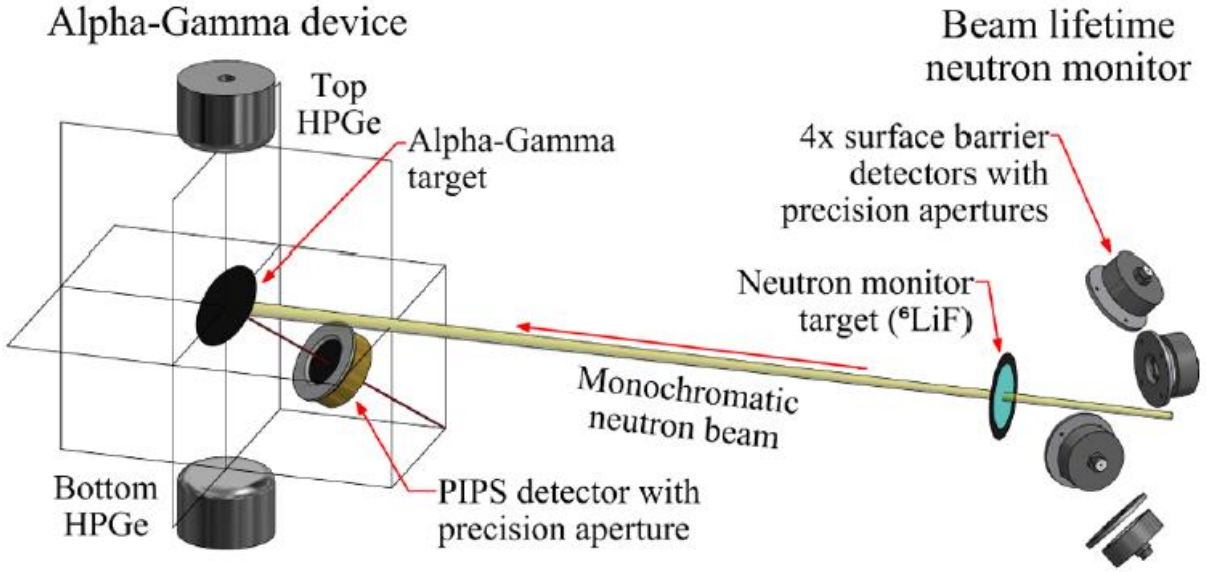
$$\frac{\tau_{\mathrm{measured},i}}{1+f_{\mathrm{Lost},i}} = \tau + X f_{\mathrm{Bsc},i}$$



– simulated –

: NIST beam lifetime post-analysis

Byrne et al, Phys. Rev. Lett. 65 (1990) 289
Byrne et al, EPL 33 (1996) 187
Dewey et al, Phys. Rev. Lett. 91 (2003) 152302
Nico et al, Phys. Rev. C 71 (2005) 055502
Yue et al, Phys. Rev. Lett. 111 (2013) 222501



Extensive calibration of neutron monitor

- Comparison with Alpha-Gamma device → no need to know ^{6}Li(n,t)^{4}He cross section which had relevant uncertainty

$$R_{\alpha,t} = \epsilon_{\mathrm{th}} \frac{\lambda_{\mathrm{mo}}}{\lambda_{\mathrm{th}}} R_n, \quad \lambda_{\mathrm{th}}=1.798\ \text{Å},\ \lambda_{\mathrm{mo}}=4.9605(12)\ \text{Å}$$

- Uncertainty of neutron efficiency, dominating error budget of [Nico05], reduced by factor 5

τ = 887.7(1.2^{stat})(1.9^{sys})s

The Alpha-Gamma device

- Totally absorbing counter of cold and thermal neutrons, counting prompt gammas from $^{10}B_4C$ target
- 2 HPGe detectors calibrated with ^{239}Pu α source against PIPS detector

Source of uncertainty	Correction (s) to [Nico05]	Uncertainty (s)
Improved neutron fluence determination	+1.4	0.5
Change in ^{6}Li deposit mass	+0.0	0.9
Systematics unassociated with neutron fluence	←Largest: neutron halo 1.0, non 1/v of deposit 0.8, trap non-linearity 0.8	1.7
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	+1.4	2.3

No change to the corrections in [Nico05]. Largest:
-5.3 s trap nonlinearity, +5.2 s non 1/v of deposit

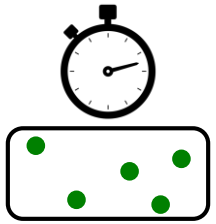
: Summary of important concepts

The long way to precision…

- Use of thin neutron detectors with $\sigma \propto 1/v$ compensating for variations in neutron flight time $T \propto 1/v$ through the decay volume
- Magnetic guidance of the decay products to the detectors for effective 4π detection of the charged decay products
- Use of neutron guides to measure far away from the neutron source in a low-background environment
- In-beam trapping of decay protons and their sudden release onto a detector to considerable reduce background
- Use of a proton trap of variable length eliminating edge effects

D. Dubbers and M. G. Schmidt, Rev. Mod. Phys. 83 (2011) 1111

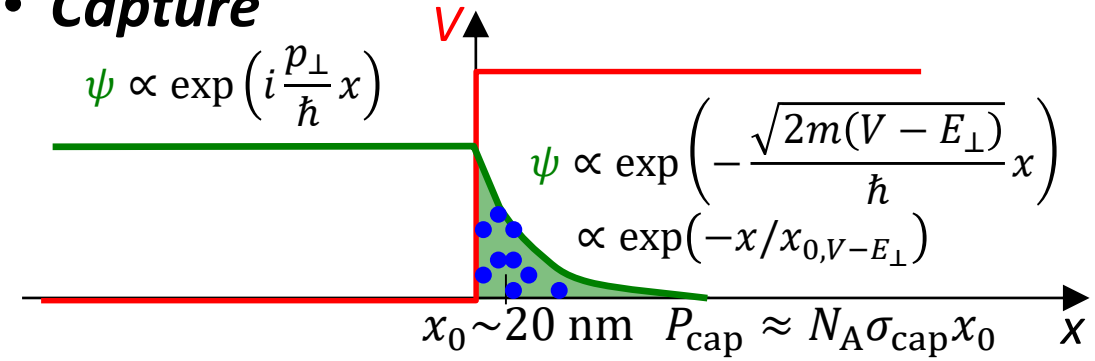
Counting the survivors



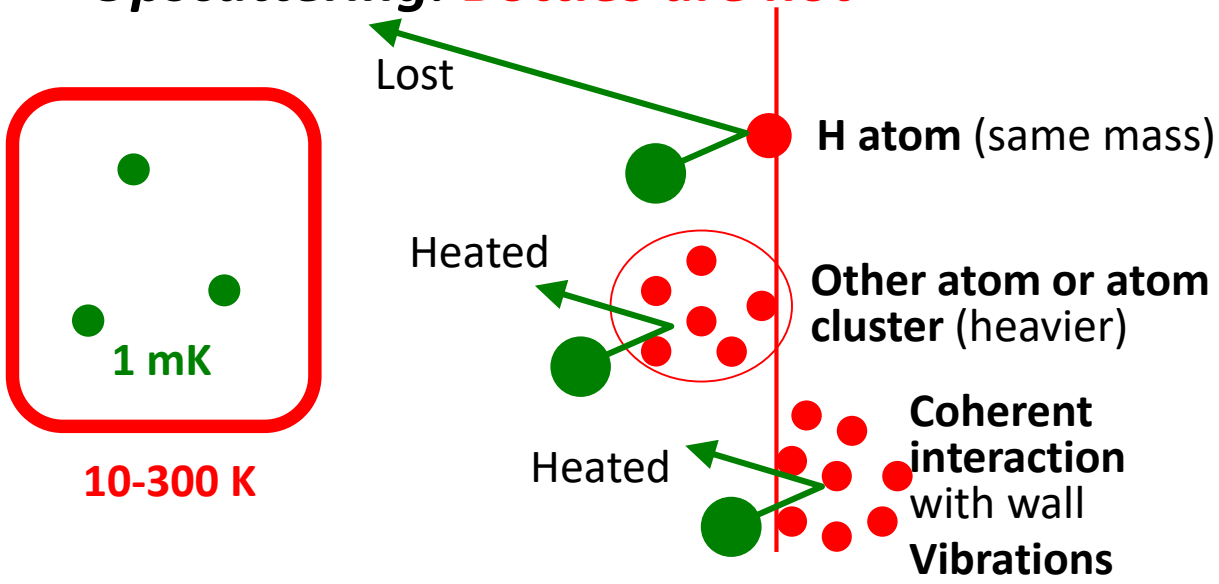
$$N(t) = N_0 \exp\left(-\frac{t}{\tau}\right)$$

Material bottles: Determine losses

- ***Capture***



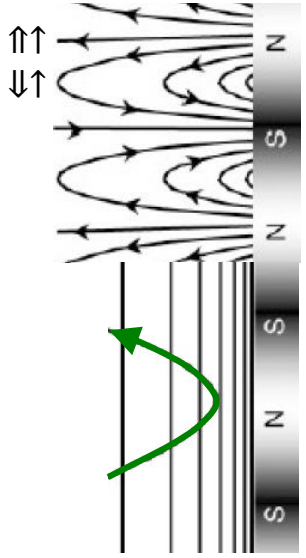
- ***Upscattering: Bottles are hot***



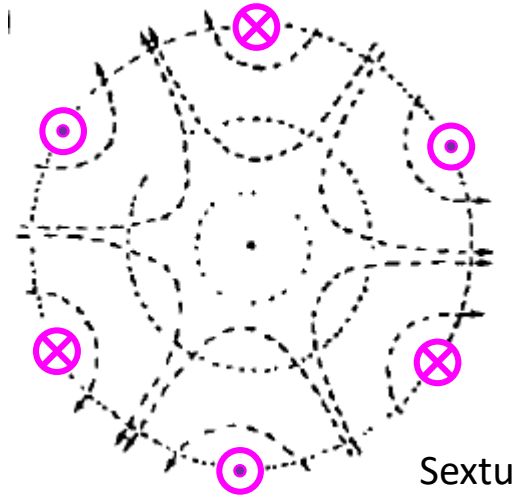
Magnetic bottles: No losses!?

