Neutron Lifetime Measurements

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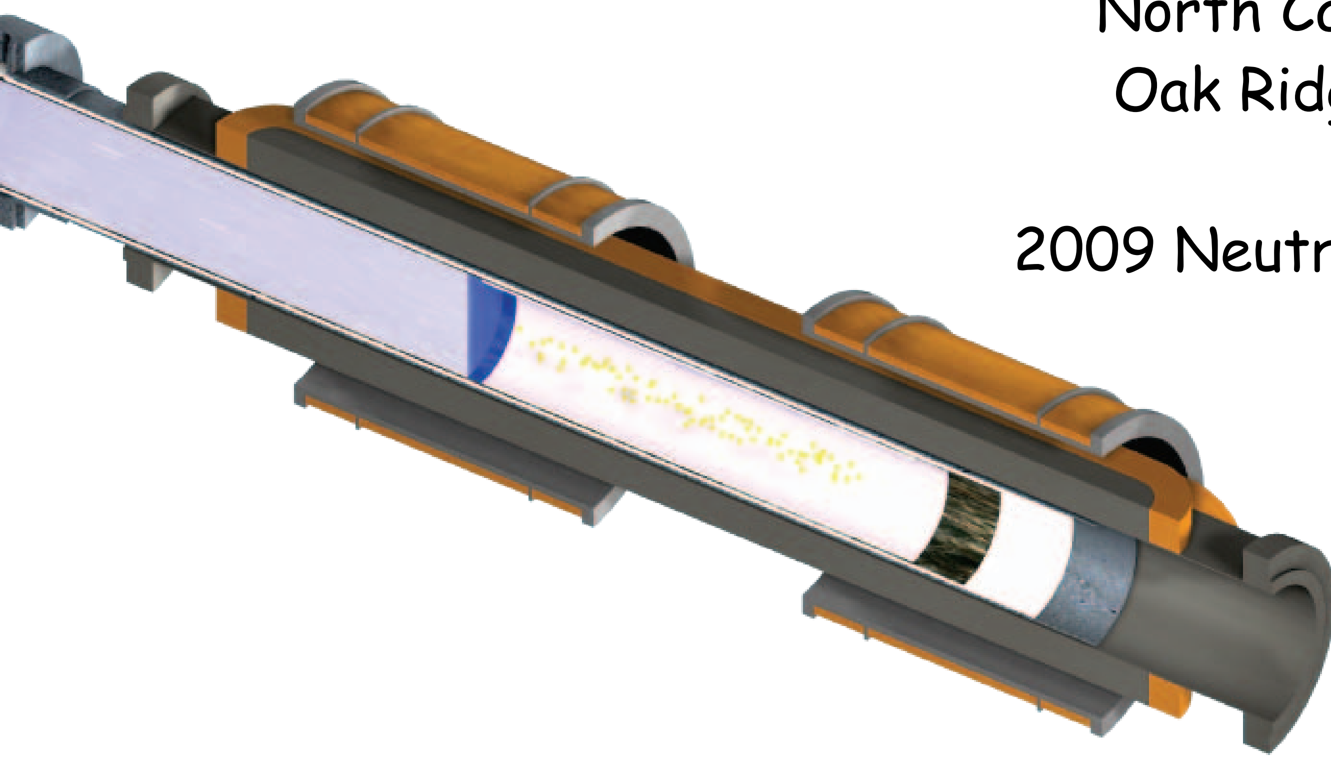
2009 Neutron Physics Summer School



NC STATE UNIVERSITY

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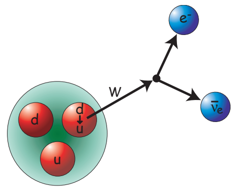
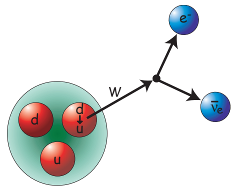
Outline



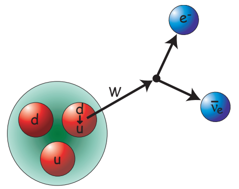
- History of the lifetime
  (short - only about 15 minutes)
- Physics highlights (not previously covered)
- Measurements that constitute the world average
- Measurements either in progress or under development

Measuring the Lifetime: The Early Years



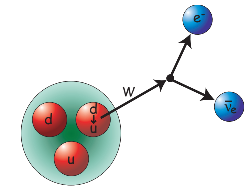
It took many years from the discovery of the neutron by Chadwick in 1932 and the conjecture of its instability by Chadwick & Goldhaber in 1935 until its radioactive decay was observed in 1948.

Why is it so Difficult?



- Long lifetime -> low decay rate
- Limited numbers of neutrons
- Difficult to obtain a "well-defined" sample
- Many ways to either lose neutrons from your container or miss counting them

The early years



PHYSICAL REVIEW VOLUME 74, NUMBER 9 NOVEMBER 1, 19

Proceedings of the American Physical Society

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

F12. On the Radioactive Decay of the Neutron. ARTHUR H. SNELL AND L. C. MILLER, *Clinton National Laboratories.*—A collimated beam of neutrons, three inches in diameter, emerges from the nuclear reactor and passes axially through a thin-walled, aluminum, evacuated cylindrical tank. A transverse magnetic field behind the thin entrance window cleans the beam of secondary electrons. Inside the vacuum, axially arranged, an open-sided cylindrical electrode is held at +4000 volts with respect to ground. Opposite the open side a smoothed graphite plate is held at −4400 volts. The field between these electrodes accelerates and focuses protons which may result from decay of neutrons, so that they pass through a $2\frac{7}{8}\times 1\frac{5}{8}$ inch aperture in the center of the graphite plate, and strike the first dynode of a secondary electron multiplier. The first dynode is specially enlarged so as to cover the aperture. Readings are taken (1) with and without a thin B^{10} shutter

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

Proton counter

n lifetime must exceed 21 minutes

PHYSICAL REVIEW VOLUME 77, NUMBER 5 MARCH 1, 1950

Proceedings of the American Physical Society

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

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

Proton counter

n lifetime between 13 and 26 minutes

1st "precise" lifetime experiment
Robson et al., 1951

Chalk River reactor; 3 cm diameter beam
thermal beam with 2×10^9 n/cm^2/s flux

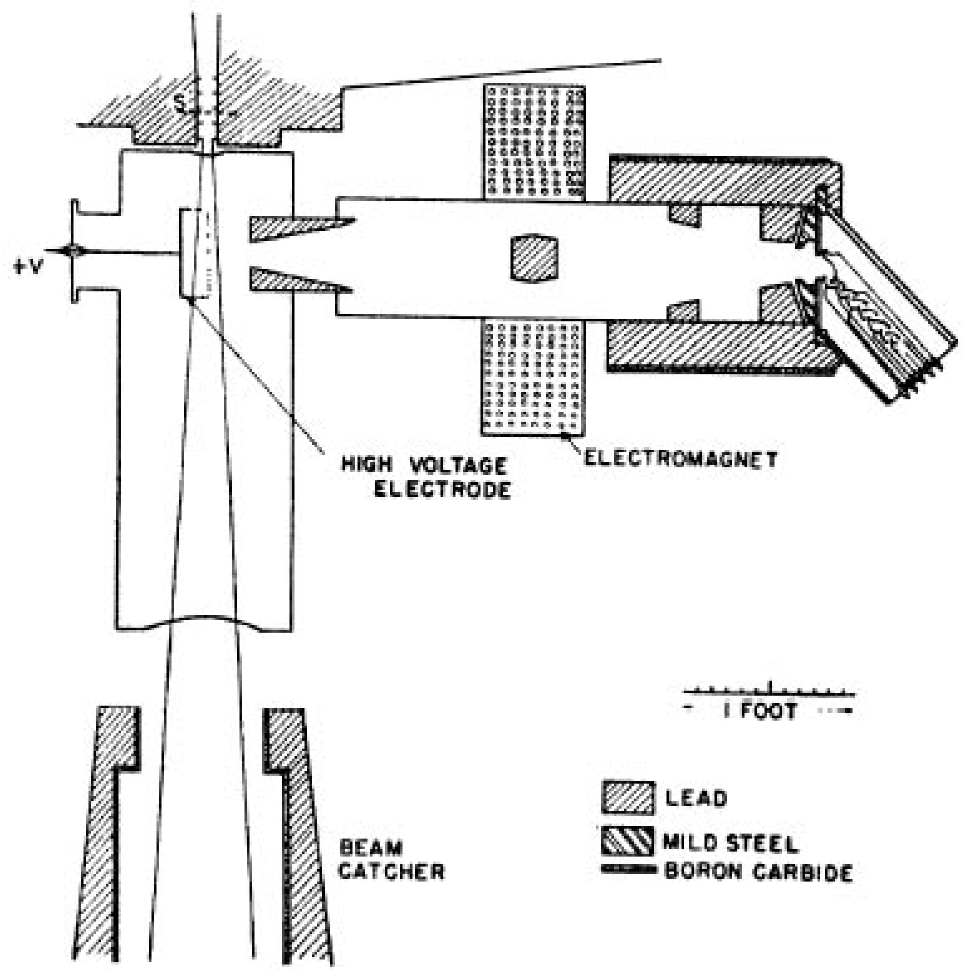


FIG. 1. Plan view of the apparatus.

e-p coincidence
τ_n = 1108 (216) s

A major step forward
Christensen et al. in 1972

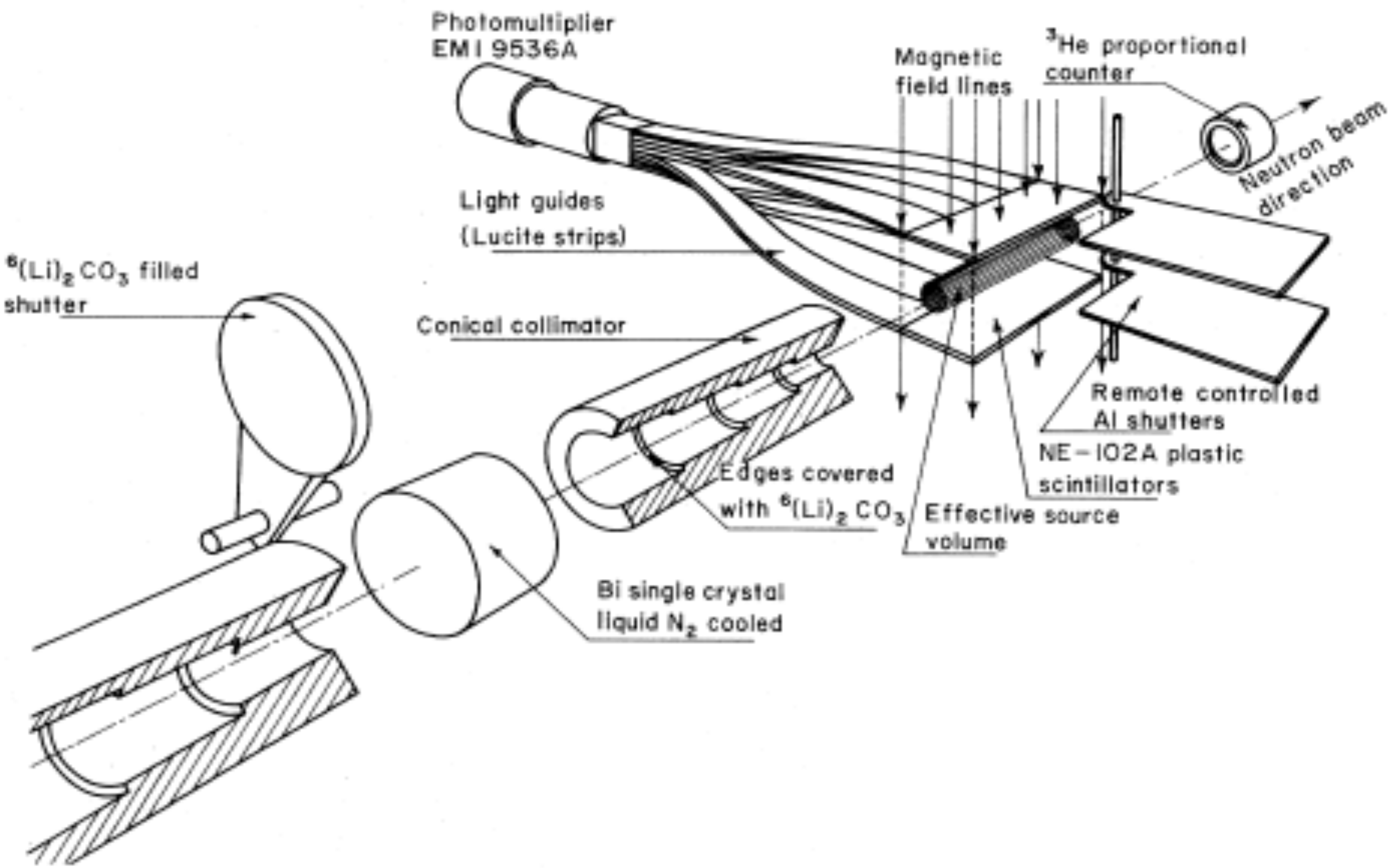
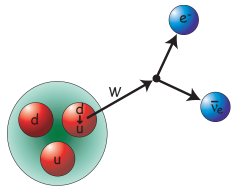
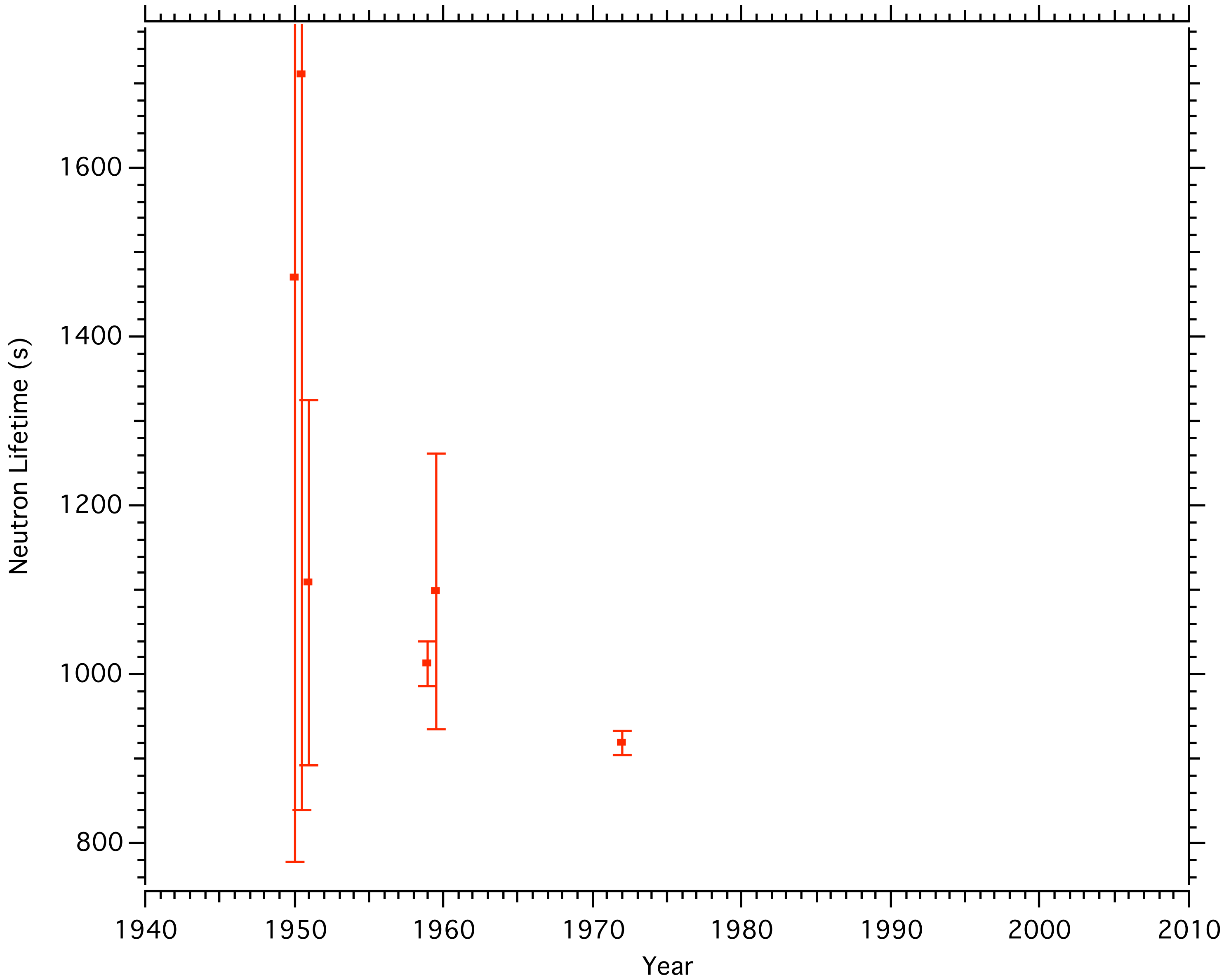


FIG. 1. Diagram of the Risö neutron half-life measurement equipment showing the β spectrometer and the source volume definition.