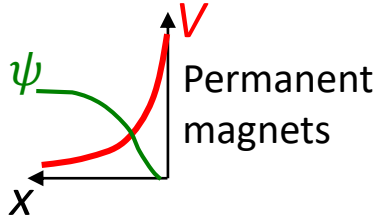
- ***No contact with matter***

$$V = -\boldsymbol{\mu}\,\boldsymbol{B},\ \ \boldsymbol{F} = \pm\mu\boldsymbol{\nabla}|\boldsymbol{B}|$$



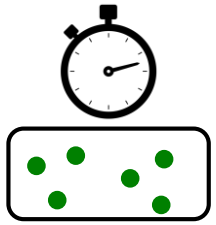
➢Need field gradient





➢Can only store one spin direction

➢Loss by depolarization / spin flip



: Material bottles – Extrapolations

$$N(t) = N_0 exp\left(-\frac{t}{\tau_{\mathrm{Stor}}}\right) \quad \frac{1}{\tau_{\mathrm{Stor}}} = \frac{1}{\tau} + \frac{1}{\tau_{\mathrm{ups}}} + \frac{1}{\tau_{\mathrm{Cap}}} + \frac{1}{\tau_{\mathrm{Other}}}$$

$$\tau_{\mathrm{Stor}} = \frac{\Delta t_2 - \Delta t_1}{\ln(N_1/N_1)}$$

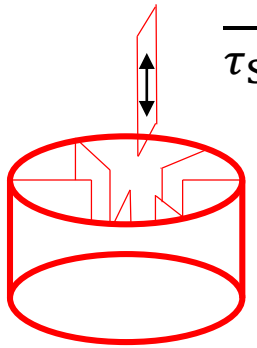
Ideal

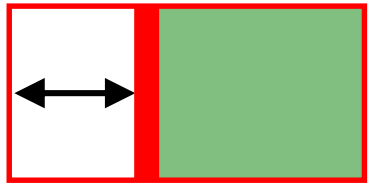
- Typical loss per bounce: $\eta \lesssim \mathfrak{O}(10^{-5})$
- Storage times of several 100 s possible
- **Minimize losses**: Careful selection and preparation of material surfaces
- **Determine losses**: Vary collision rate

$$\gamma = \left\langle \frac{v}{\Lambda} \right\rangle, \quad \Lambda = \frac{4V}{S} \text{ mean free path}$$

in controlled way and extrapolate to 0:

$$\frac{1}{\tau_{\mathrm{Stor}}} = \frac{1}{\tau} + \eta(v)\,\gamma\left(v, \frac{V}{S}\right)$$





Reality

- Losses energy-dependent → Extrapolation only accurate for monoenergetic neutrons
- Initial spectrum not monoenergetic
- Energy for wall interaction height-dependent
- Spectrum of stored neutrons changes with time: faster neutrons → higher losses (via γ and η)
  → More than one time constant τ_{Stor}

$$N(t) = N_0 \sum_i a_i \exp\left(-\frac{t}{\tau_{\mathrm{Stor},i}}\right)$$

- Change of neutron energy by upscattering

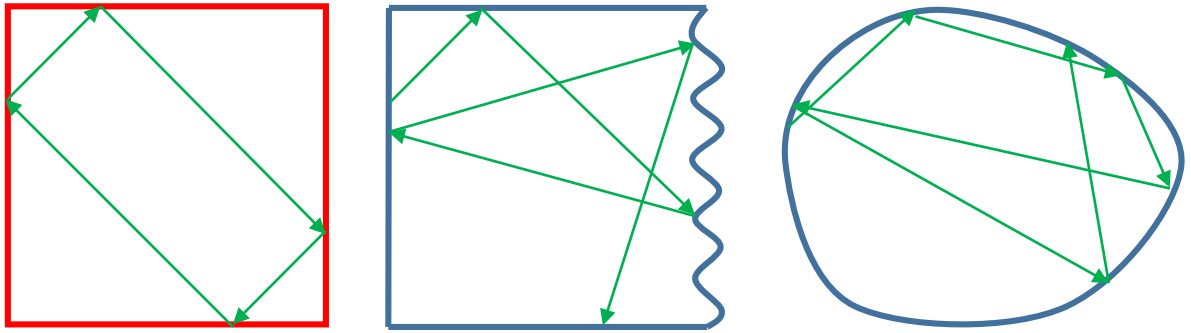
→Calculation of wall loss rate as function of varied feature requires models & assumptions

← [Kosvintsev et al, JETP Lett. 31 (1980) 257] ↑[Mampe et al, Phys. Rev. Lett. 63 (1989) 593]

: Material bottles – Measurement

General considerations

- Extrapolation methods require **isotropic and homogeneous neutron population**
  - →corrugated surfaces to obtain chaotic trajectories and avoid quasi-stable ones



- UCN above wall potentials may be stored for some time on **quasi-stable trajectories**
  - →avoid quasi-stable trajectories
  - →period of spectrum cleaning

- Took over after advent of strong UCN sources available from 1986

General procedure

1. Bottle filling
2. Spectrum cleaning
3. Storing for holding time Δt_i
4. Counting the survivors

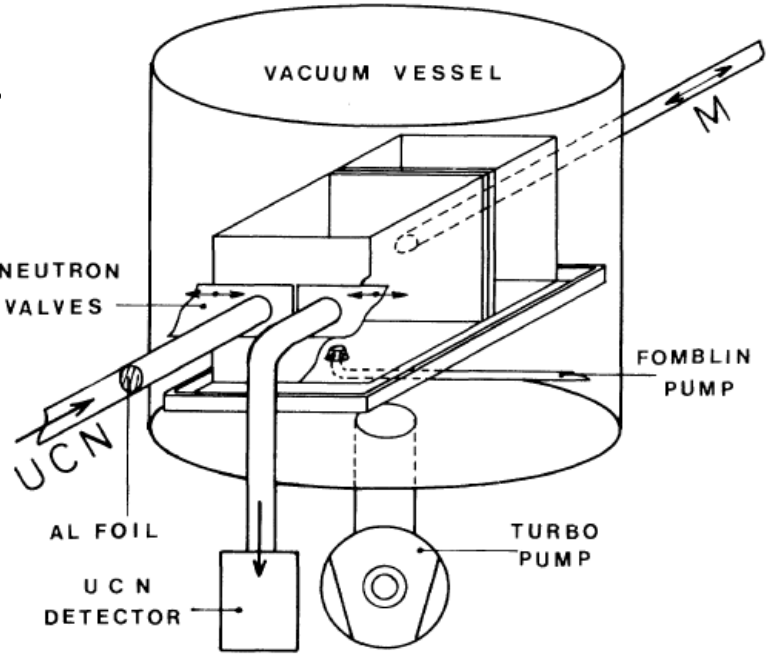
Repeat…

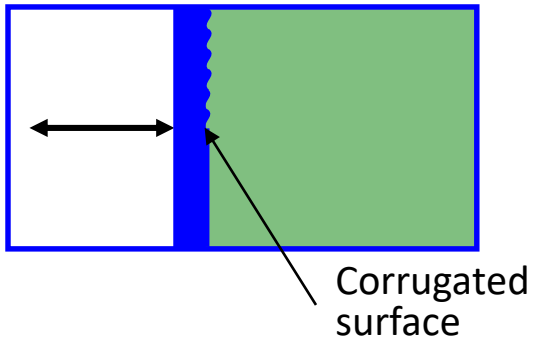
: MAMBO @ PF2/ILL

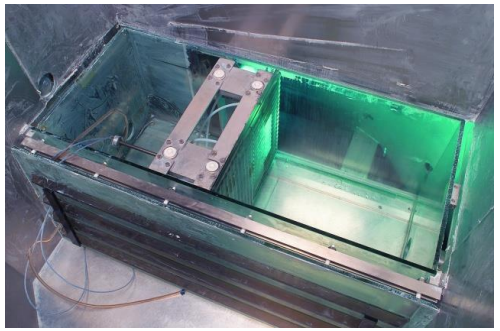
First precision storage experiment (PF2)

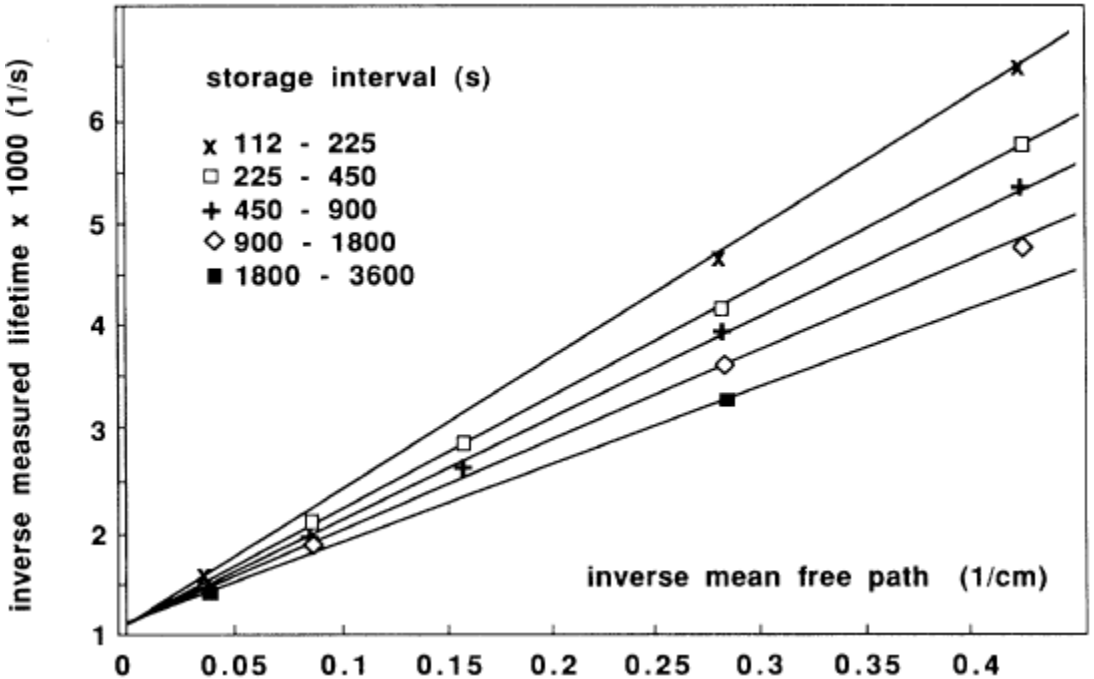
- **Variable volume** up to 120 l
- "Fomblin" oil (hydrogen-free fluorated polymer, 106 neV, η=(2–3)·10^{-5}/bounce) as wall coating
- Temporal spectrum change compensated by choice of storage intervals:

  $\frac{t_1^a}{t_1^b} = \frac{t_2^a}{t_2^b} = \frac{\Lambda^a}{\Lambda^b}$ → number of wall collisions in t_i independent on trap-size for each velocity bin → spectral evolution during storage volume independent
- Largest measured τ_{Stor}=730 s extrapolated by 150 s to τ=887.6(3.0) s







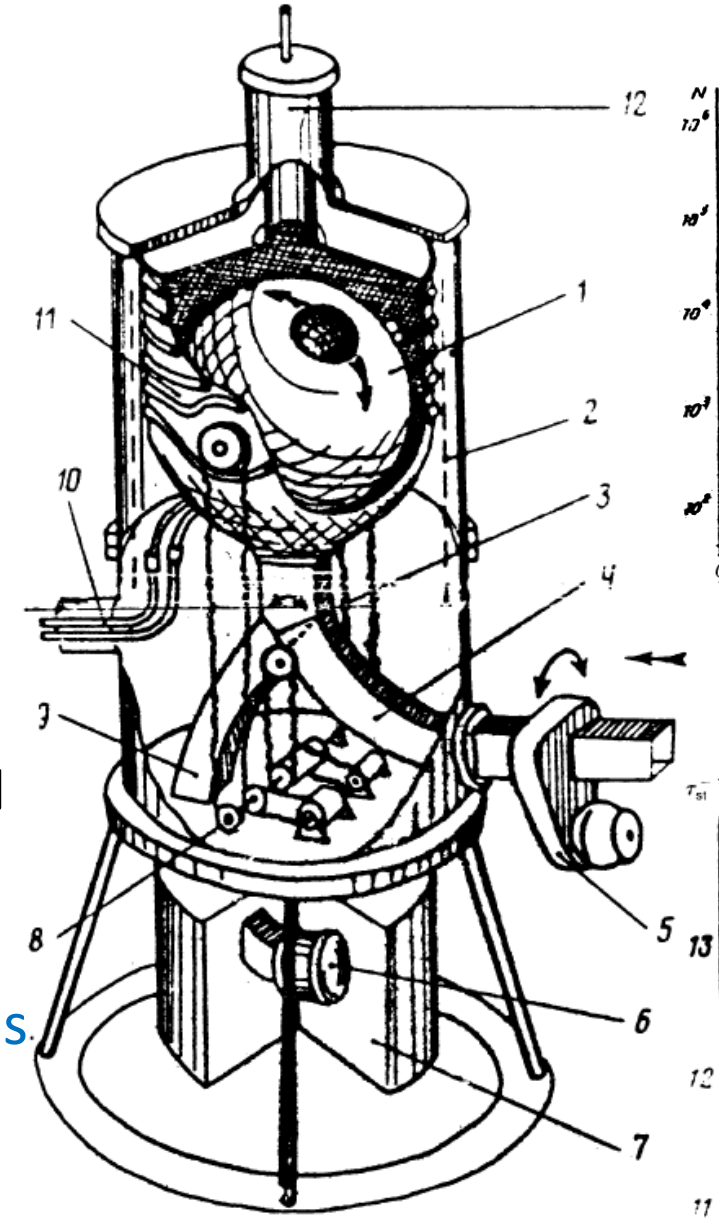


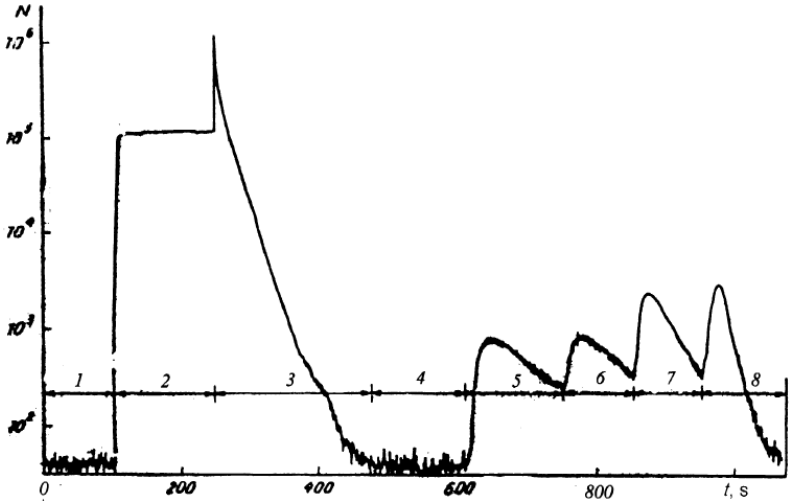
Mampe et al, Phys. Rev. Lett. 63 (1989) 593. Photo probably from MAMBO II.

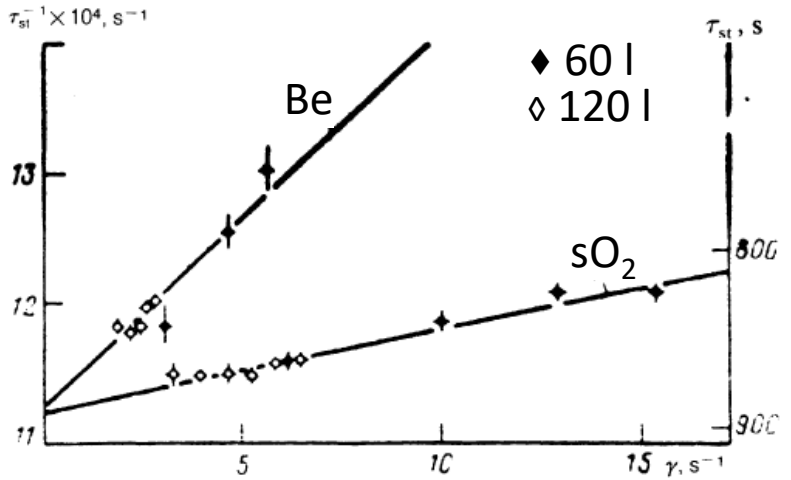
: Gravitational trap @ PNPI

Experiment at lowest temperature

- Confinement by walls and gravity
- Two ways to vary wall collision rate:
  - **Variable spectrum**: Gravitational selection of neutron spectrum
  - **Two volumes**: 60 l and 240 l
- Bottle at 15 K, surfaces Be or coated with solid oxygen
- Successive counting of different UCN energy ranges
- Largest measured τ_{Stor}=876 s extrapolated by 12 s to τ=888.4(3.3) s.





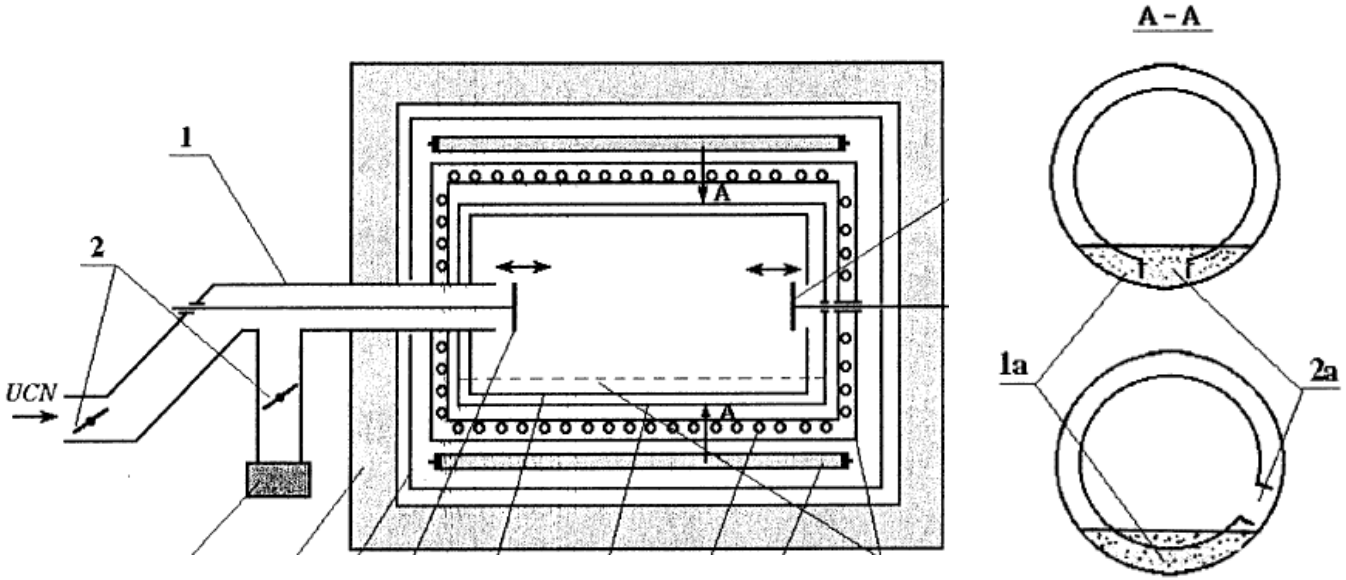


Nesvizhevskii et al, JETP 75 (1992) 405.