e-spectrometer; τ_n = 918 (14) s

1950-1972




Neutron Lifetime (s)
800
1000
1200
1400
1600
1940
1950
1960
1970
1980
1990
2000
2010
Year

Proton counting experiments at KI in Moscow

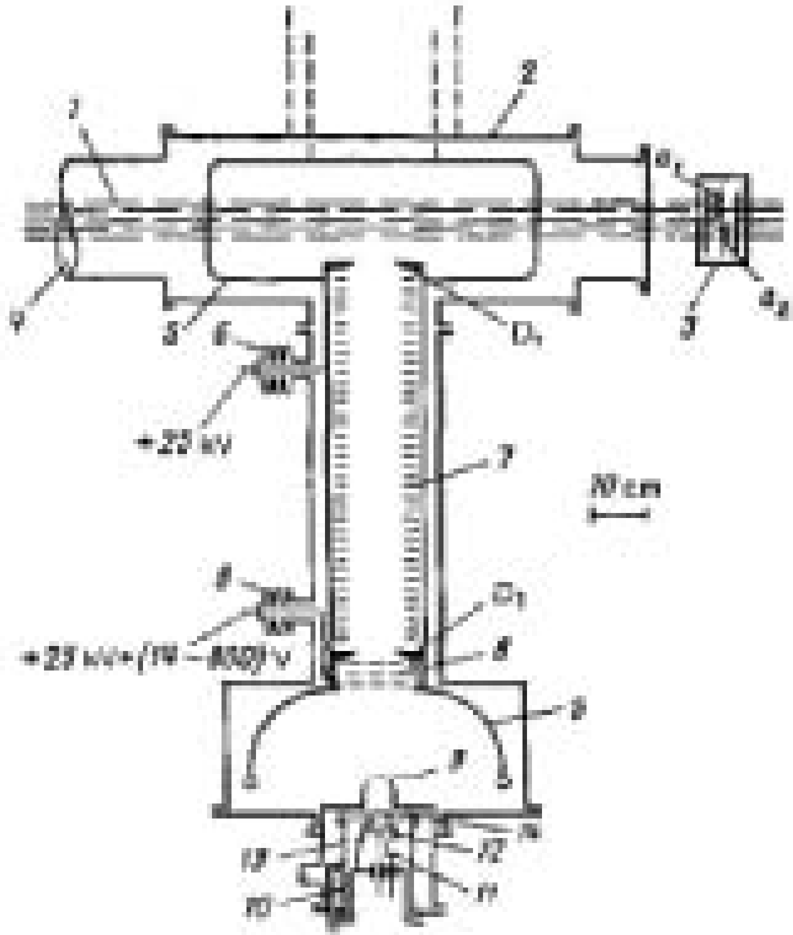


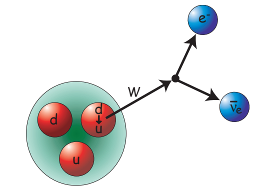
Figure 8. The IAE neutron lifetime experiment counting decay protons [13, 20]. 1, neutron beam; 2, vacuum chamber; 3, monitor chamber (a_1 and a_2 are ^{235}U layers); 4, channel for passage of extracted neutron beam to a trap and to a vacuum port; 5, electrodes; 6, ceramic insulators; D_1, D_2, diaphragms; 7, aluminium-foil rings; 8, electrostatic filter grids; 9, hemispherical grid; 10, detector vacuum chamber; 11, detector gas-filled volume; 12, detector comprising a proportional counter with a drift grid; 13, film-covered detector port; 14, valve separating the volumes of chambers 2 and 10.

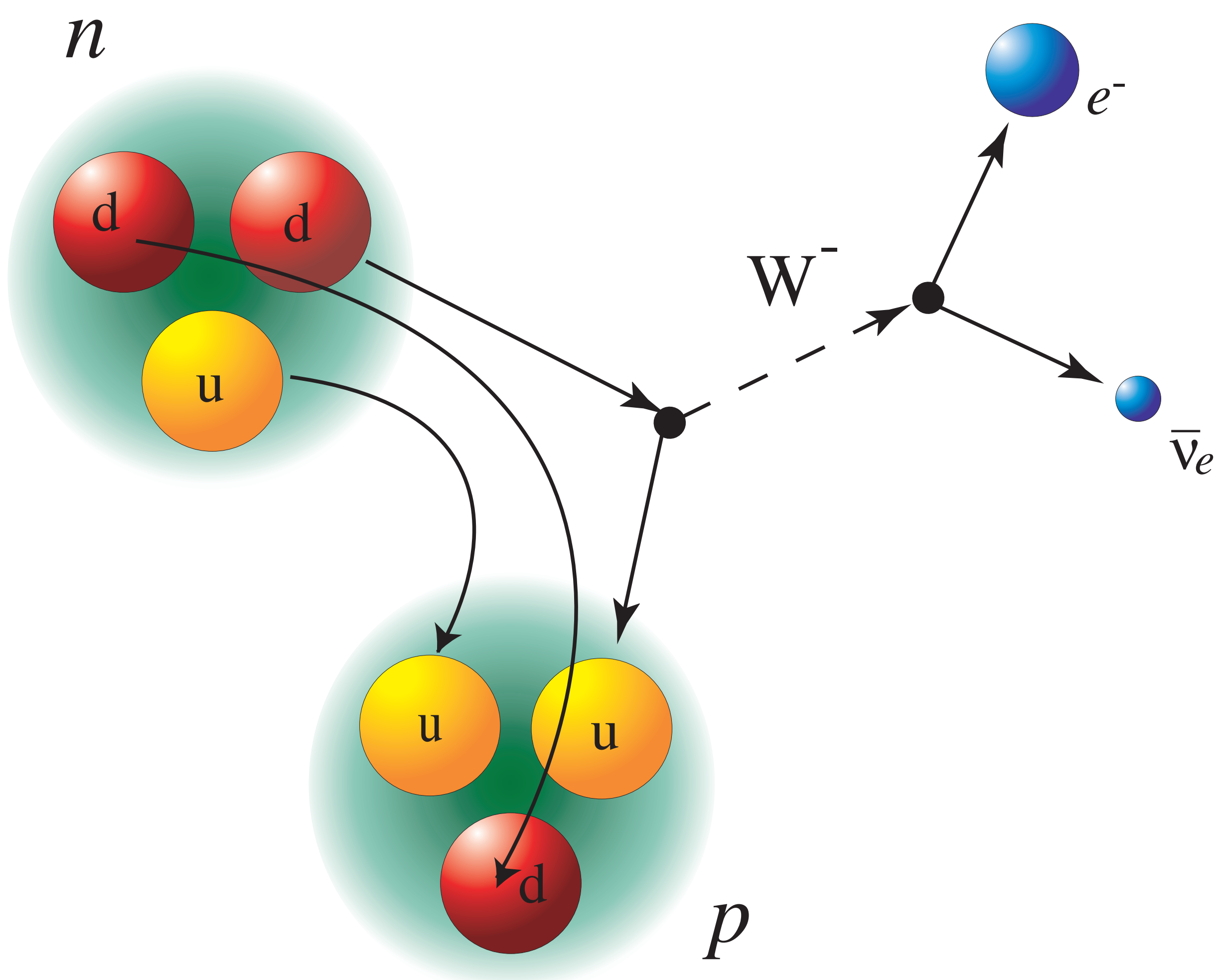
1972 Christensen result: τ_n = 918 (14) s

1978 KI result: τ_n = 877 (11) s

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

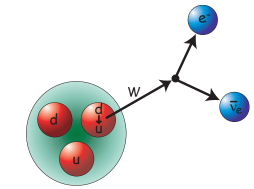
Neutron Decay



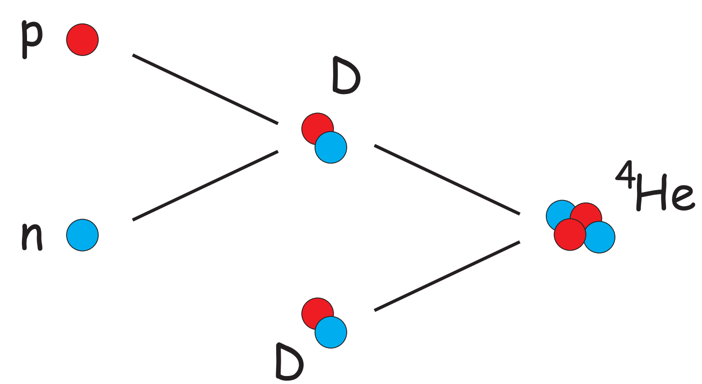


$$n \to p^+ + e^- + \bar{\nu}_e + 782 \text{ keV}$$

Importance of Neutron Decay Parameters

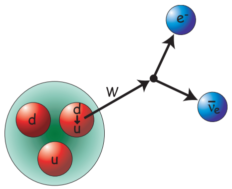


- τ_n: Big Bang Nucleosynthesis - determines primordial helium abundance
- g_V: determines V_{ud}, test of CKM unitarity
- g_a: axial vector coupling in weak decays
- D: search for new CP violation
- a, A, B: precise comparison is sensitive to non-SM physics:
  - right handed currents
  - scalar and tensor forces
  - CVC violation
  - second class currents



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

Neutron Beta Decay



$$\frac{\hbar}{\tau_n} \propto (g_V^2 + 3g_A^2)F(E)\left[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_eE_\nu} + \vec{\sigma}\cdot\left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_eE_\nu}\right)\right]$$

$$\tau_n \propto \frac{1}{g_V^2 + 3g_A^2} \approx 886\ \mathrm{s}$$ **neutron lifetime**

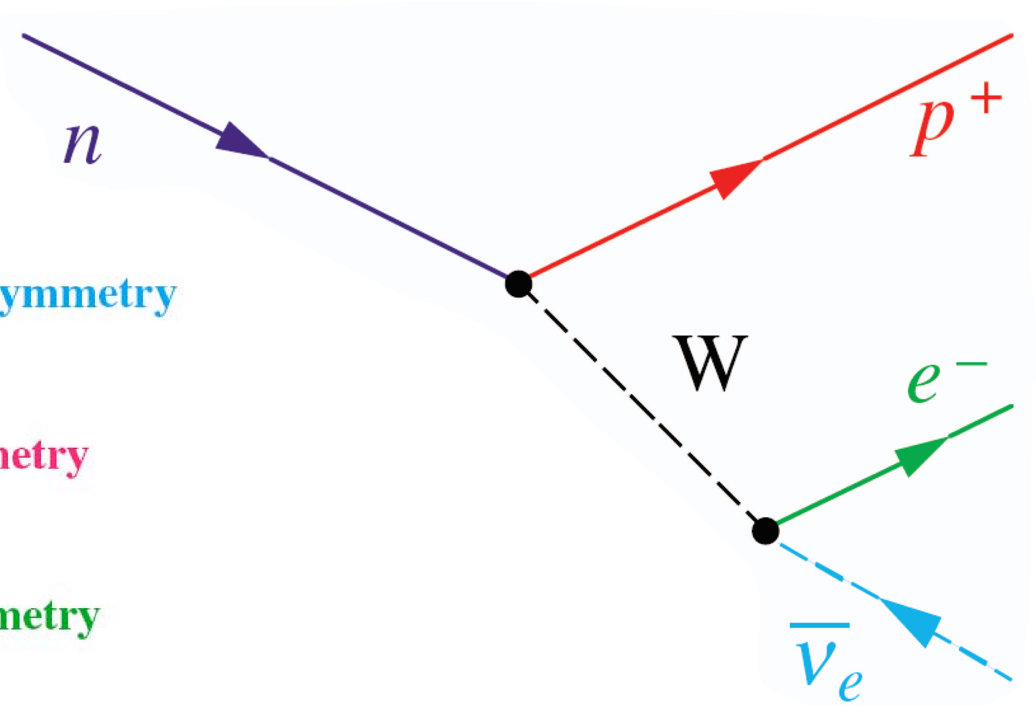
$$\lambda = \frac{g_A}{g_V}$$

$$a = \frac{1-\lambda^2}{1+3\lambda^2} \approx -0.102$$ **electron-neutrino asymmetry**

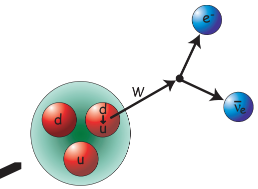
$$A = -2\frac{\lambda^2 + Re(\lambda)}{1+3\lambda^2} \approx -0.110$$ **spin-electron asymmetry**

$$B = 2\frac{\lambda^2 - Re(\lambda)}{1+3\lambda^2} \approx 0.983$$ **spin-neutrino asymmetry**

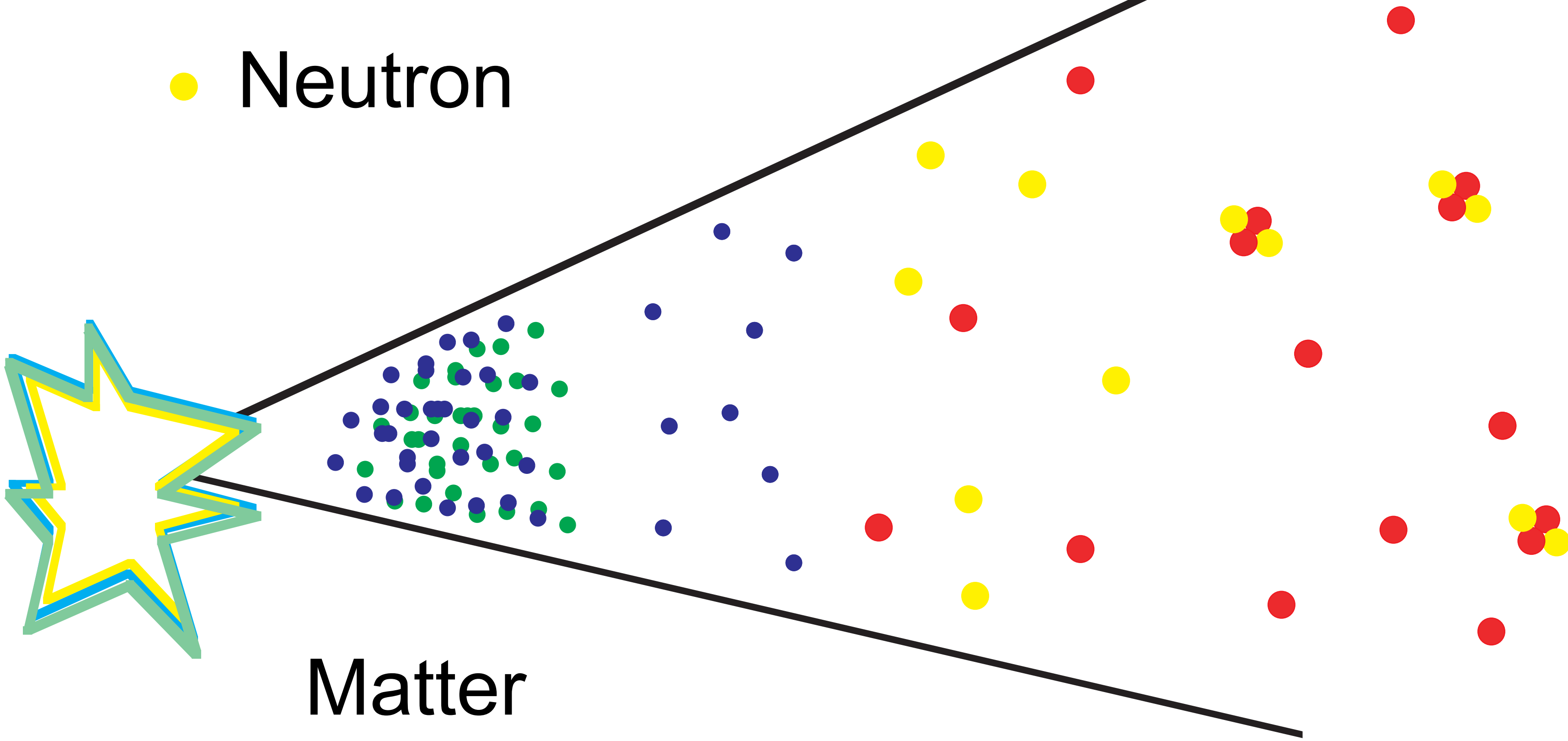
$$D = 2\frac{Im(\lambda)}{1+3\lambda^2} \approx 0$$ **spin-electron-neutrino triple correlation**



Big Bang Nucleosynthesis

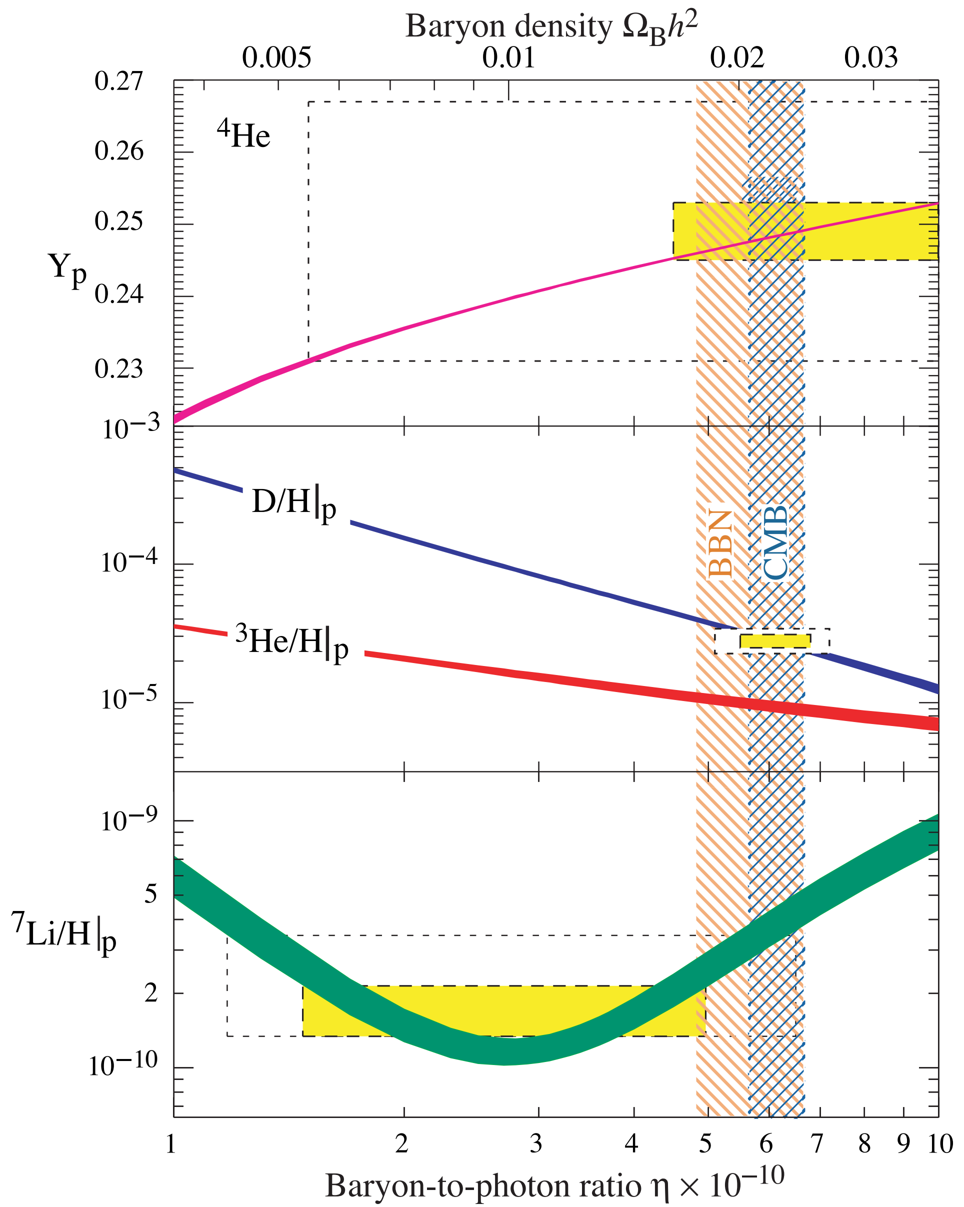


- Proton
- Neutron



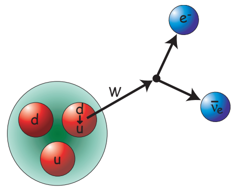
Matter Antimatter Annihilation	Nucleon Freeze Out	Light Element Formation
1 μs	1 s	10 min

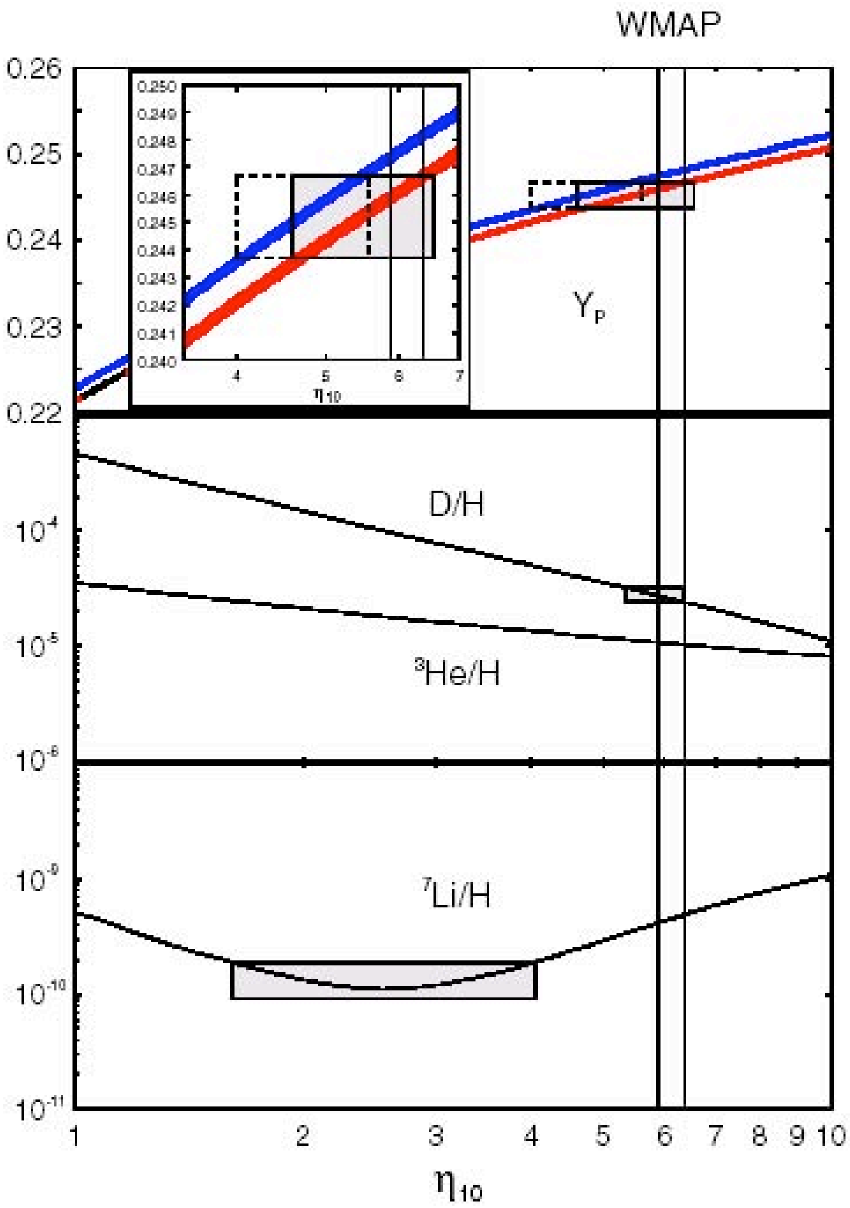
Light Element Abundances



PDG BBN Review (2007)

Light Element Abundances



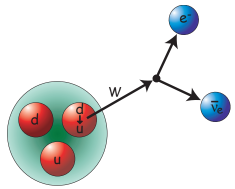


τ_n = 885.7 s (PDG2004)

τ_n = 881.9 s (+PNPI-ILL)

G.J. Mathews, T. Kajino, T. Shima, PRD 71 (2005) 021302

CKM Unitarity



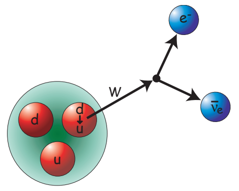
- $|V_{us}|$ and $|V_{ub}|$ obtained from high-energy experiments

- $|V_{ud}|$ obtained from:

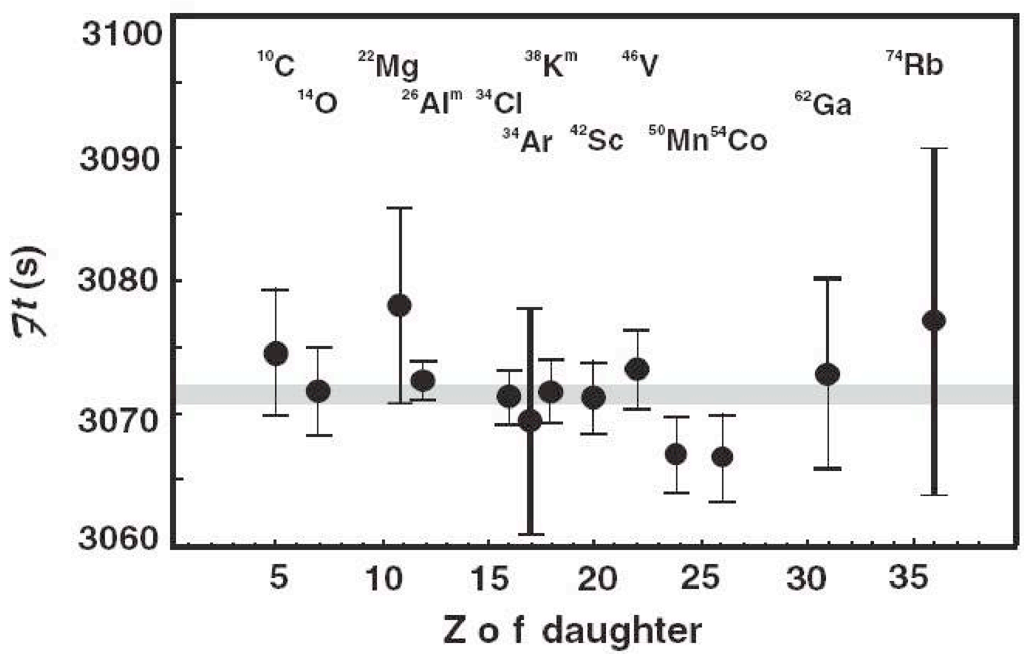
1. $0^+ \rightarrow 0^+$ nuclear beta decay
2. neutron beta decay
3. pion beta decay

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

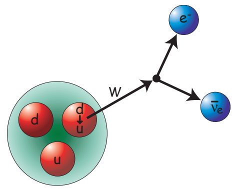
$0^+ \rightarrow 0^+$ Nuclear Beta Decay



- Corrected ft (Ft) values should be constant
- $|V_{ud}|^2 \propto 1/\langle Ft \rangle$
- $|V_{ud}|^2 = 0.9490 \pm 0.0005$



g_A and g_V

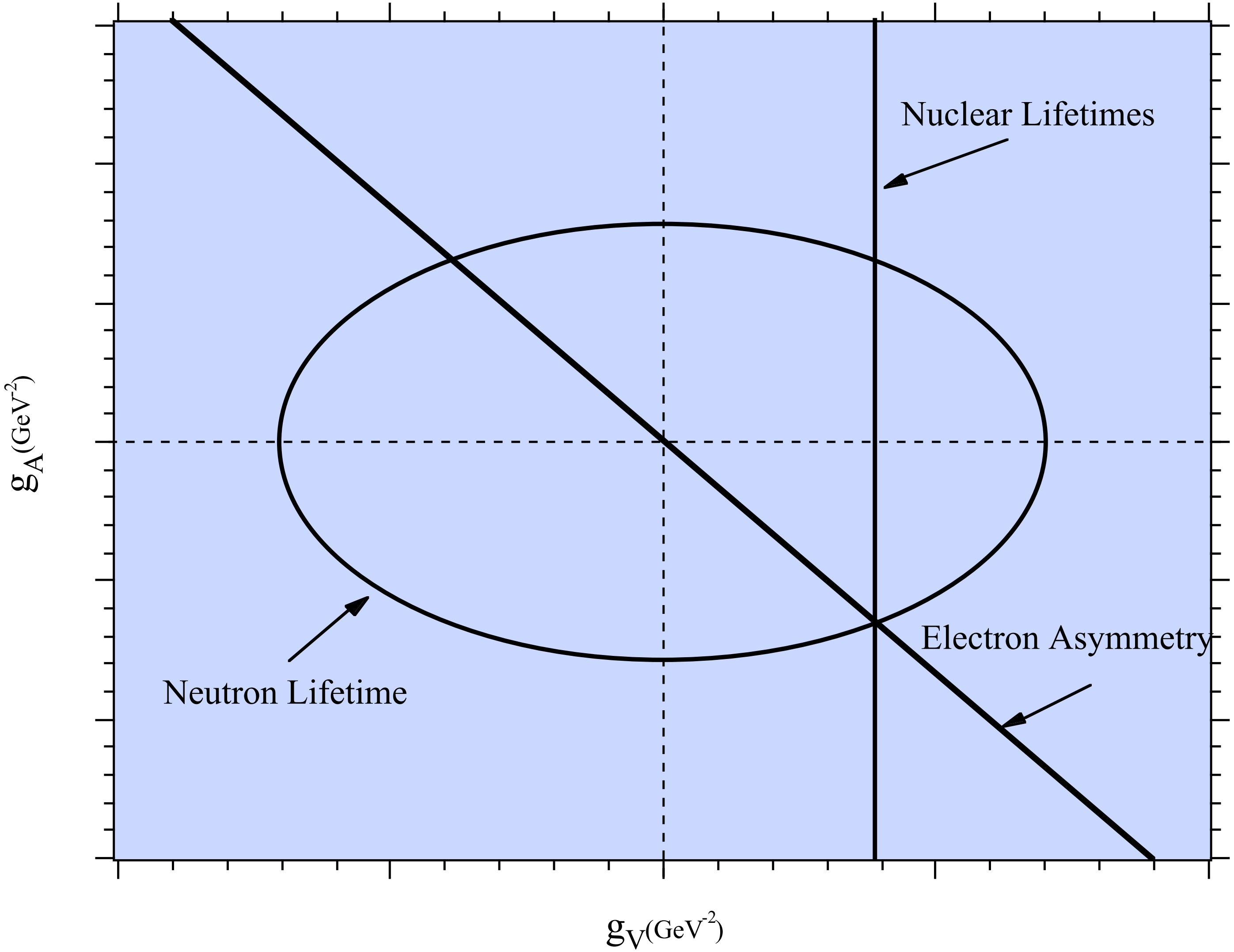


$$|V_{ud}| \propto g_v$$

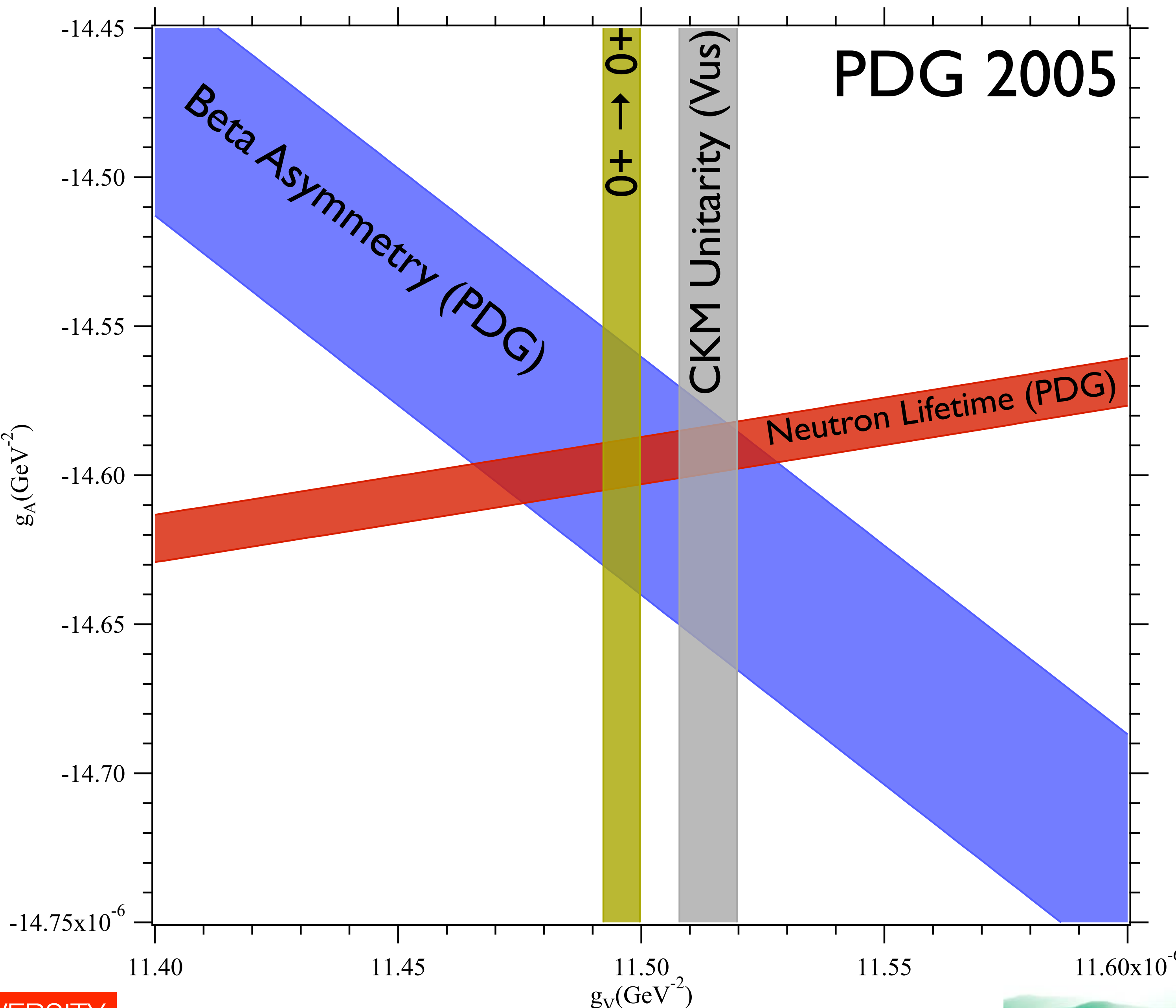
$$\tau_n \propto \frac{1}{(g_v^2 + 3g_a^2)}$$