: Experiment from KI @ PF2/ILL

Detection of escaping neutrons

- **Two volumes**
- **Detection of upscattered UCN** (thermal neutron detectors around storage volume)
- Measurement of initial N_i and final N_f number of UCN and of upscattered UCN J. All efficiencies cancel in calculation of τ.
- Fomblin coating, measurements at +20, -9 and -26°C.
- Largest τ_Stor=780 s extrapolated by 100 s to τ=885.4(1.0) s



Results so far:

MAMBO:	τ_Stor=730 s	τ=887.6(3.0) s
PNPI trap:	τ_Stor=876 s	τ=888.4(3.3) s
UpsDet trap:	τ_Stor=780 s	τ=885.4(1.0) s
Perfectly consistent:		$\langle\tau\rangle$=885.8(0.9) s

Large extrapolations seem to work, consistent results… **but…**

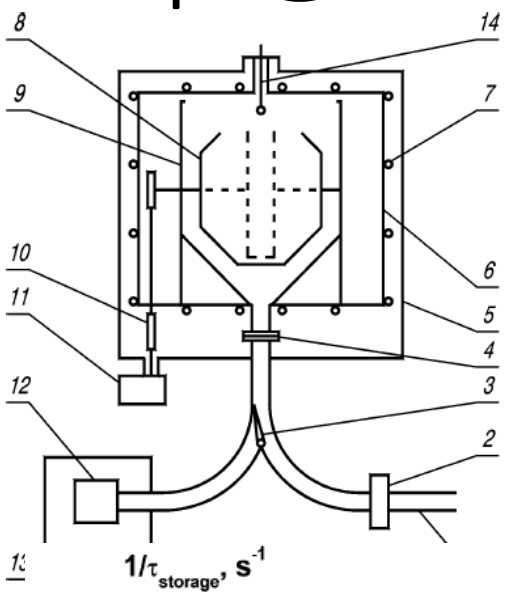
Arzumanov et al, Phys. Lett. B 483 (2000) 15

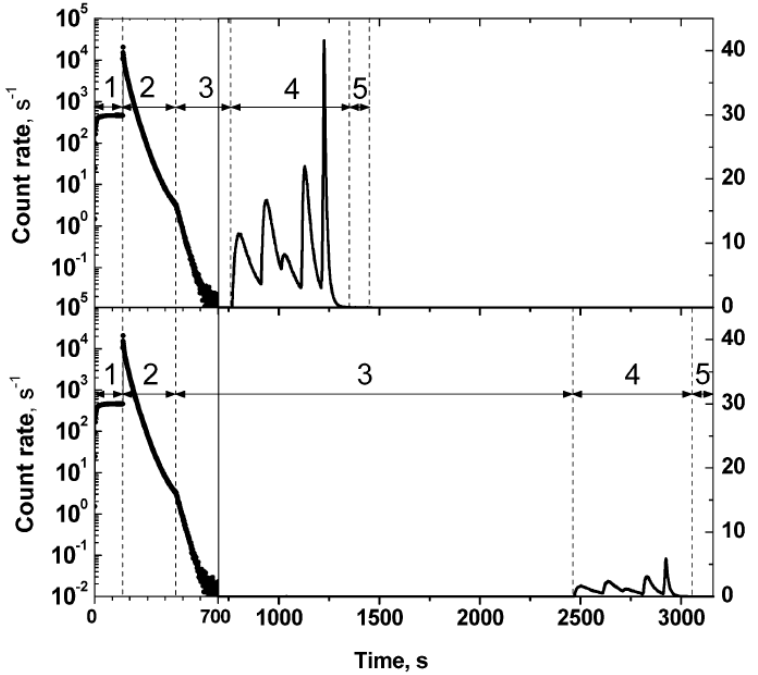
: Gravitational PNPI trap @ ILL

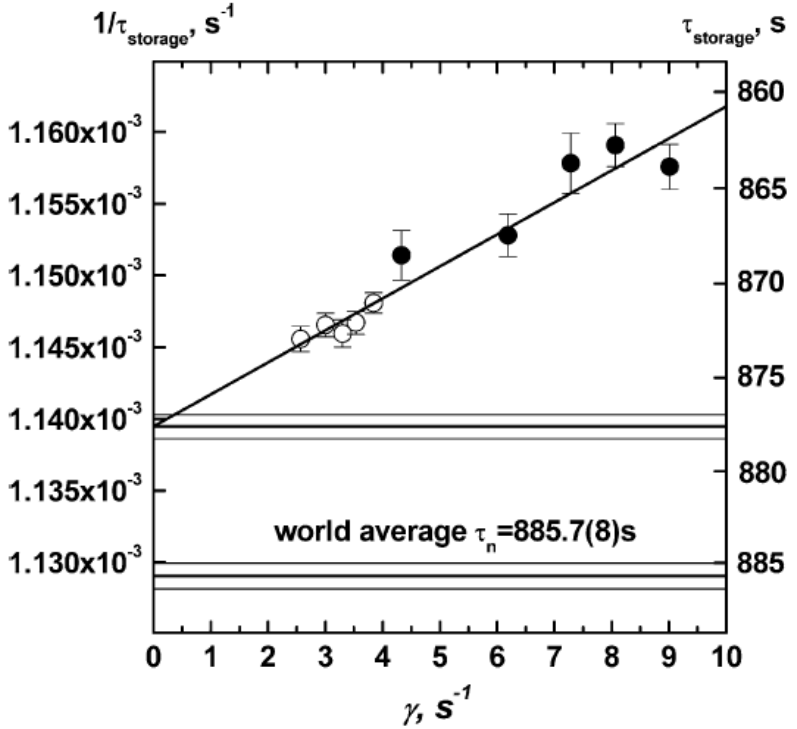
Similar to gravitational trap at PNPI

- Confinement by walls and gravity
- Two ways to vary wall collision rate:
  - **Variable spectrum**: Gravitational selection of neutron spectrum
  - **Two volumes**: 60 l and 240 l
- Coating by low-temperature Fomblin:
  - Full **suppression of quasielastic scattering** below -120°C
  - Low remaining losses: $\eta = 2 \cdot 10^{-6}$
  - Coating tested with Ti compared to Be bottle, more efficient than sO_2
- Largest measured τ_{Stor}=872.2 s extrapolated by 6 s to τ=878.5(0.8) s

Serebrov et al, Phys. Lett. B 605 (2005) 72







5.6 σ deviation from 2005 world average!

: Summary material bottles

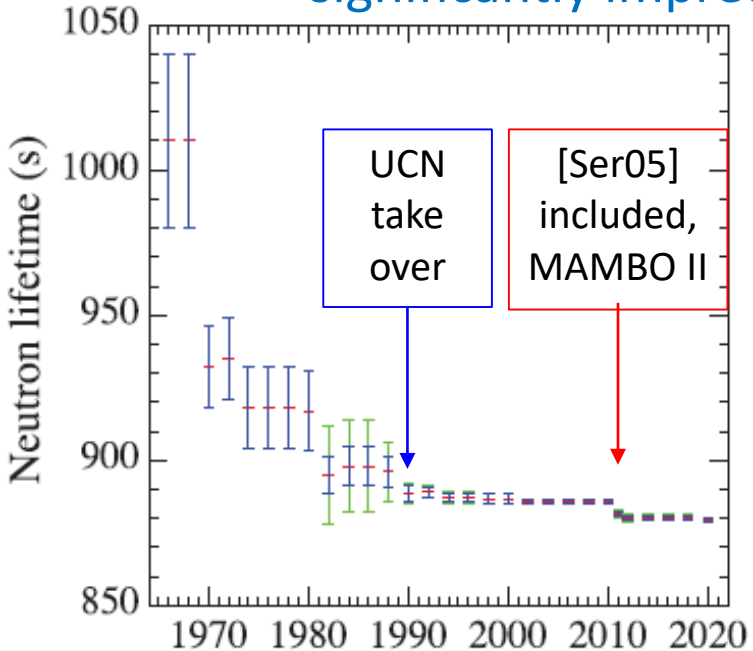
New material storage experiments:
MAMBO II: Pichlmaier et al, Phys. Lett. *B* 693 (2010) 221
New KI trap : Arzumanov et al, *Phys.Lett.B* 745 (2015) 79
New Gravitrap: Serebrov et al, *Phys.Rev.C* 97 (2018) 055503
Corrections to earlier results:
KI trap (2000): Arzumanov et al, *JETP Lett.* 95 (2012) 224
MAMBO (1989): Steyerl et al, *Phys.Rev.C* 85 (2012) 065503

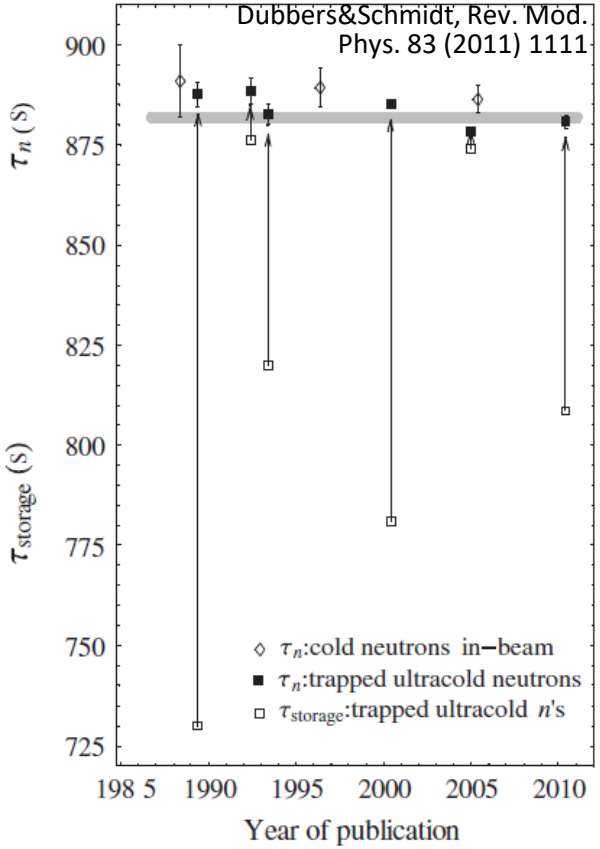
Explanations and consequences

- 2.9σ discrepancy to PNPI (1992) result (same group) may be from imperfections of sO_2 coating for small volume
- Discrepancy of MAMBO and KI traps (at higher temperatures) probably caused by weak heating of UCN not known at the time, plus heating by shutter movements
- Corrected value for KI trap and result of MAMBO II (2010) consistent with Serebrov 2005
- Serebrov 2005 value was excluded from PDG average until 2010 since too far off, but finally "initiated" shift in bottle value

Lessons

- Agreement with other results does not tell that yours is "right".
- If your result disagrees, it may still be "right"!
- Small corrections are good – but can still be significantly imprecise.