$$A = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$$

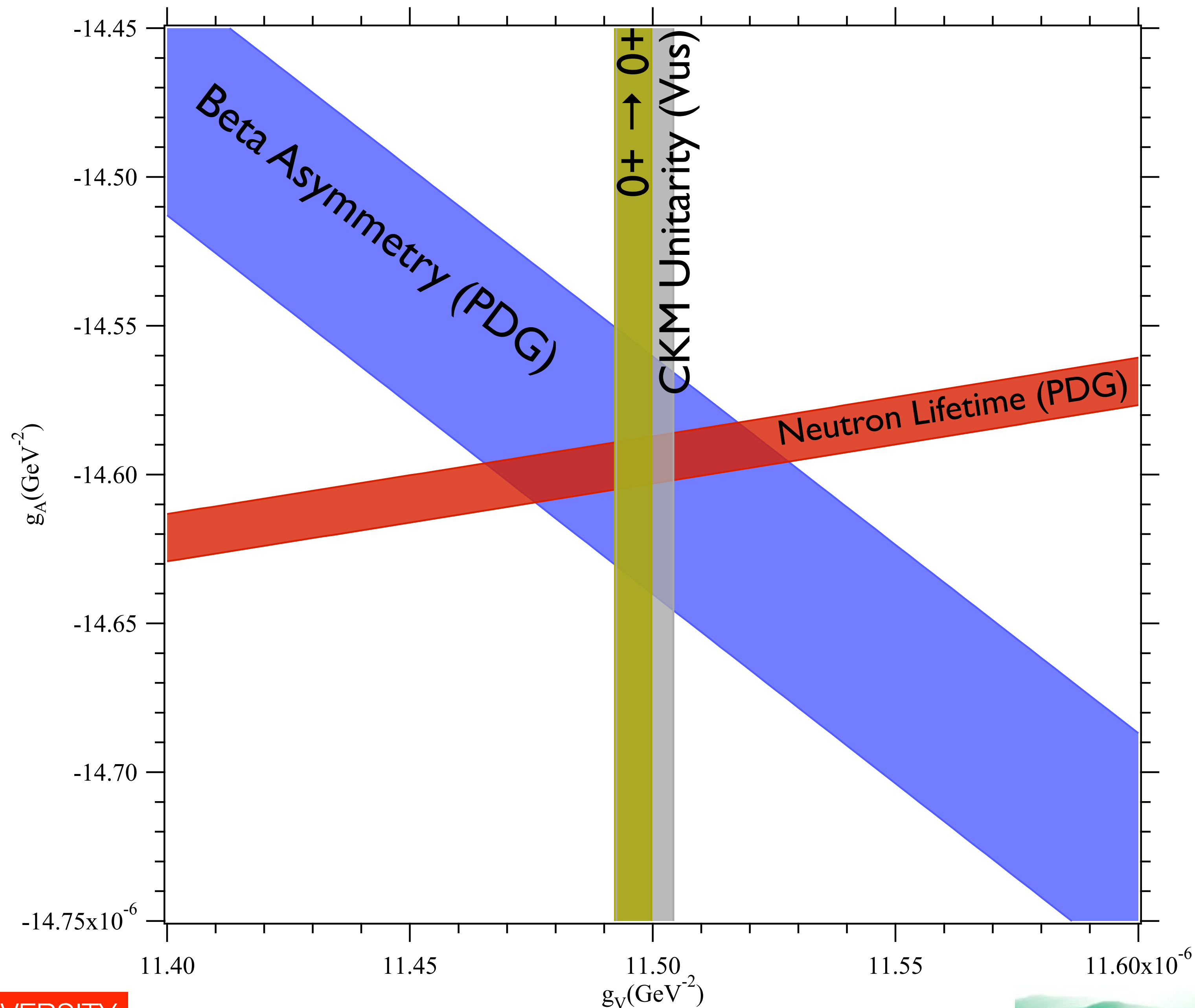
$$\lambda = \frac{g_a}{g_v}$$



CKM Unitarity



CKM Unitarity



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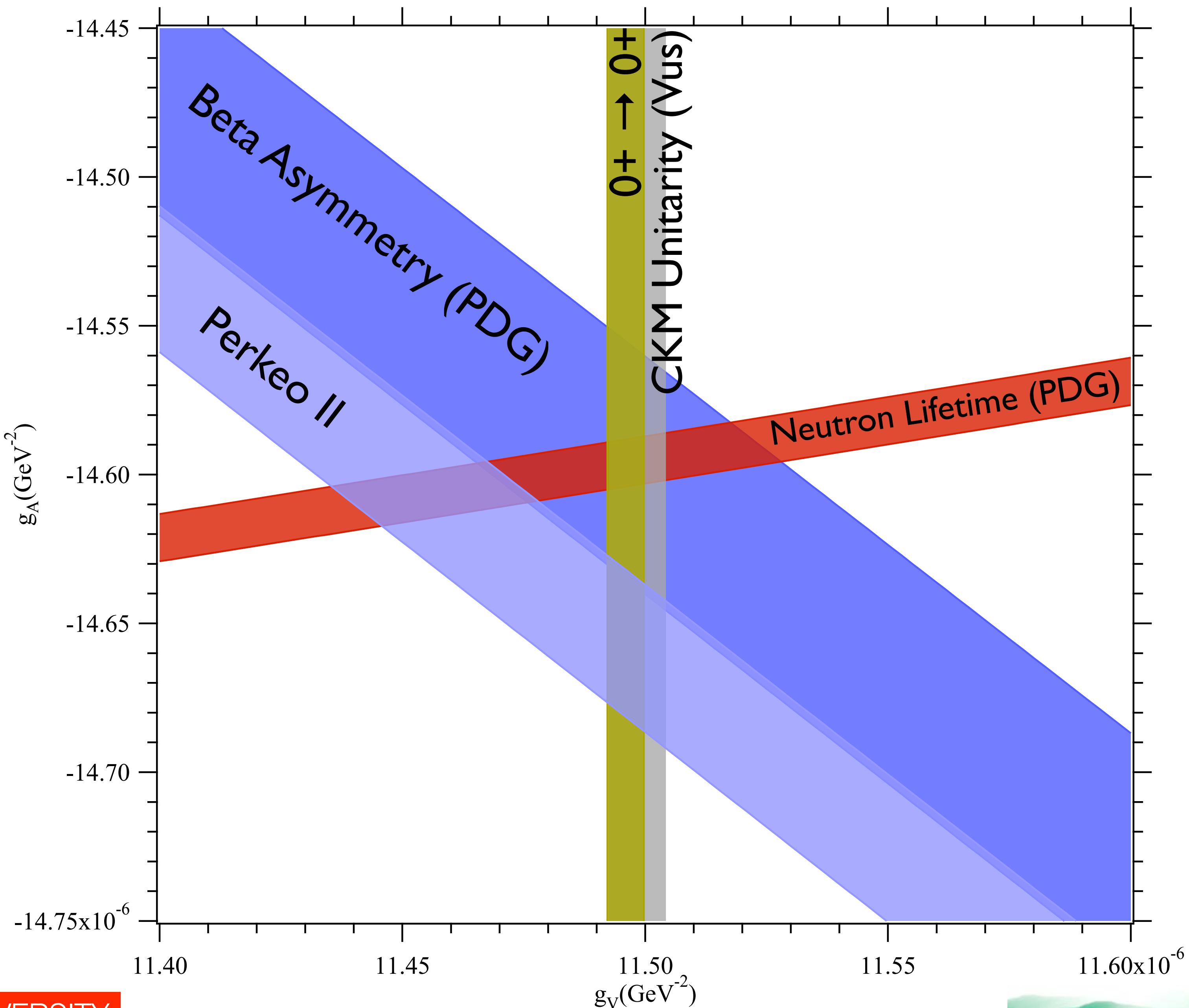

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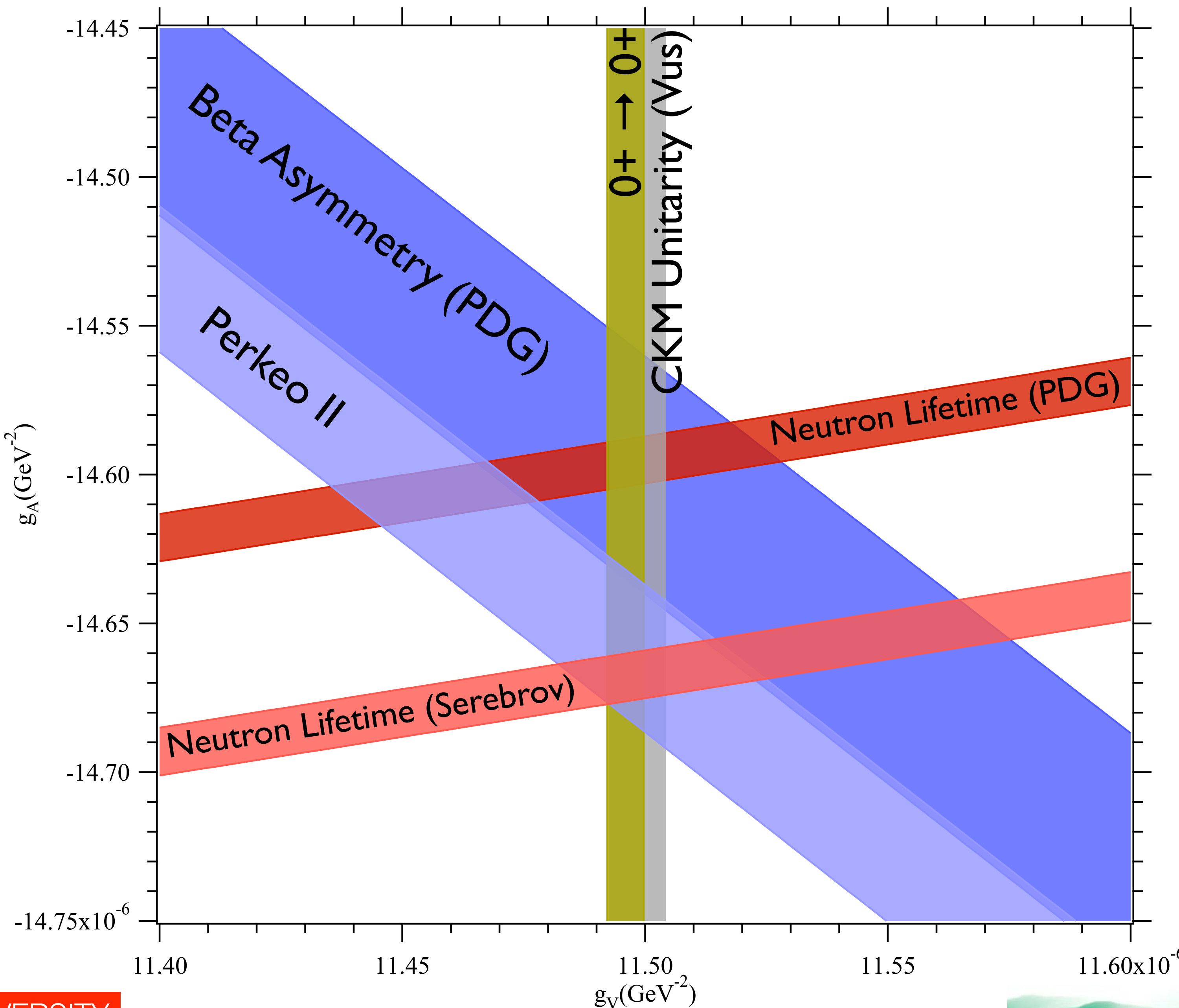
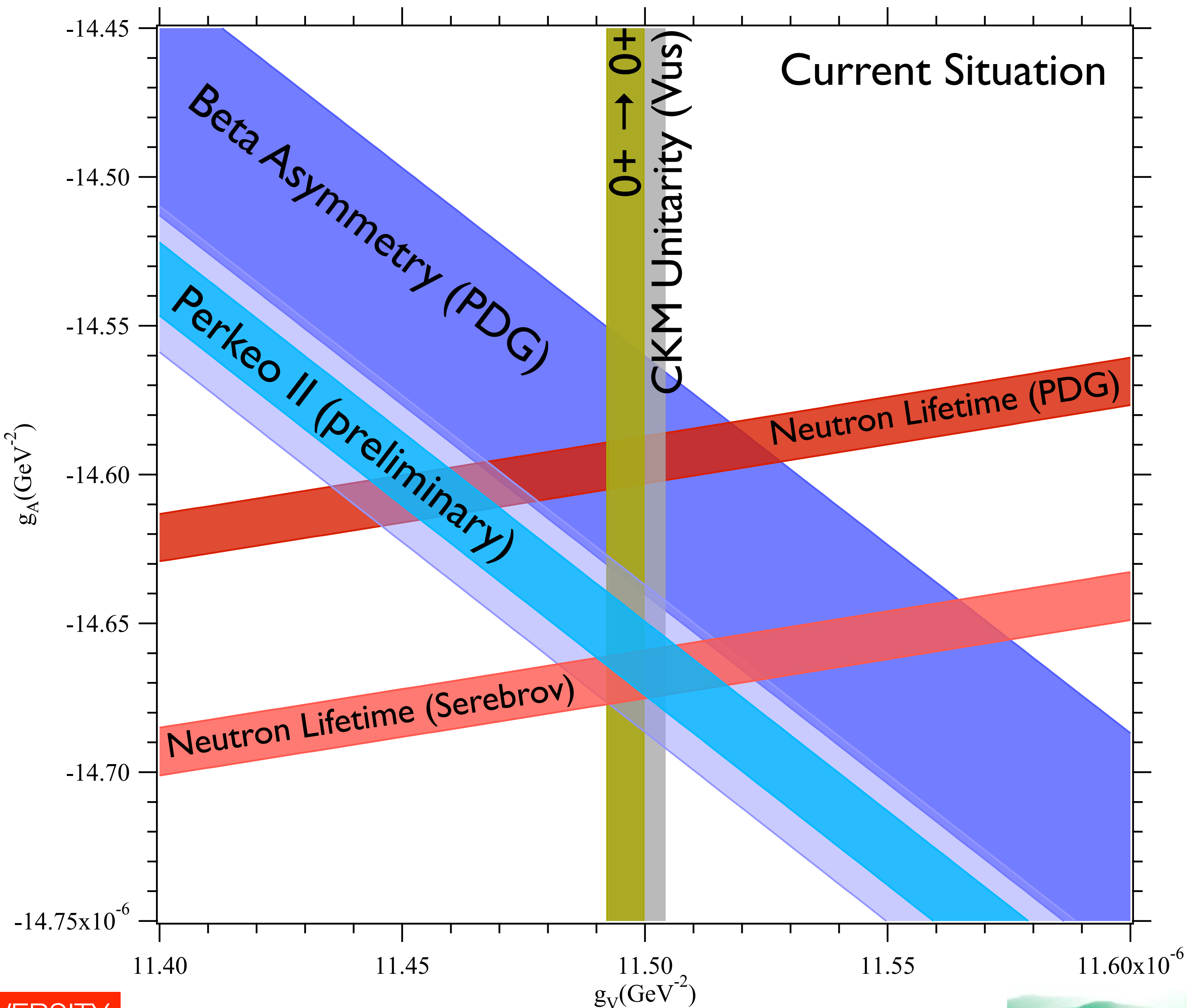
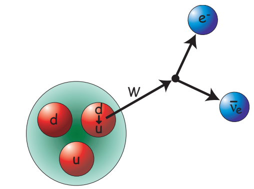


CKM Unitarity

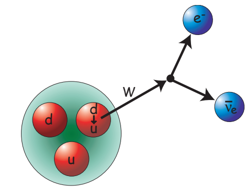


Energy Scales/Nomenclature

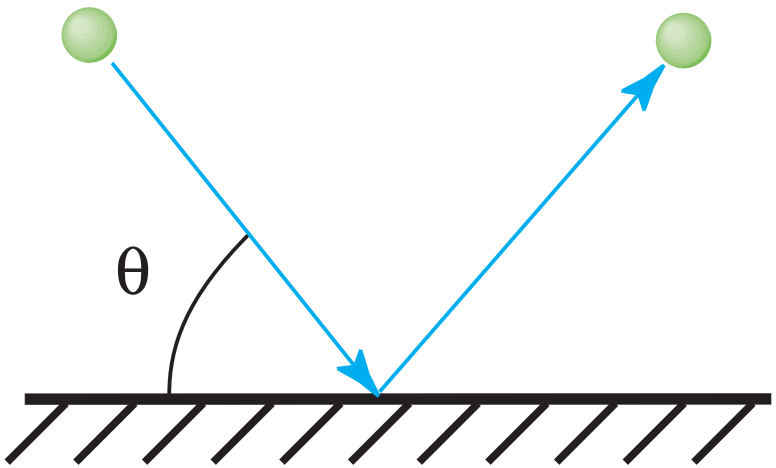


	Energy	Wavelength	Temperature	Velocity
Fast	> 500 keV			> 1 x 10^7 m/s
Epihermal	500 keV - 25 meV			1 x 10^7 m/s- 2200 m/s
Thermal	25 meV	0.18 nm	300 K	2200 m/s
Cold	25 meV - 0.05 meV	0.18 nm - 4 nm	300 K - 0.6 K	2200 m/s - 100 m/s
Very Cold	50 ueV - 0.2 ueV	4 nm - 64 nm	0.6 K - 0.002 K	100 m/s - 6 m/s
Ultracold	< 0.2 ueV	> 64 nm	< 2 mK	< 6 m/s

Ultracold Neutrons



- Strong Interaction



$$\sin\theta \leq \sin\theta_c = (V/E)^{1/2}$$

$$V = \frac{2\pi\hbar^2}{m} Na$$

$$V \sim 10^{-7}\,\text{eV}$$

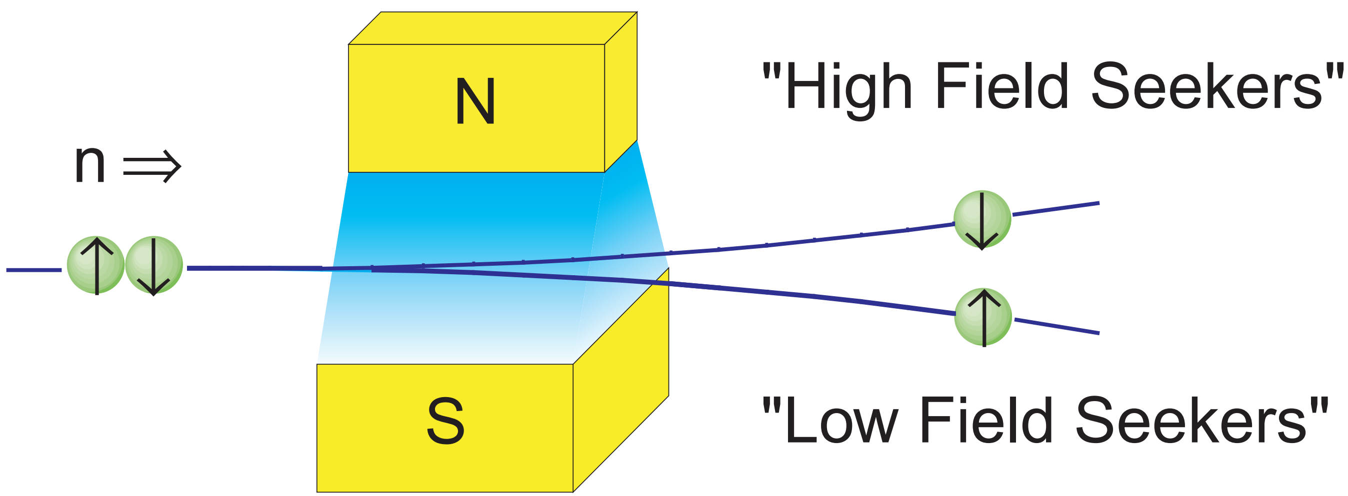
- Gravitational Interaction

$$V_g = mgh$$

$$10^{-7}\,\text{eV/m}$$

Ultracold Neutrons

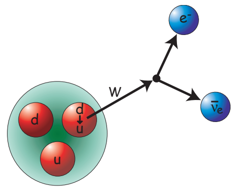
- *Magnetic Interaction*



$$V_m = -\vec{\mu} \cdot \vec{B}$$

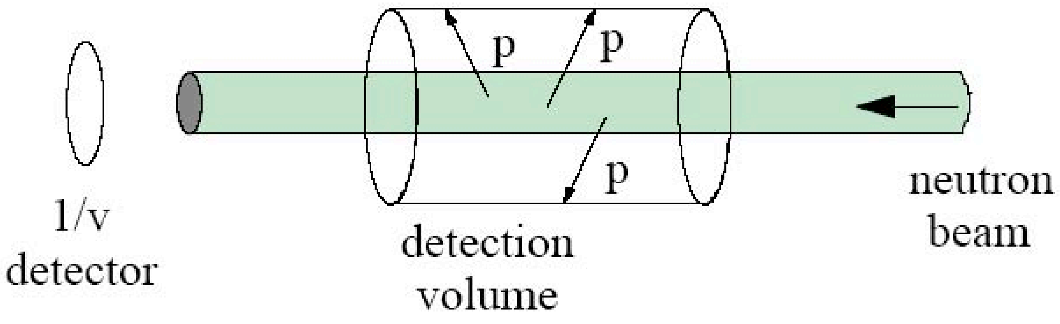
10^{-7}eV/T

Types of Measurements



- Cold Beam
- Material Bottle
- Magnetic Storage

Cold Beam Technique



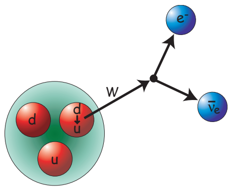
neutron decay rate $\Gamma = \frac{N}{\tau}$

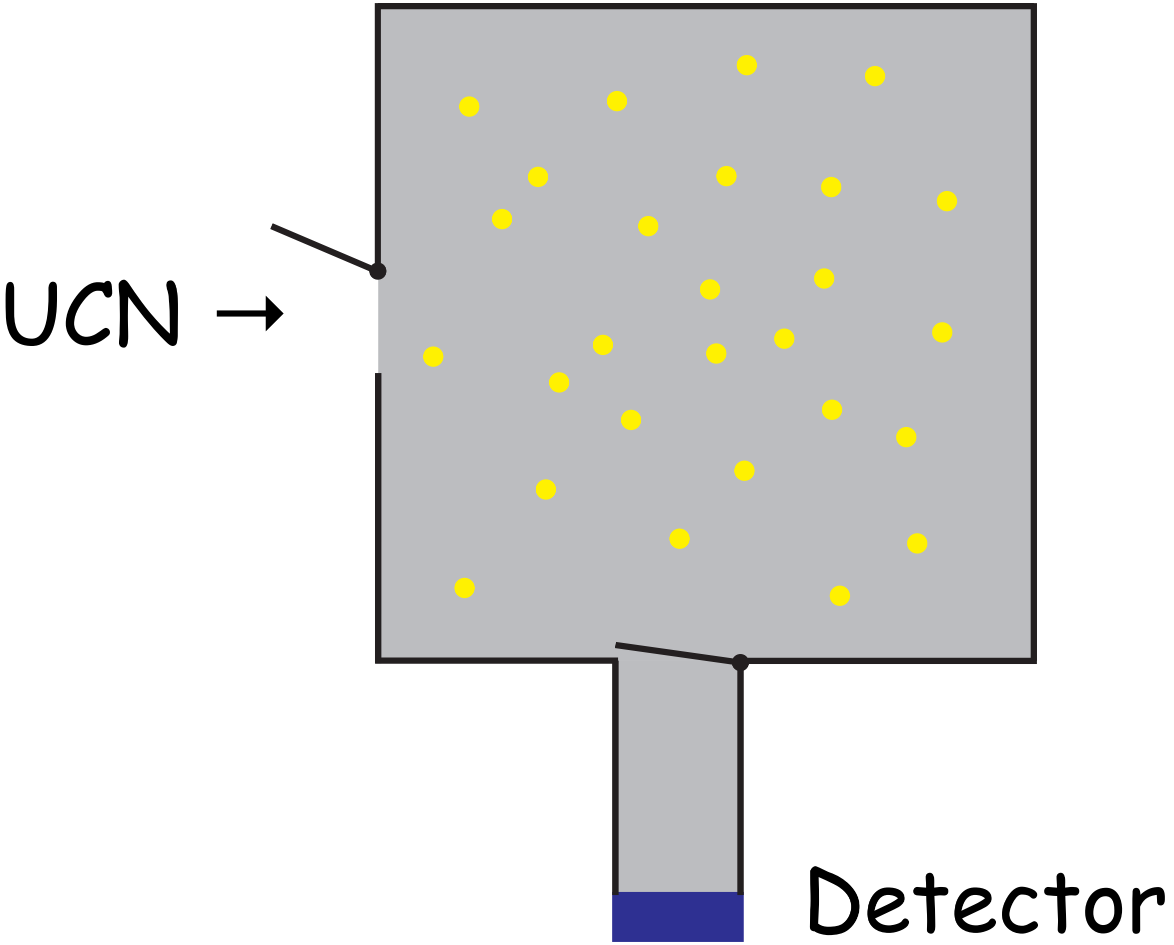
$$\text{so} \quad \tau = \frac{\phi \, V_{det}}{v \, \Gamma}$$

Need to measure:

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

UCN Bottle Technique

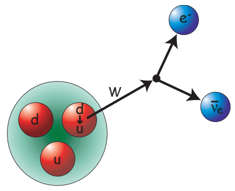




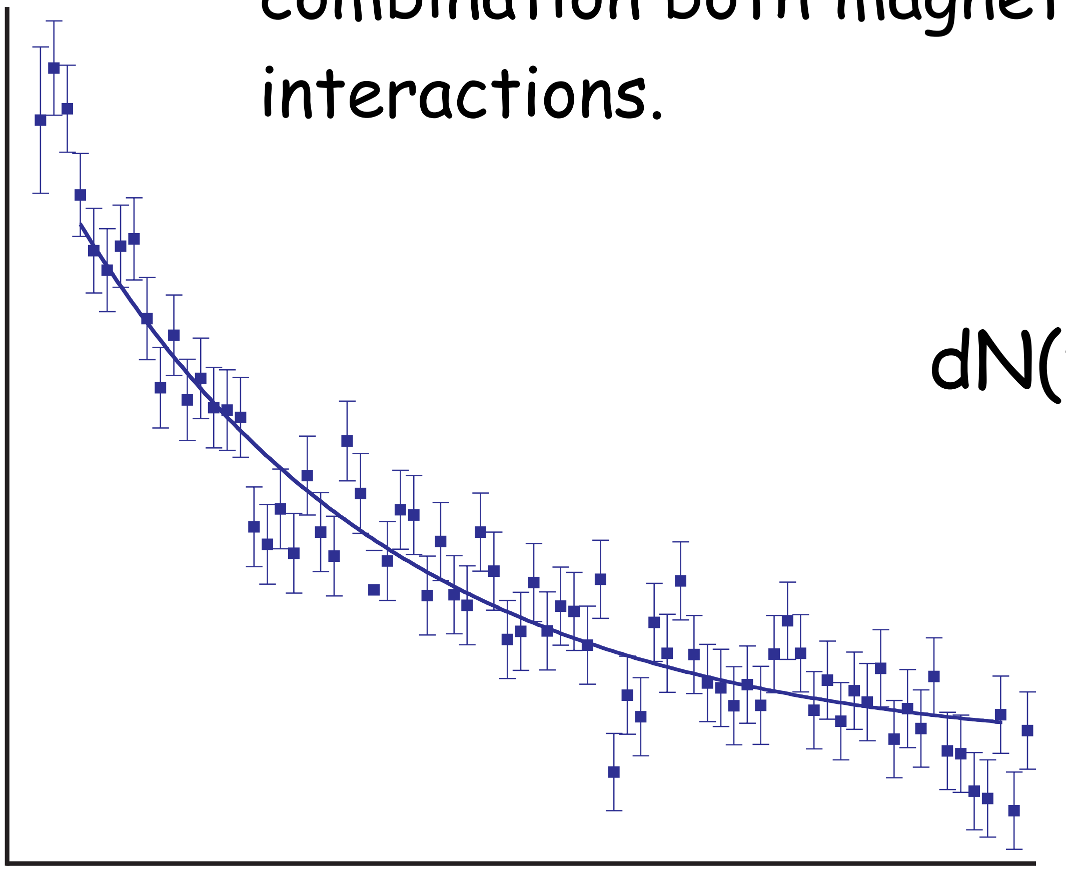
$$1/\tau = 1/\tau_n + 1/\tau_{wall} + \ldots$$

$$\tau = T / \log (N_0/N)$$

Magnetic Storage

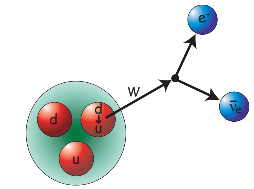


- Originally proposed in 1961 by Vladimirskii
- First realized in 1983 by Abov et al. using a combination both magnetic and gravitational interactions.



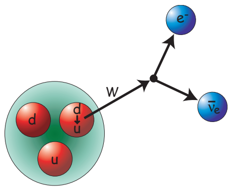
$$dN(t)/dt = -(N_0/\tau)\, e^{-t/\tau}$$

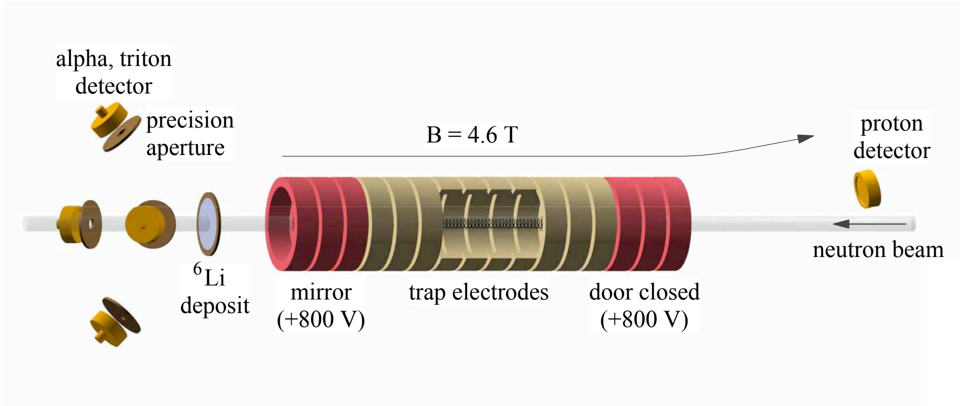
Lifetime Measurements

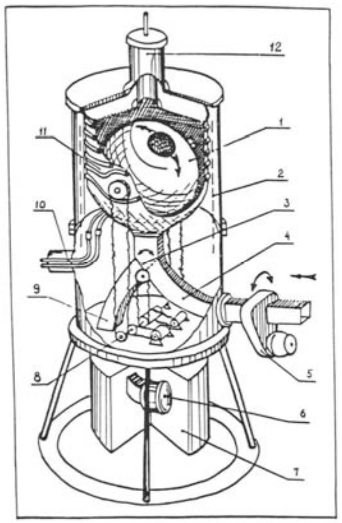


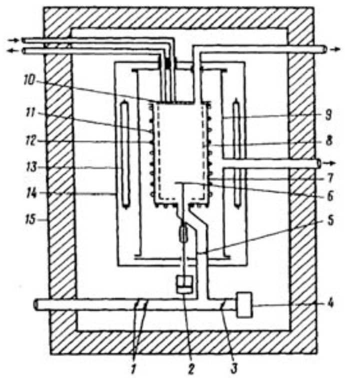
Technique		Challenges
❶ **Neutron Beam** Detect decay products from a beam with a well defined neutron fluence rate	$-\frac{dN}{dt} = N\lambda$	Absolute neutron flux (10^{-3})
❷ **Material Bottle** Measure change in number of confined neutrons as a function of time	$N_1/N_2 = e^{-\lambda(t_1 - t_2)}$	Understanding neutron energy spectrum Loss mechanisms (walls)
❸ **Magnetic Bottle** Measure change in number of confined neutrons as a function of time		Complicated Orbits Spin Flips
❹ **Magnetic Trap** Count decay products of magnetically trapped neutrons as a function of time and measure the slope.	$ln(N/N_0) = -\lambda t$	Complicated Orbits To date: poor signal to noise