: Magnetic storage

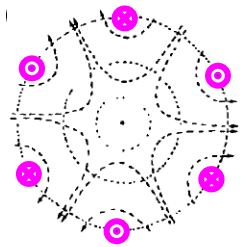
Kugler et al, Phys. Lett B 72 (1978) 422
Kugler et al, Nucl. Instr. Meth. 228 (1985) 240
Paul et al, Z. Phys. C 45 (1989) 25

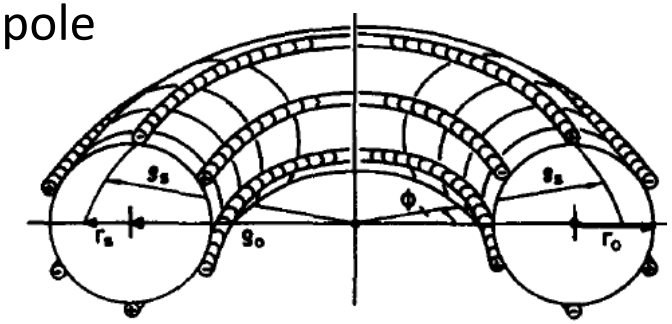
First lifetime measurement with NESTOR

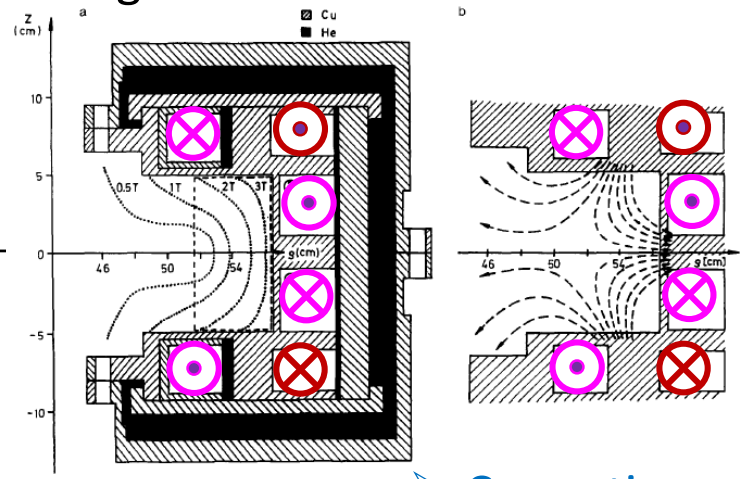
- Guiding and focusing of neutral atoms and neutrons by sextupole field proposed in 1951

Friedburg&Paul, Naturwiss. 38 (1951) 159
Paul, Int Conf Nucl Phys & Phys Fund Part, Chicago (1951) 172

- Magnetic storage ring for neutrons:
  - ➢ Analogy with charged particles. Magnetic moment requires multipoles one order higher
  - → Sextupole





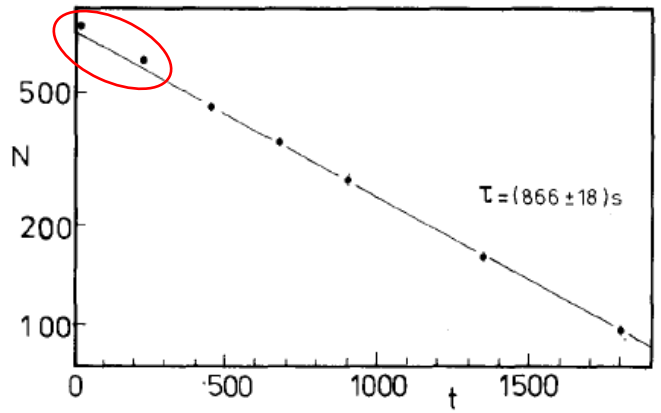


  - ➢ Inner coils replaced by centrifugal force (access, filling from inside)
  - ➢ Additional coils add higher-order term to harmonic field, to limit oscillation amplitudes

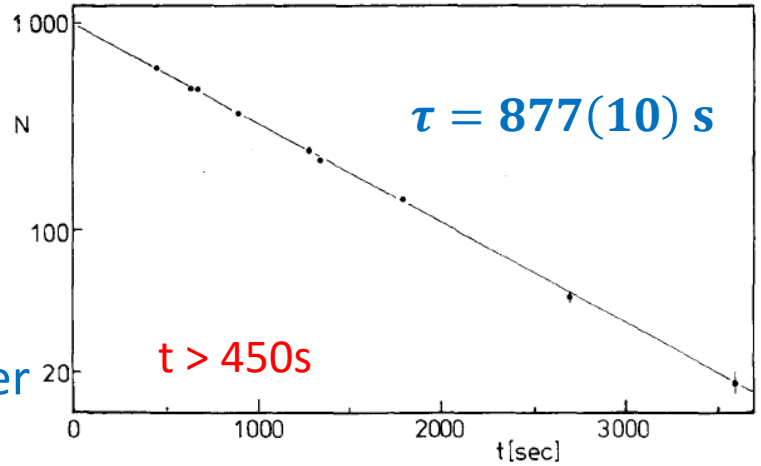
Final result at new, intense UCN source – PF2

- Storage only in radial directions. Trajectories which could mix longitudinal and radial velocities to be removed

➢ Importance of cleaning →



➢ Correction- and model-free lower limit on τ →



: Magnetic storage

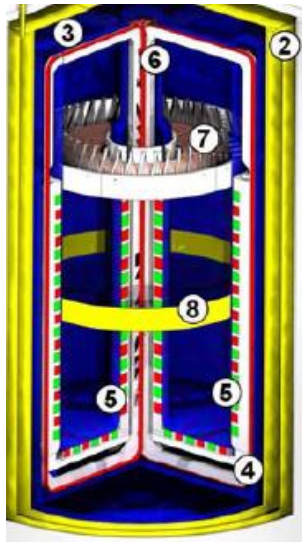
Losses and Counting

- **Can only store low field seekers**
  → Losses by depolarization
  - Adiabaticity condition:
    $$\frac{1}{B}\frac{dB}{dt} \ll \frac{-2\mu_n}{\hbar} B \equiv \omega_{\mathrm{L}}$$
  - Avoid $B = 0$, cancelation of fields
- **Marginally trapped neutrons**
  - Prevent quasi-stable trajectories
  - Clean the UCN spectrum
- **Count survivors or decay products – it remains a "bottle" experiment:**

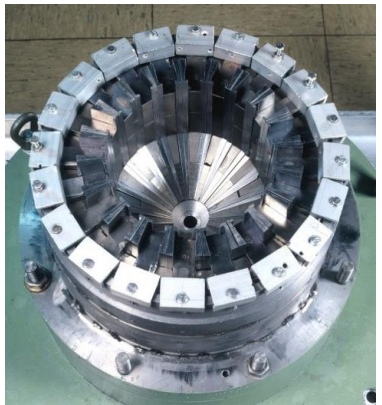
$$\frac{N_n(t)}{N_n(0)} = \frac{n_{e,p}(t)}{n_{e,p}(0)} = \exp\left(-\frac{t}{\tau_{\mathrm{Stor}}}\right)$$

Experiments

- Magnetic field from coils



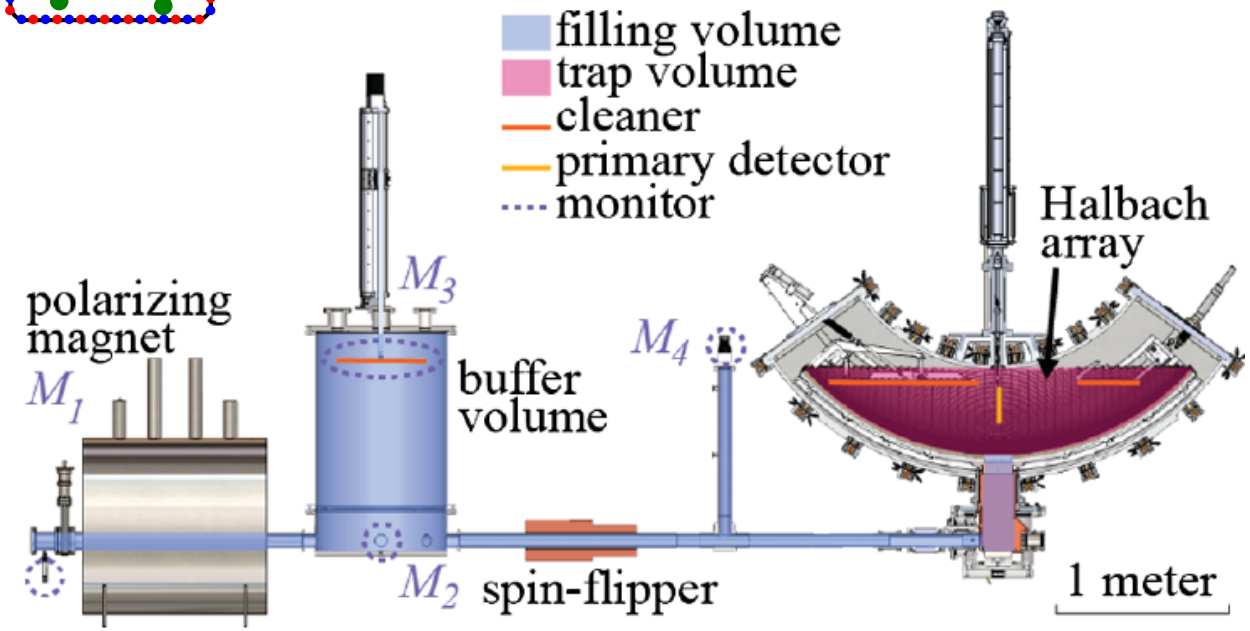
  - **NESTOR** $\tau = 877(10)$ s
  - **NIST-UCN experiment** Huffman et al, Nature 403 (2000) 62
    - In-situ UCN production and storage in 250 mK ^{4}He bath Dzhosyuk et al, J. Res. Natl. Inst. Stand. Technol. 110 (2005) 339
    - Detect decay electron by He scintillation
      $\tau = 833^{+74}_{-63}$ s
  - ← **PENeLOPE** Materne et al, Nucl. Instr. Meth. A 611 (2009) 176
- Magnetic field with permanent magnets



  - ← **Magneto-gravitational trap** Ezhov et al, JETP Lett. 107 (2018) 671
    $\tau = 878.3(1.9)$ s
  - **UCNτ** Next slide
  - **Hope** $\tau = 878(39)\ s$ Leung et al, Phys. Rev. C 94 (2016) 045502
  - **τSPECT** https://ultracoldneutrons.uni-mainz.de/tauspect/

: UCNτ @ LANL

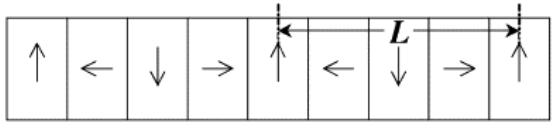
Gonzales et al, Phys. Rev. Lett. 127 (2021) 162501
Pattie et al, Science 360 (2018) 627



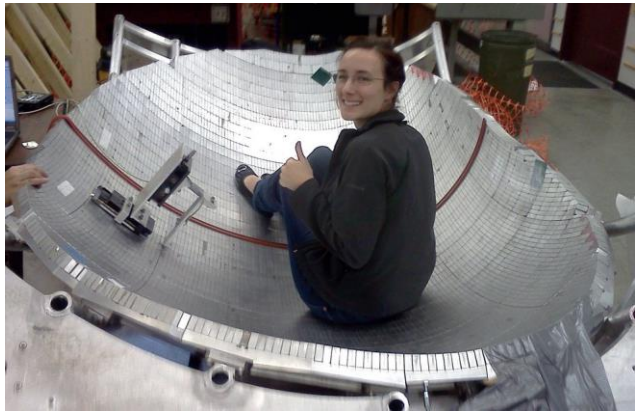
Trap

- M_i: Monitor detectors to correct for variations in UCN source intensity and UCN energy spectrum (e.g. D_2 crystal quality)
- Buffer volume for pre-cleaning and smoothing of fluctuations in UCN production rate (2018)

Trap

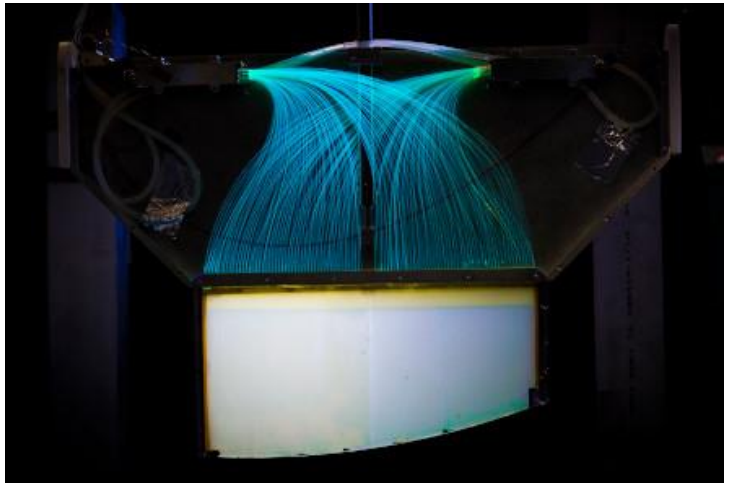


- NdFeB Halbach array
- Asymmetric bowl-shaped trap + ripple for chaotic trajectories
- Trap height 50 cm (51 neV)
- 60-120 G holding field
- Magnet door for filling from below



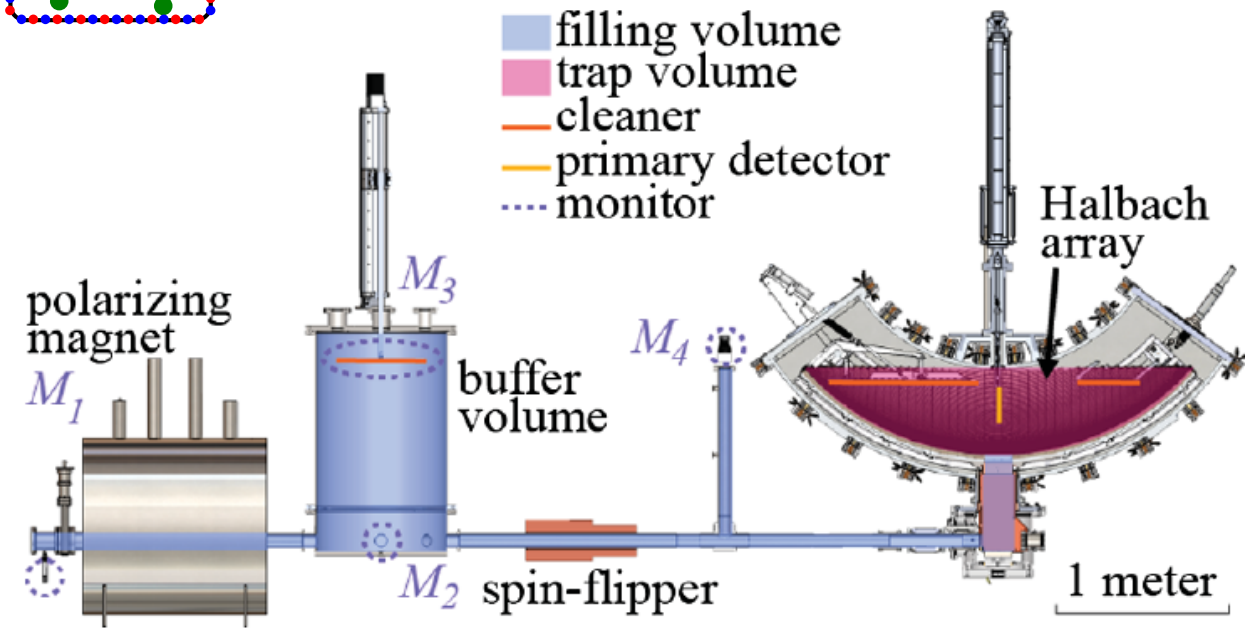
UCN detector

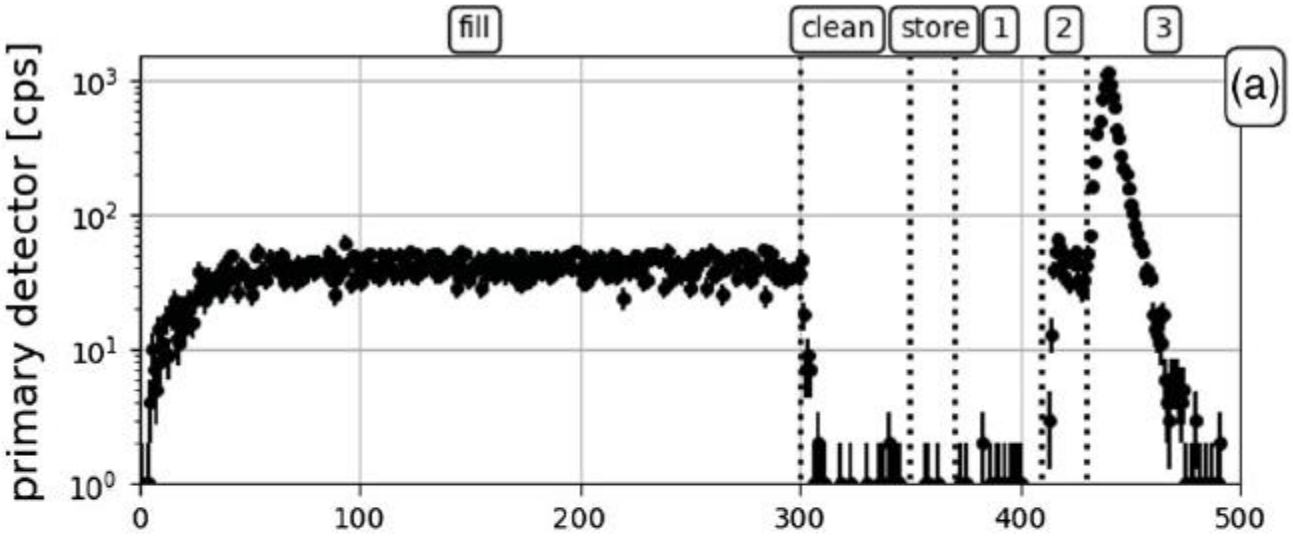
- ^{10}B-coated ZnS scintillator



: UCNτ @ LANL

Gonzales et al, Phys. Rev. Lett. 127 (2021) 162501
Pattie et al, Science 360 (2018) 627



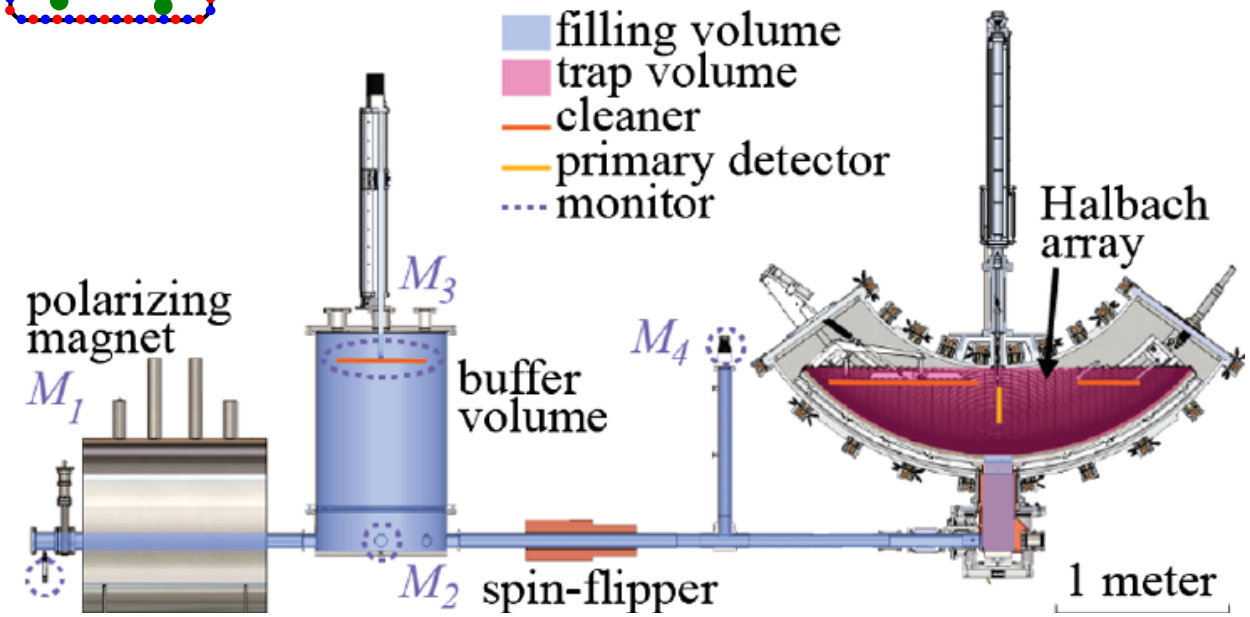


Measuring procedure

1) UCN from source: $E_n \lesssim 180$ neV
2) Polarize (5.5 T solenoid) and spin-flipp to become low-field seeker
3) Fill (from below)
4) Clean: $E_n \gtrsim 38$ neV (50 s), lift cleaners
   - Upscattering by PE sheets
   - Capture in lowered detectors
5) Hold for 20 … 1550 s
   - Pairs of short and long holding times ($\lesssim$500 s)
   - **Blinding**: Adjust nominal holding times by factor unknown to analysis team
6) Count with detector lowered from top:
   - At height of cleaners (40 s): detect uncleaned or heated UCN
   - Middle (20 s)
   - Bottom (150 s)

: UCNτ @ LANL

Gonzales et al, Phys. Rev. Lett. 127 (2021) 162501
Pattie et al, Science 360 (2018) 627