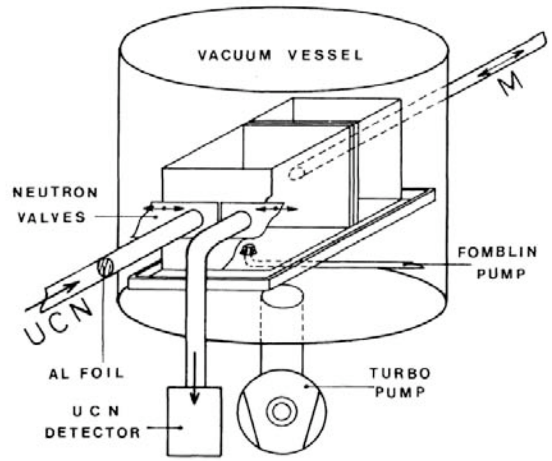
Existing Measurements

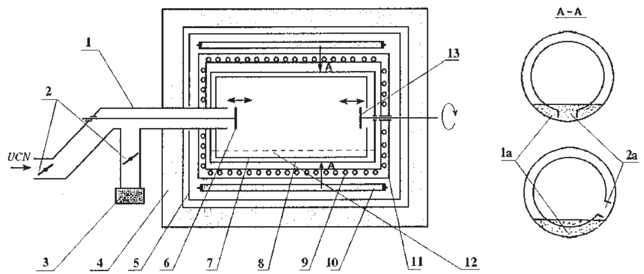


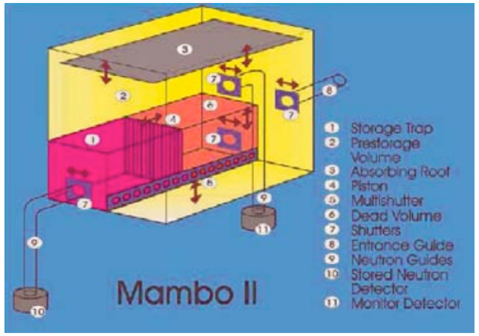




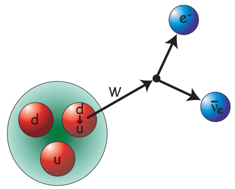


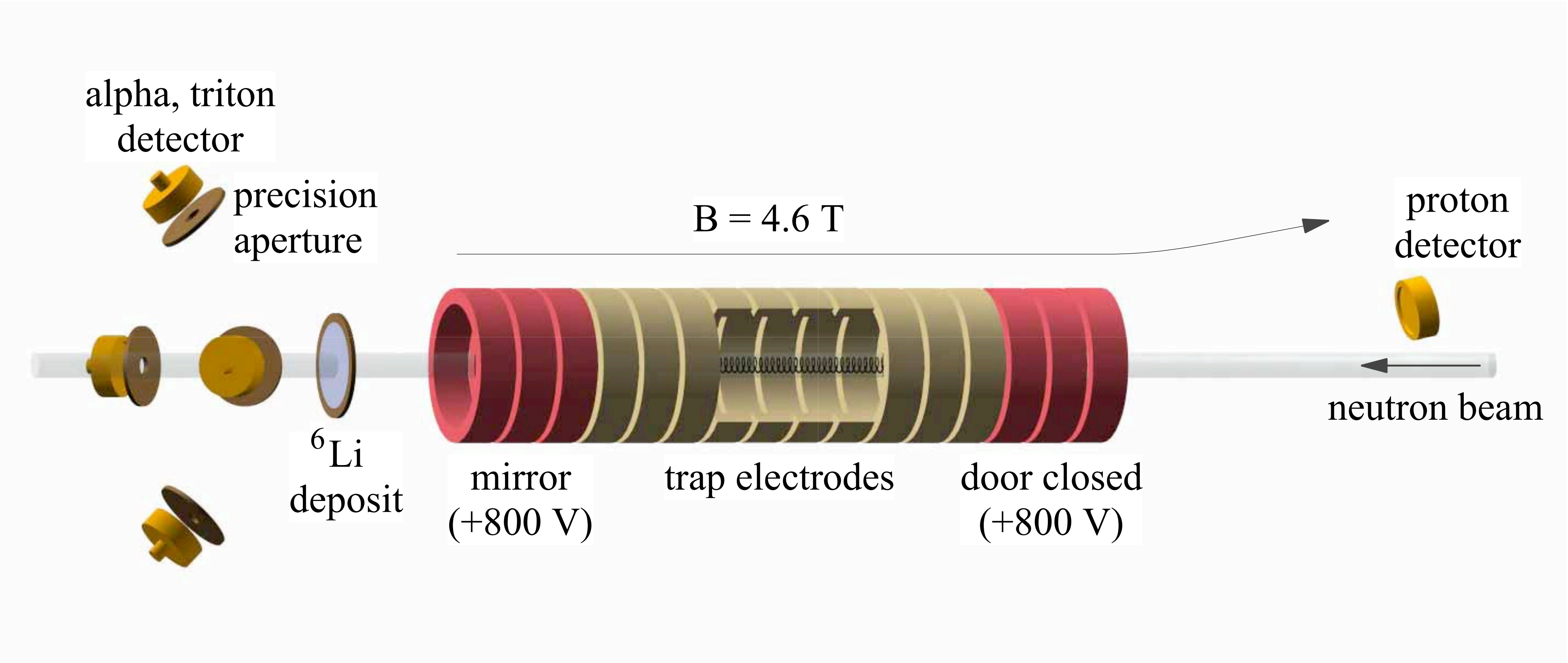






Beam Lifetime





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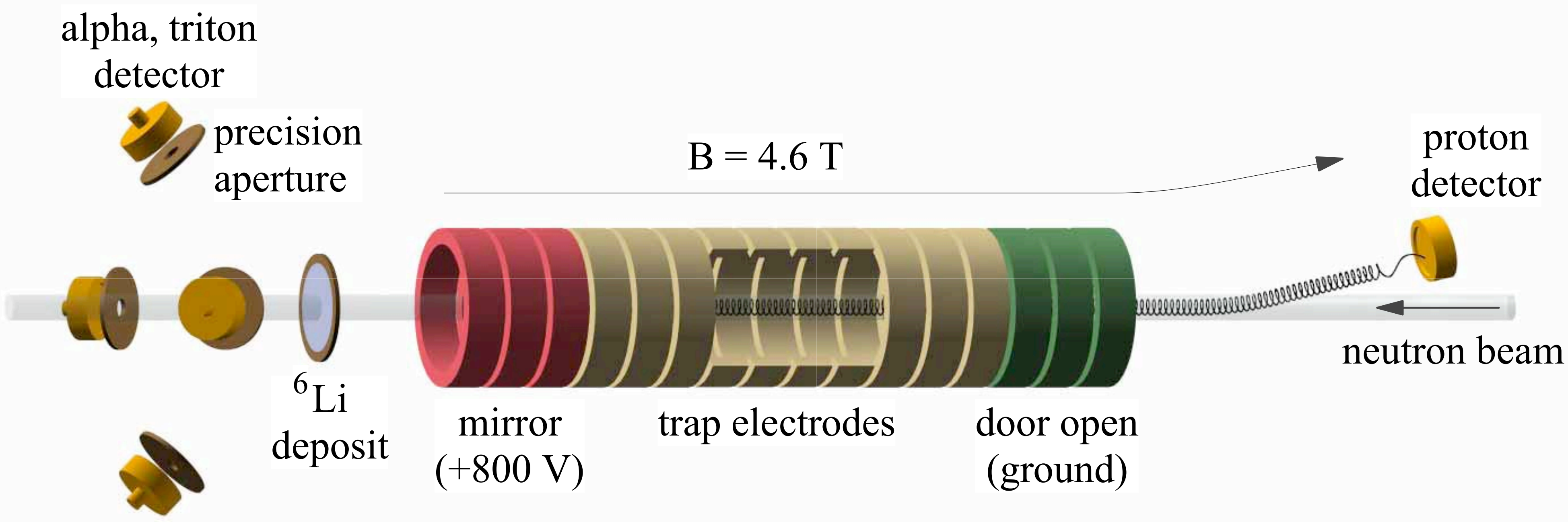
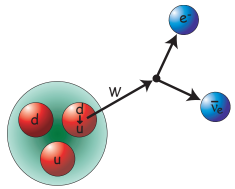


ILL Beam Lifetime



VOLUME 65, NUMBER 3 PHYSICAL REVIEW LETTERS 16 JULY 1990

Measurement of the Neutron Lifetime by Counting Trapped Protons

J. Byrne, P. G. Dawber, J. A. Spain, and A. P. Williams[(a)]
University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

M. S. Dewey, D. M. Gilliam, G. L. Greene, and G. P. Lamaze
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

R. D. Scott
Scottish Universities Research and Reactor Center, East Kilbride, Glasgow G75 0QU, United Kingdom

J. Pauwels, R. Eykens, and A. Lamberty
Commission of the European Communities, Joint Research Center,
Central Bureau for Nuclear Measurements, B-2440 Geel, Belgium
(Received 21 March 1990)

The neutron lifetime τ_n has been measured by counting decay protons stored in a Penning trap whose magnetic axis coincided with a neutron-beam axis. The result of the measurement is $\tau_n = 893.6 \pm 5.3$ s which agrees well with the value predicted by precise measurements of the β-decay asymmetry parameter A and the standard model.

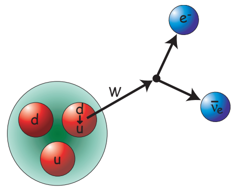
PACS numbers: 14.20.Dh, 13.30.Ce

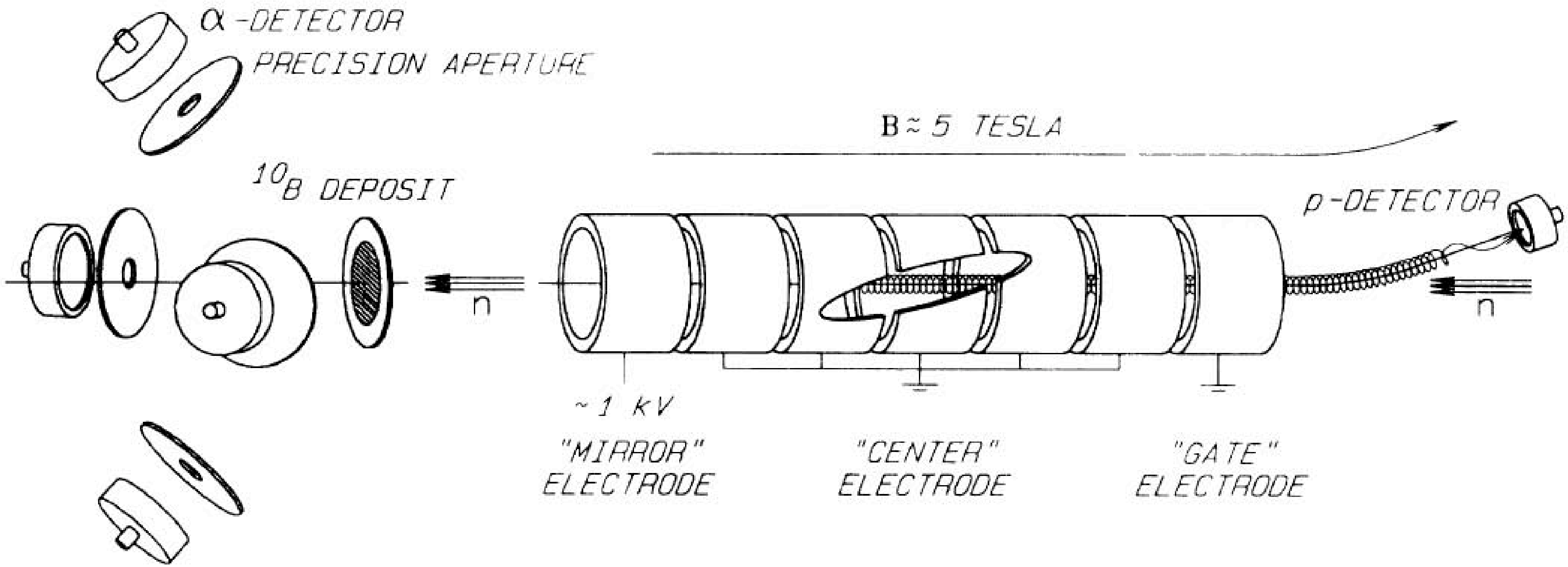
Self-consistency among experimental values for the neutron lifetime τ_n, the various angular and polarization correlation coefficients in free-neutron β decay, and ft values of pure Fermi $0^+ \rightarrow 0^+$ superallowed β transitions provides one of the best tests of the standard $V-A$ theory of semileptonic weak processes.[1] For neutron de- action. In an earlier version of this technique[8] the magnetic field was oriented normal to the neutron beam.

In the parallel configuration any dependence on the spatial distribution and velocity distribution of the neutrons within the neutron beam is eliminated[7] and τ_n is given by