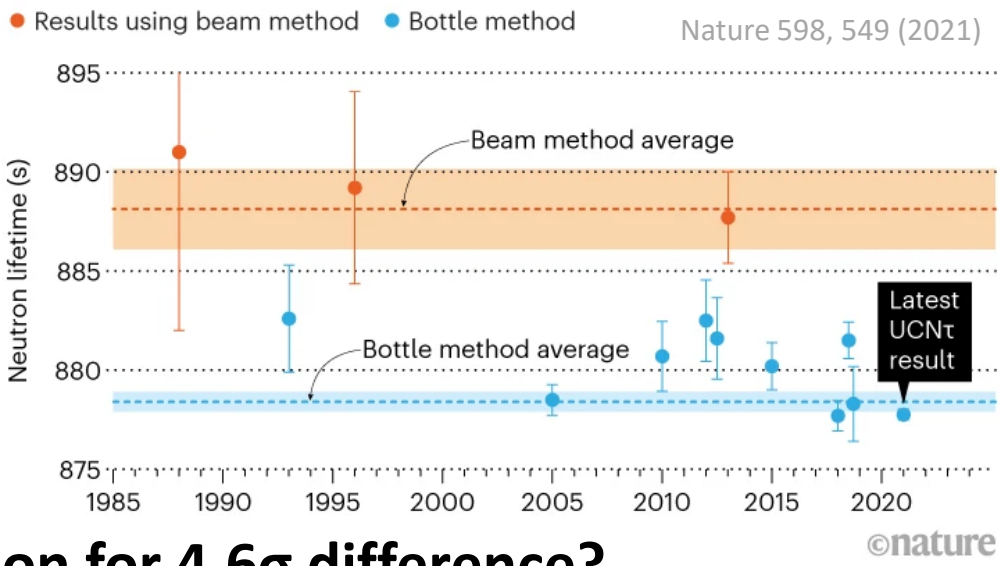
Effect	Correction	Uncertainty
UCN event definition	···	±0.13
Normalization weighting	···	±0.06
Depolarization	···	+0.07
Uncleaned UCNs	···	+0.11
Heated UCNs	···	+0.08
Al block	+0.06	±0.05
Residual gas scattering	+0.11	±0.06
Uncorrelated sum	$0.17^{+0.22}_{-0.16}$ s	

Analysis

- 3 analyses A, B, C (methods, algorithms, choices)
- Long scintillation time constants of ZnS result in rate-dependent effects (dead time, pileup, …)
  Different strategies in analysis C
- Paired analysis: Combine each pair of short and long holding time. Weighted average
  - ➢ Less sensitivity to long-term drifts
- Global analysis: Maximize likelihood of observing data for global τ and nuisance parameters
  - ➢ Higher statistical sensitivity
- Depolarization from varying holding field, fit
  $\lambda_{\mathrm{DP}} = 0.0^{+1.0}_{-0.0} \cdot 10^{-7}\ \mathrm{s}^{-1}$
- Gas up-scattering calculated run by run from pressure and periodic rest gas analysis data

$$\boldsymbol{\tau = 877.75 \pm 0.28_{\mathrm{stat}} + 0.22/-0.16_{\mathrm{sys}}\ \mathrm{s}}$$

Status of the neutron lifetime



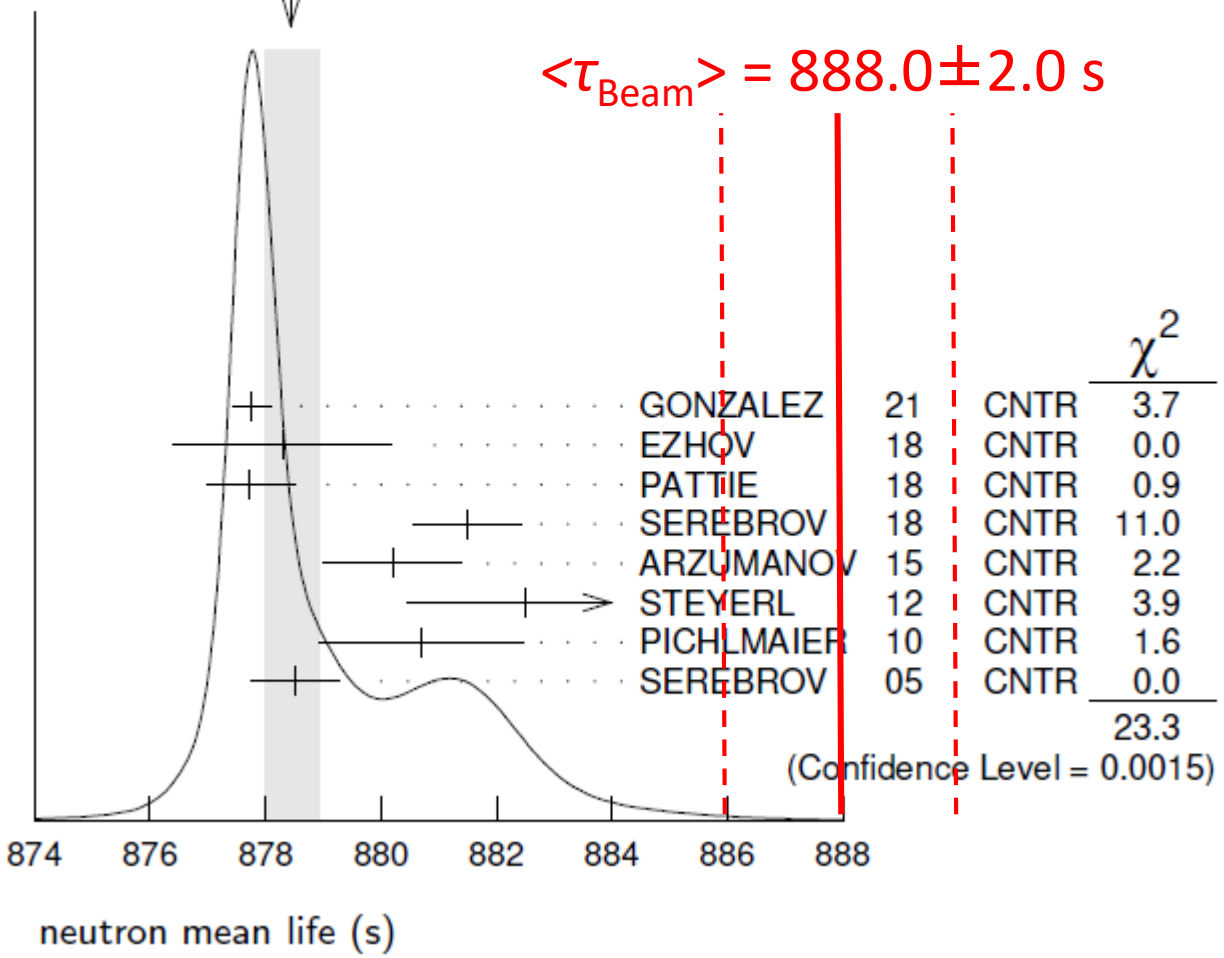
PDG 2023

WEIGHTED AVERAGE
878.4±0.5 (Error scaled by 1.8)

Beam lifetime not included

Little influence: 878.6±0.6 s (esf 2.2)

$\langle\tau_{Beam}\rangle$ = 888.0±2.0 s

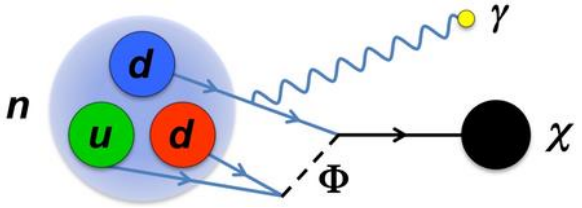


Explanation for 4.6σ difference?

- τ_{Beam} partial lifetime into proton
- τ_{Bottle} inclusive lifetime (all branches)

Invisible branches of $\mathfrak{O}(1\%)$?

- $n \to H + \bar{\nu}$ expected is $4 \cdot 10^{-6}$, $\Delta\tau$ gives experimental upper limit — Green & Thompson, J. Phys. G 16 (1990) L75
- Dark Decay — Fornal & Grinstein, Phys. Rev. Lett. 120 (2018) 191801
  - $n \to \chi\,\gamma$
  - $n \to \chi\, e^+e^-$
  - $n \to \chi\,\varphi$



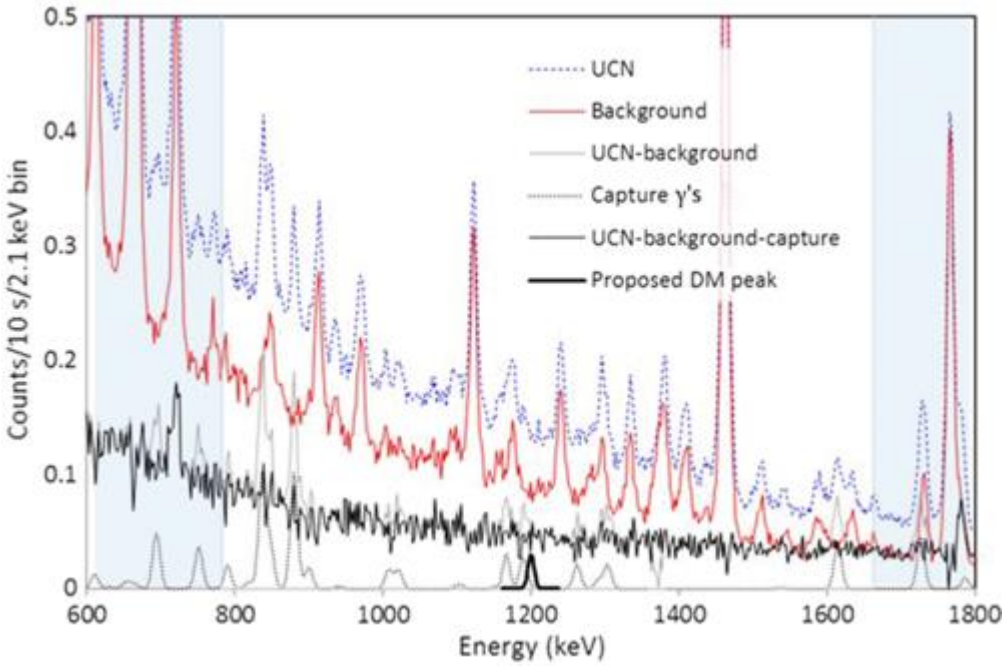
- Oscillation to mirror neutrons — Greene & Geltenbort, Sci.Am. 314 (2016) 36

Searching the invisible branches

$\boldsymbol{n \rightarrow \chi + \gamma}$

monoenergetic γ in range 782…1664 keV

→ Search with Compton-suppressed Ge detector at LANL, 1% branch excluded with 97% C.L.