J. Byrne *et al.*, Phys. Rev. Lett. 65, 289 (1990)

ILL Beam Lifetime

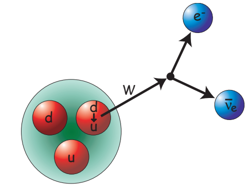


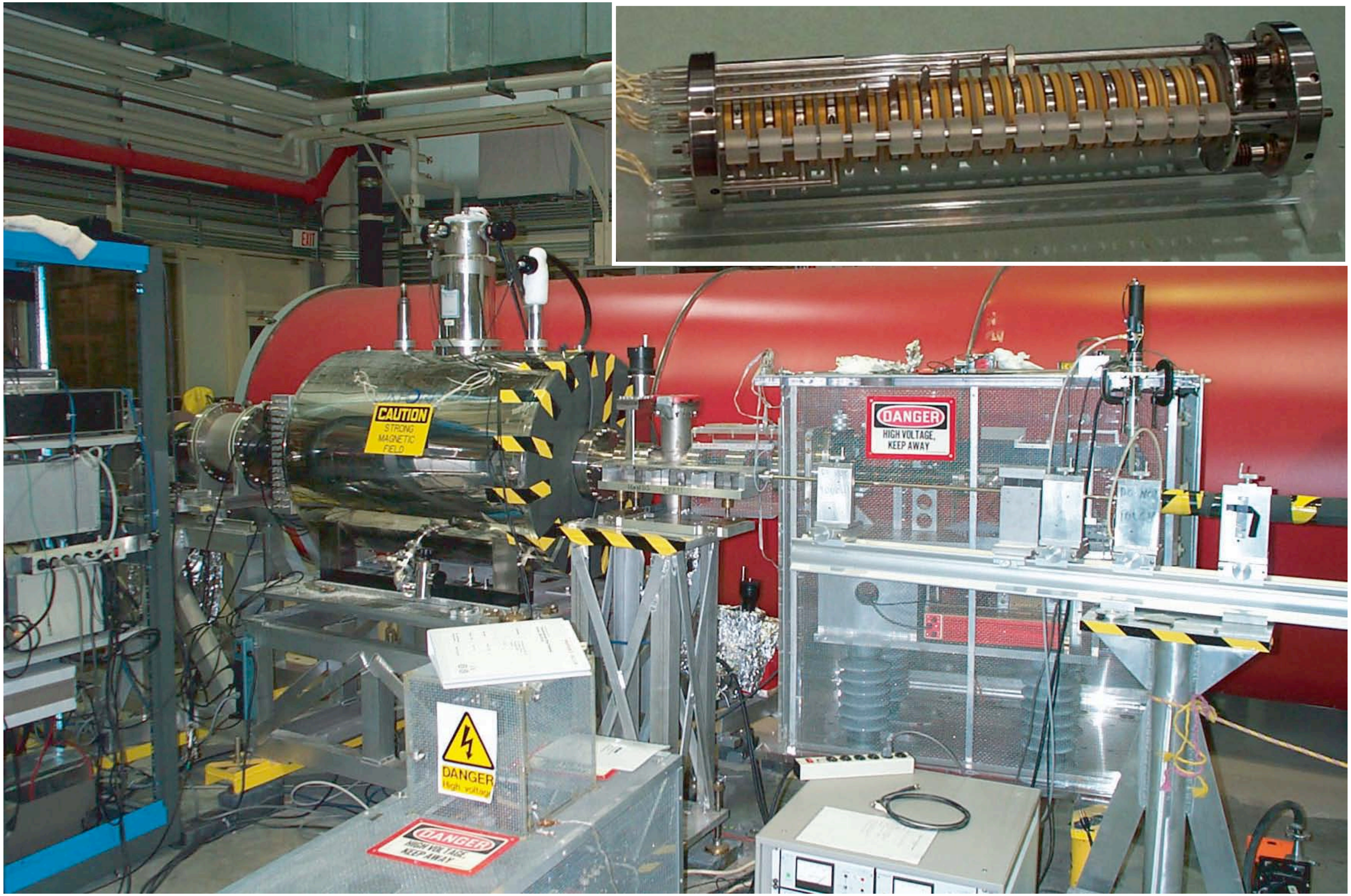


$$\tau_n = 893.6 \pm 5.3\ s$$

J. Byrne *et al.*, Phys. Rev. Lett. 65, 289 (1990)

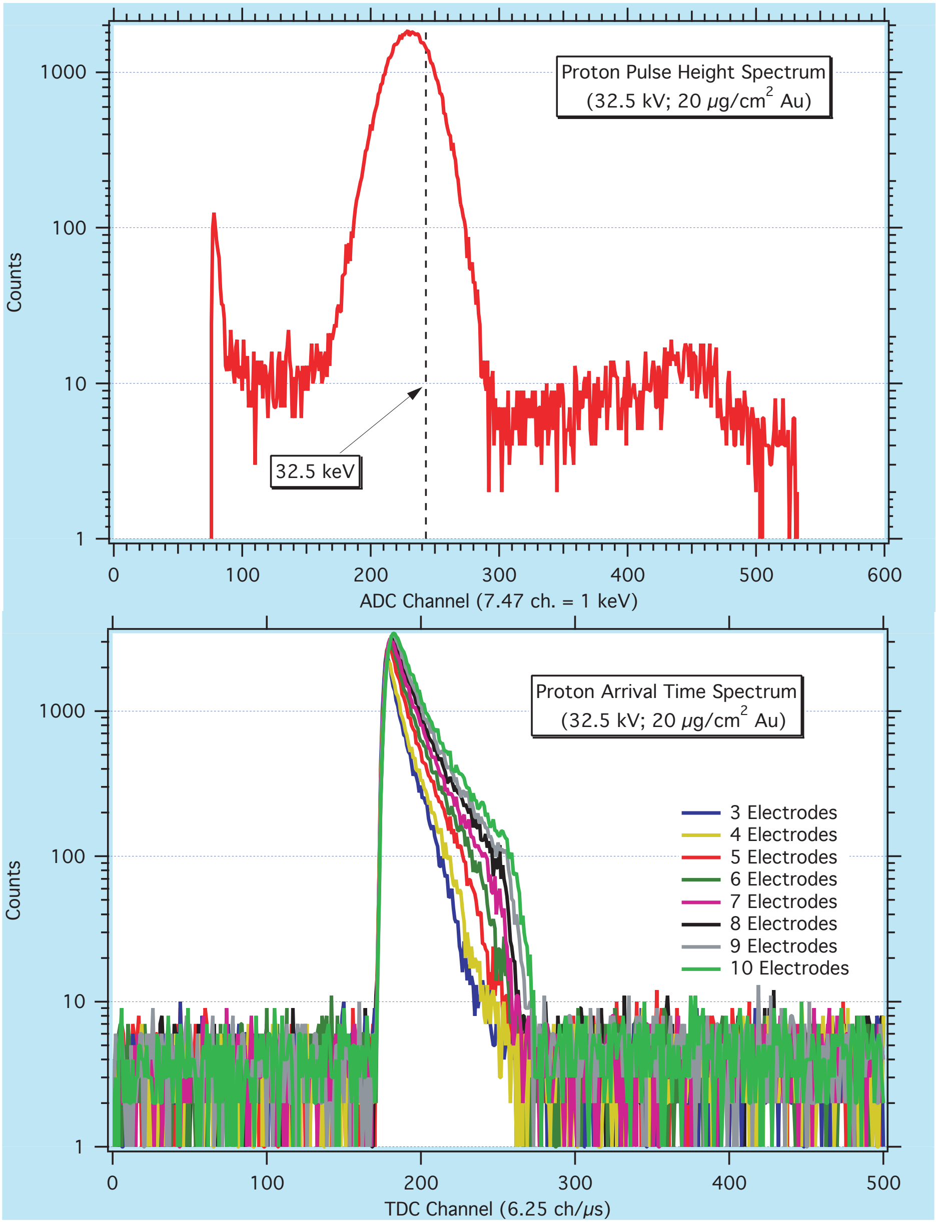
NIST Beam Lifetime





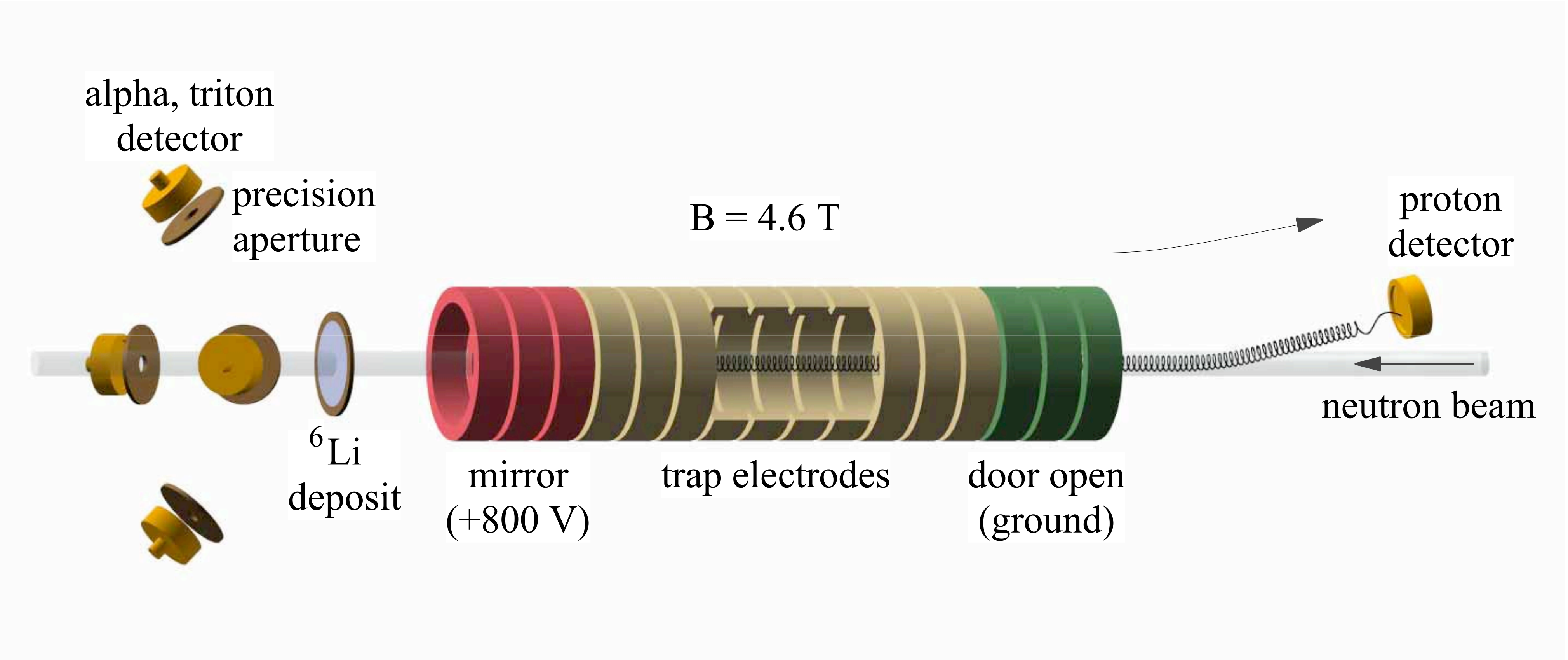
J.S. Nico *et al.*, Phys. Rev. C 71, 055502(2005)

NIST Beam Lifetime



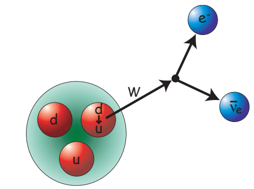
J.S. Nico *et al.*, Phys. Rev. C 71, 055502(2005)

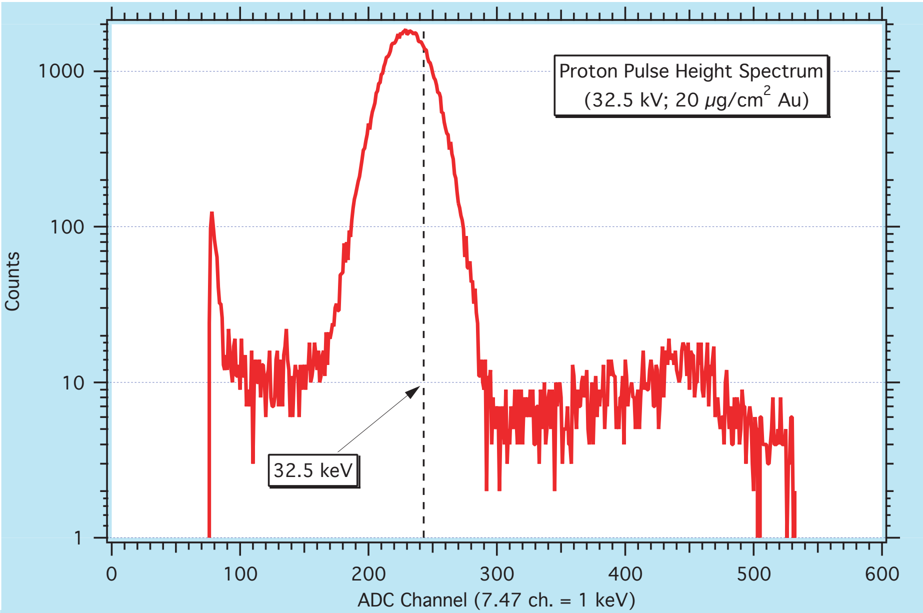
Beam Lifetime

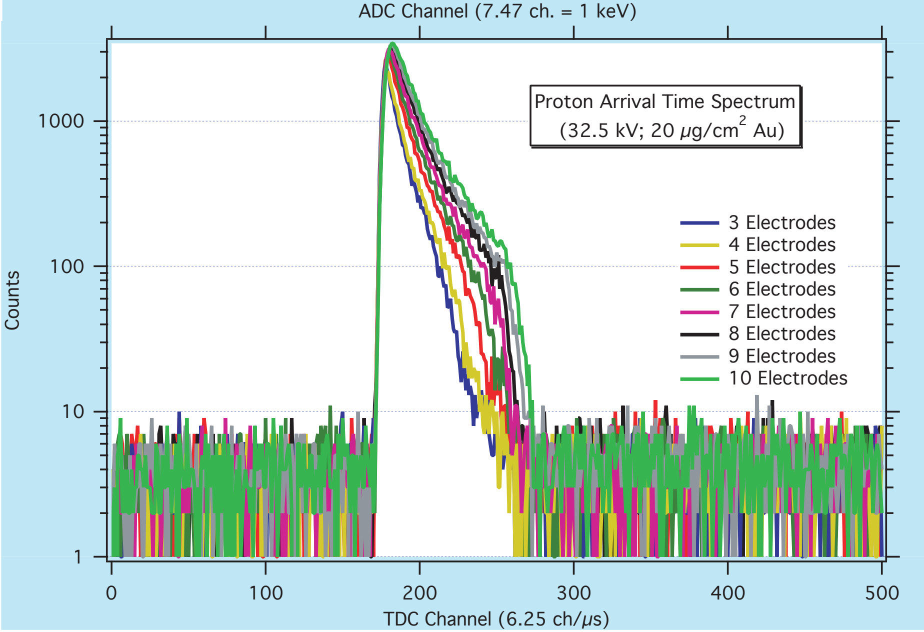


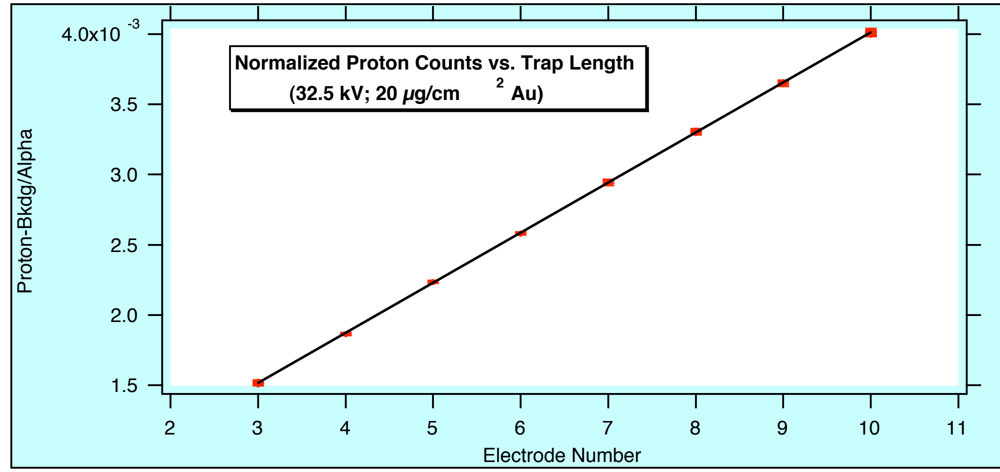
J.S. Nico *et al.*, Phys. Rev. C 71, 055502(2005)

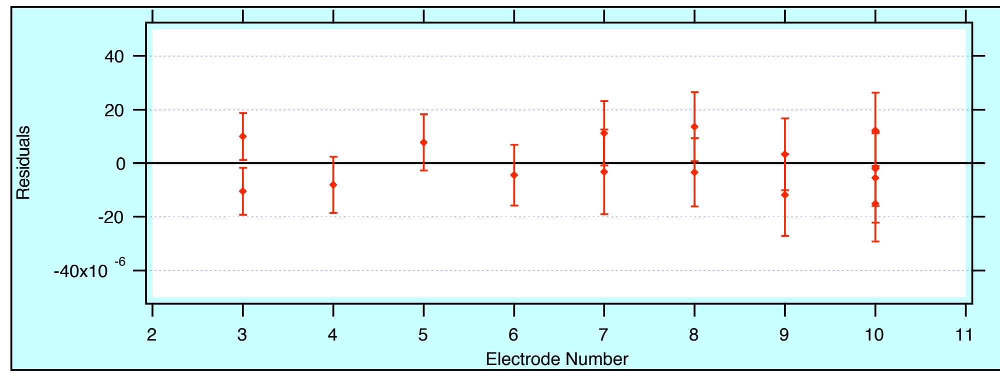
NIST Beam Lifetime

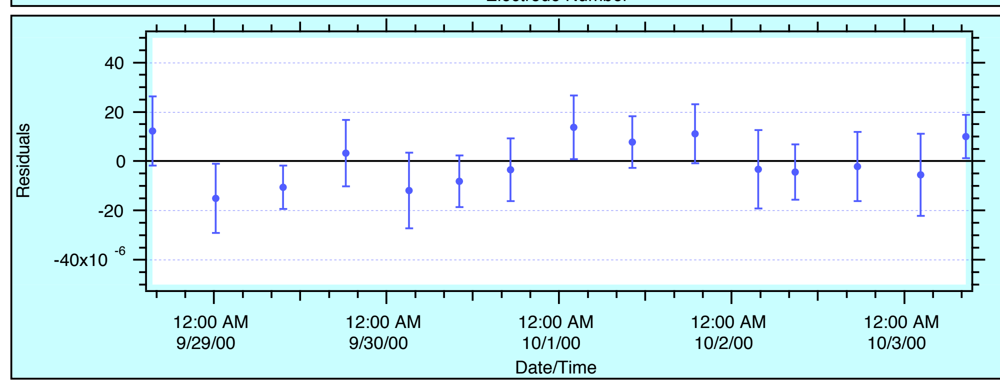






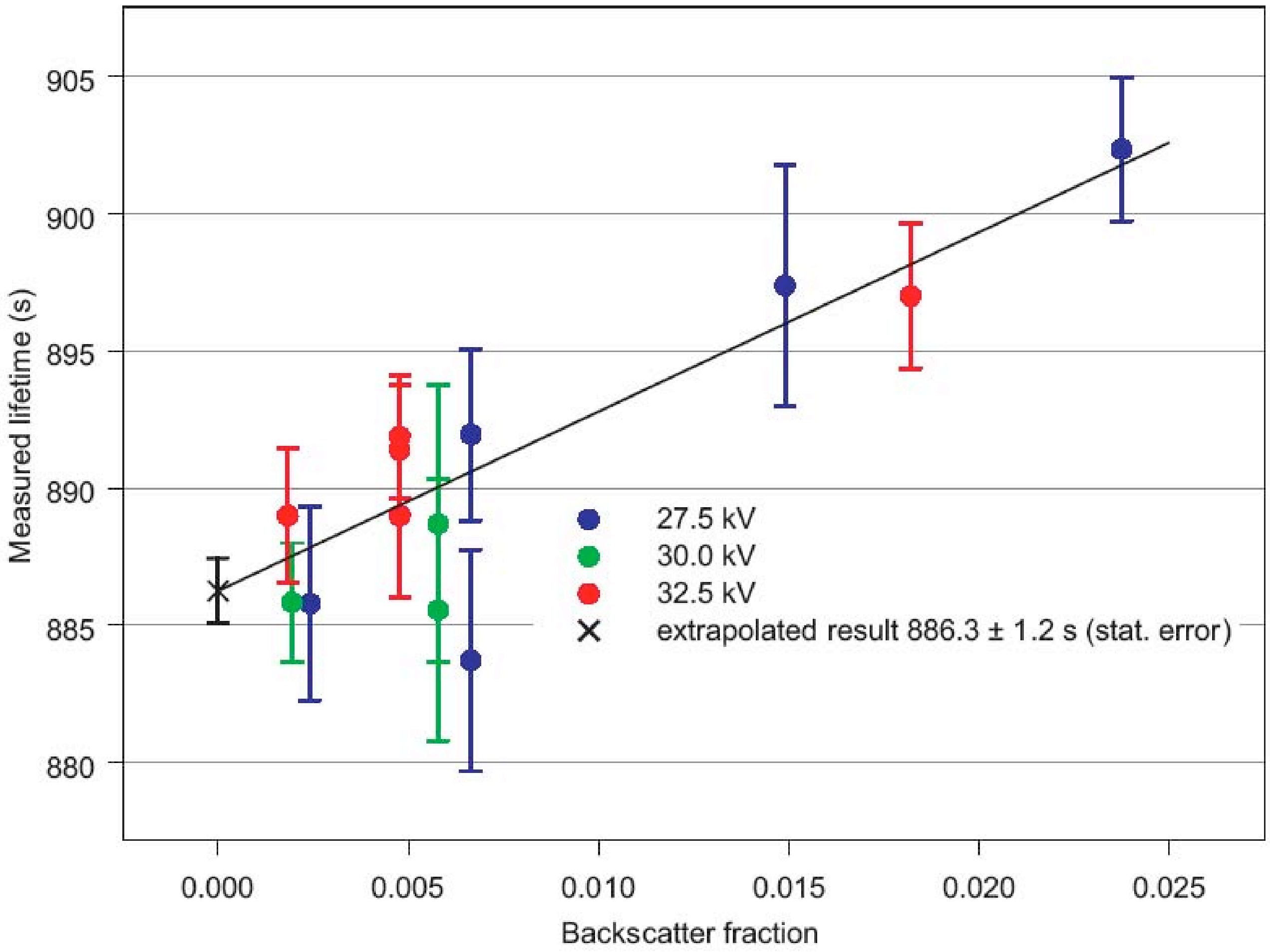






J.S. Nico *et al.*, Phys. Rev. C 71, 055502(2005)