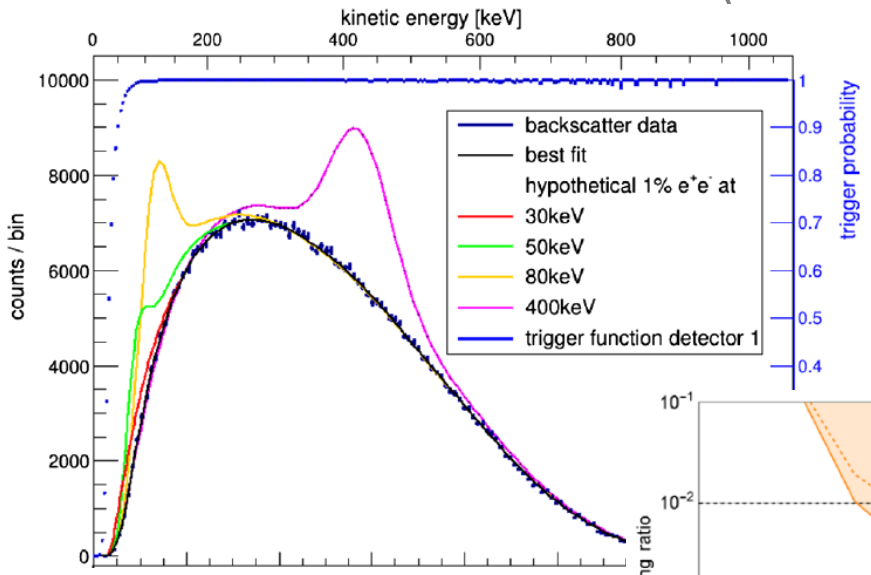


Tang et al, Phys. Rev. Lett. 121 (2018) 022505

$\boldsymbol{n \rightarrow \chi + e^{+} + e^{-}}$

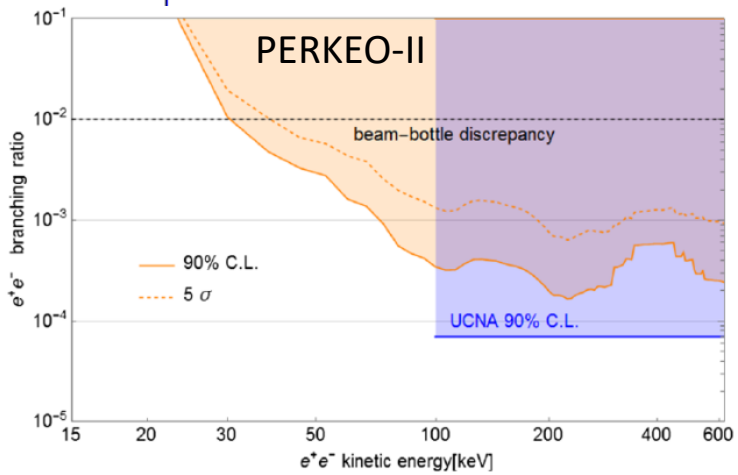
monoenergetic $e^{+}e^{-}$ pair

→Search for peak in beta spectrum in UCNA and PERKEO-II data (see Lecture II)



← PERKEO-II: Klopf et al, Phys. Rev. Lett. 122 (2019) 222503

UCNA: Sun et al, Phys. Rev. C 97 (2018) 052501



Constraining all invisible branches/channels

Conserved Vector Current

- $Ft_{0+\to 0+}$ must be equal to vector part of neutron Ft value, calculated with λ

→Calculate beta decay lifetime from $Ft_{0+\to 0+}$ and λ (from A):

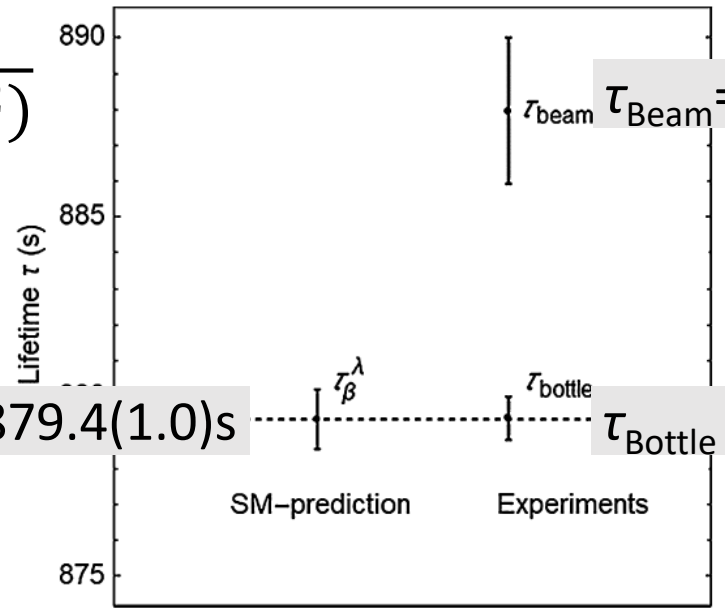
$$\tau_\beta^\lambda = \frac{2}{\ln 2}\frac{\langle Ft_{0^+\to 0^+}\rangle}{f(1+\delta_R')(1+3\lambda^2)}$$

$$= \frac{5172.3(1.1)\ \mathrm{s}}{1+3\lambda^2}$$

Independent on Δ_R!

Lifetime experiments

- τ_{Beam} partial lifetime into proton, **should correspond to τ_β^λ**
- τ_{Bottle} inclusive lifetime (all branches) **does agree with τ_β^λ**



τ_{Beam} = 888.0(2.0)s

τ_β^λ = 879.4(1.0)s

τ_{Bottle} = 879.4(0.6)s

$\tau_\beta^\lambda - \tau_{\mathrm{Bottle}}$ gives limit

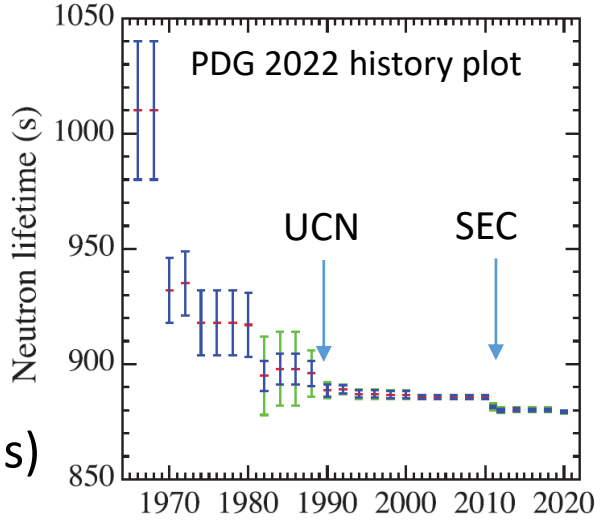
BR_{Dark} < 0.16% (95% C.L.)

(values from 2019)

→ Lifetime puzzle cannot be explained by dark decays

Czarnecki et al, Phys. Rev. Lett. 120 (2018) 202002
Czarnecki et al, Phys. Rev. D 100 (2019) 073008
Dubbers et al, Phys. Lett. B 791 (2019) 6

Outlook



$\tau_{PDG2023}$ = 878.4±0.5 s (with scaling factor 1.8)

Beam lifetime

- NIST experiment: **BL3** (<0.3 s)
  - Larger magnet and trap
  - Improved systematics
- **TPC** experiment at J-PARC
  - Similar to drift chamber experiment

Magnetic storage

All precision goals from arXiv:2304.03451

- **UCNτ** (<0.15 s)
  - Further improved results expected
  - UCNτ+: fill trap with adiabatic transfer technique to increase statistics
- **PENeLOPE, τSPECT**

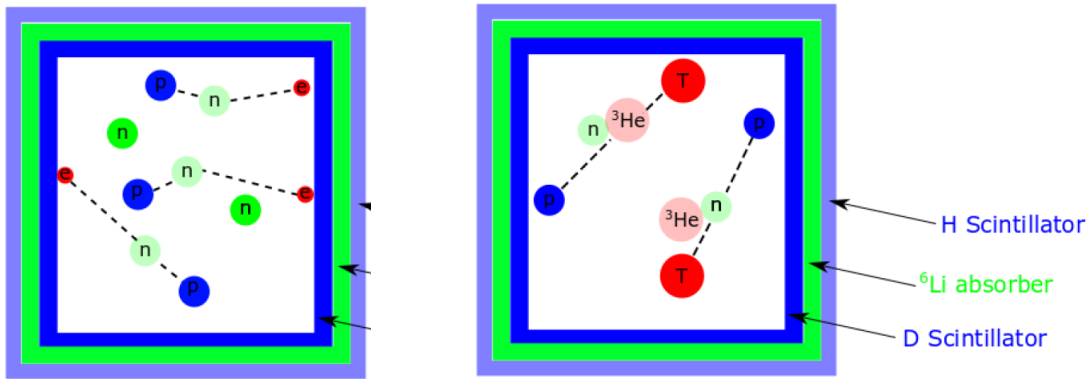
An ultimate experiment?

- Counting the dead, in absolute terms relative to the stored neutrons, and the survivors
- Just counting the dead in a storage experiment is not equivalent to beam method! :

$$\frac{N_n(t)}{N_n(0)} = \frac{n_p(t)}{n_p(0)} = \frac{n_e(t)}{n_e(0)} = \exp\left(-\frac{t}{\tau_{\mathrm{Stor}}}\right)$$

- **UCNproβe** (1.2 s): count number of decay electrons and the number of UCNs in trap to 0.1%

https://indico.fysik.su.se/event/6570/contributions/9964/attachments/4125/4727/nordita.pdf→



Literature

- D. Dubbers and M. G. Schmidt, *The neutron and its role in cosmology and particle physics*, Rev. Mod. Phys. 83 (2011) 1111.
- F. E. Wietfeldt and G. L. Greene, *The neutron lifetime*, Rev. Mod. Phys. 83 (2011) 173.
- D. Dubbers and B. Märkisch, *Precise Measurements of the Decay of Free Neutrons*, Annu. Rev. Nucl. Part. Sci. 71 (2021) 139.
- F. E. Wietfeldt, *Measurements of the Neutron Lifetime*, Atoms 2018, 6, 70.
- A. Steyerl, *Ultracold Neutrons*, World Scientific (2020).