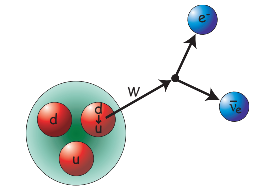
NIST Beam Lifetime



$$\tau_n = 885.5 \pm 3.4\ s$$

J.S. Nico *et al.*, Phys. Rev. C 71, 055502(2005)

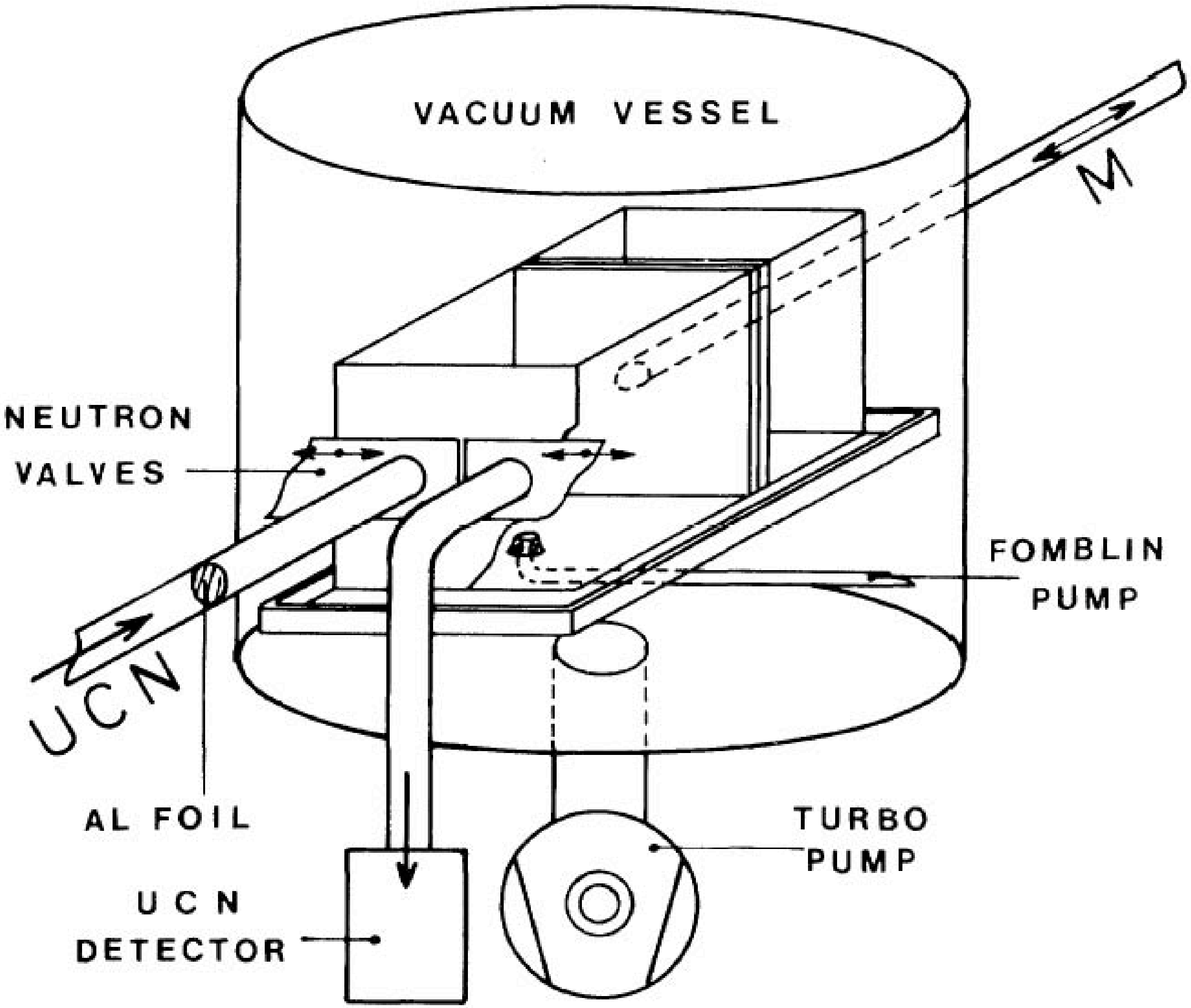
Bottle Experiments



- MamBo I - material bottle
- MamBo II - material bottle
- Bottle w/Upscatter - material bottle
- ILL Bottle - material bottle
- Gravitrap - material bottle
- NESTOR - magnetic storage ring
- ILL permanent magnet

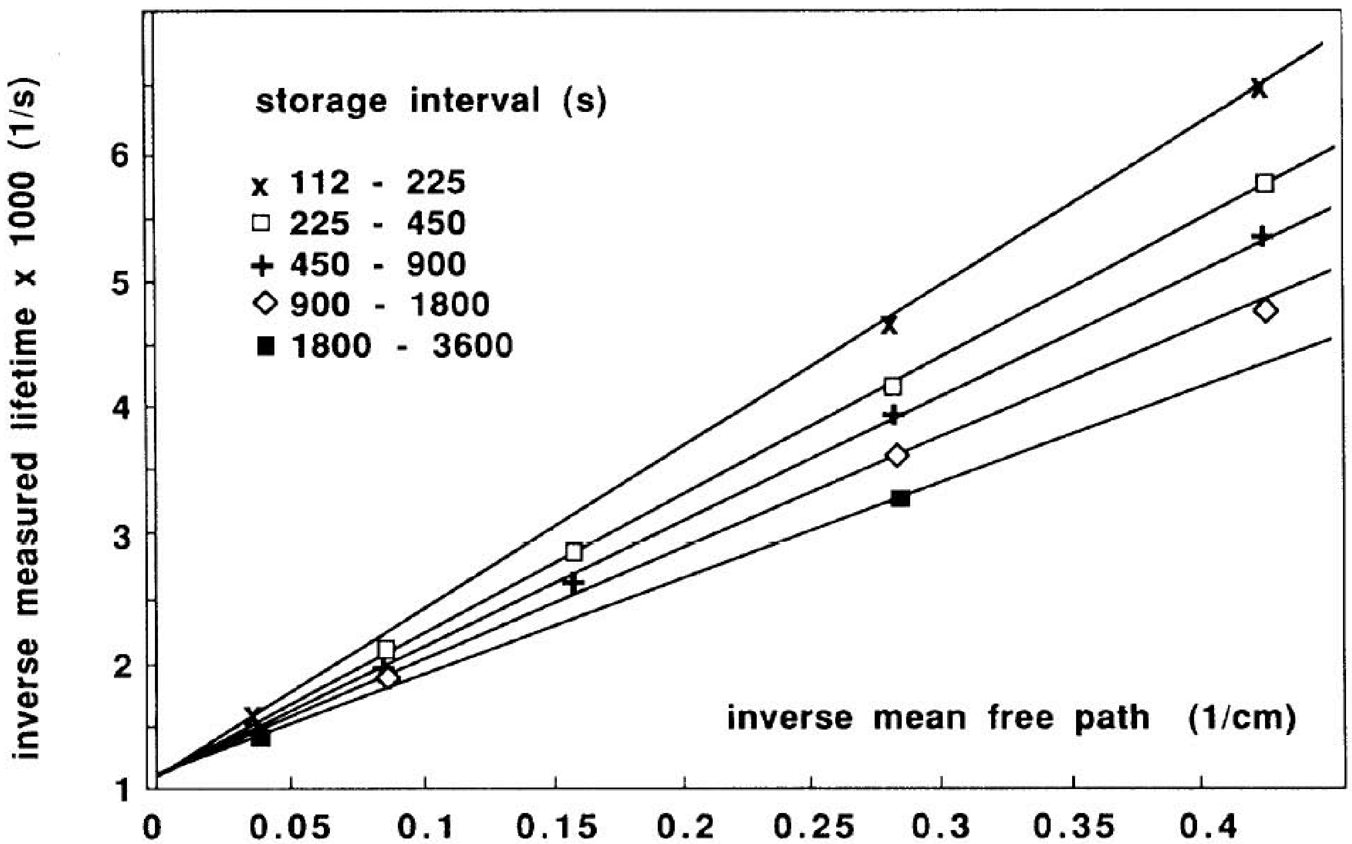
MamBo I

- Fill with UCN
- Vary surface area to volume ratio
- $1/\tau = 1/\tau_n +$ $1/\tau_{wall} + \ldots$
- Extrapolate to infinite volume



W. Mampe *et al.*, PRL, 63 (1989) 593

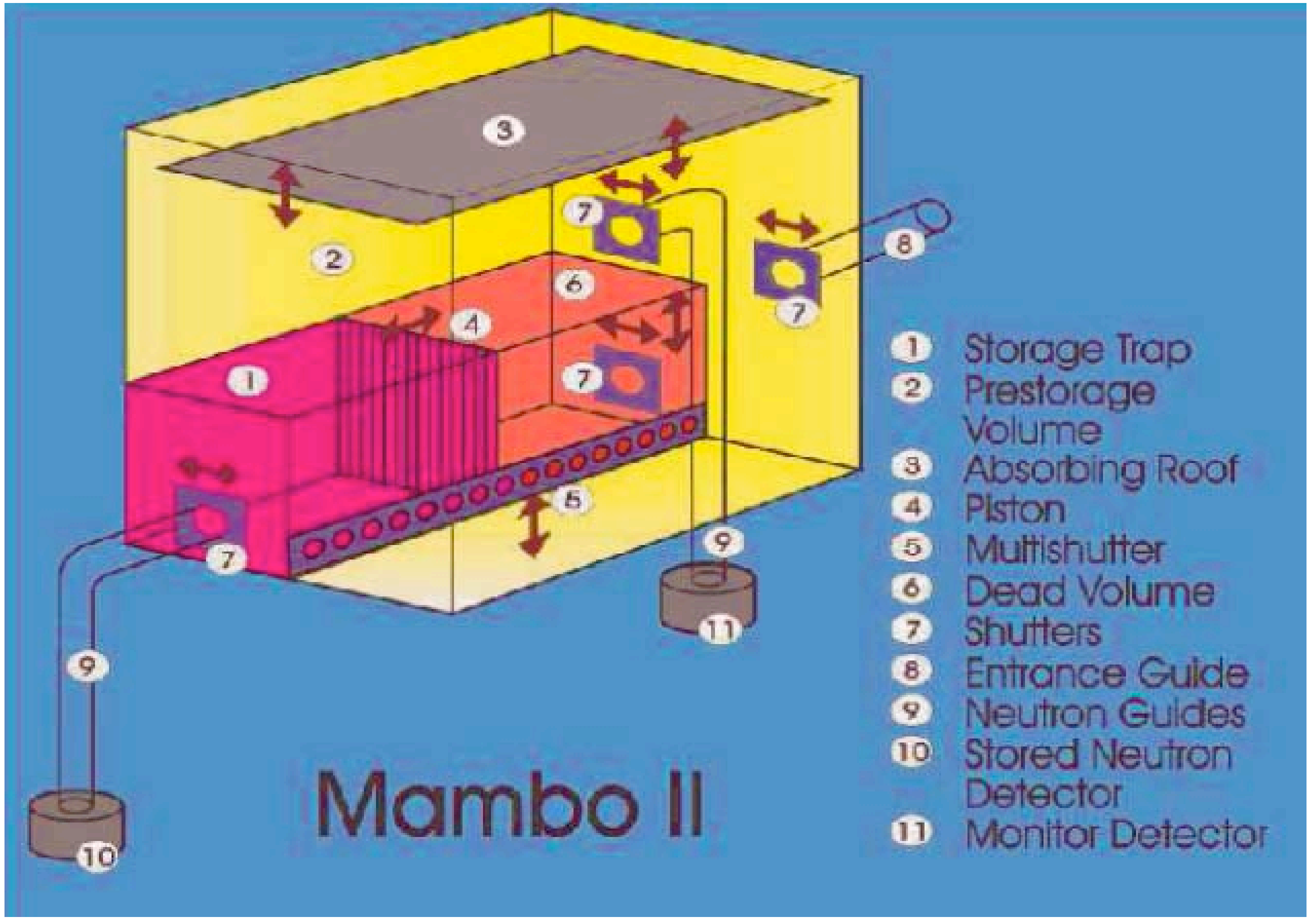
MamBo I



$$\tau_n = 887.6 \pm 3\ s$$

W. Mampe *et al.*, PRL, 63 (1989) 593

MamBo II

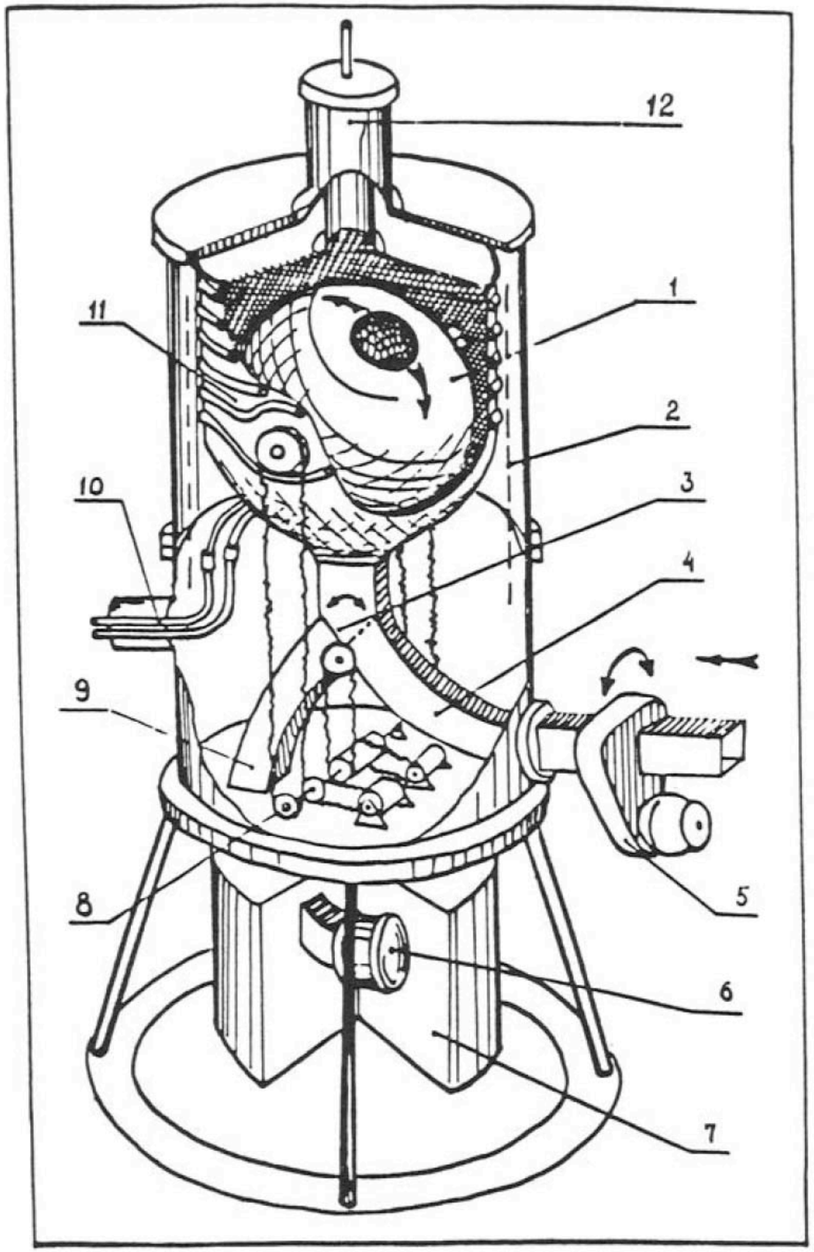


$\tau_n = 881 \pm 3$ s

(unpublished)

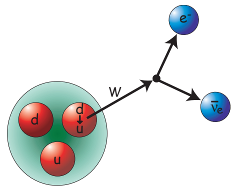
Pichlmaier, PhD thesis, TU Munich

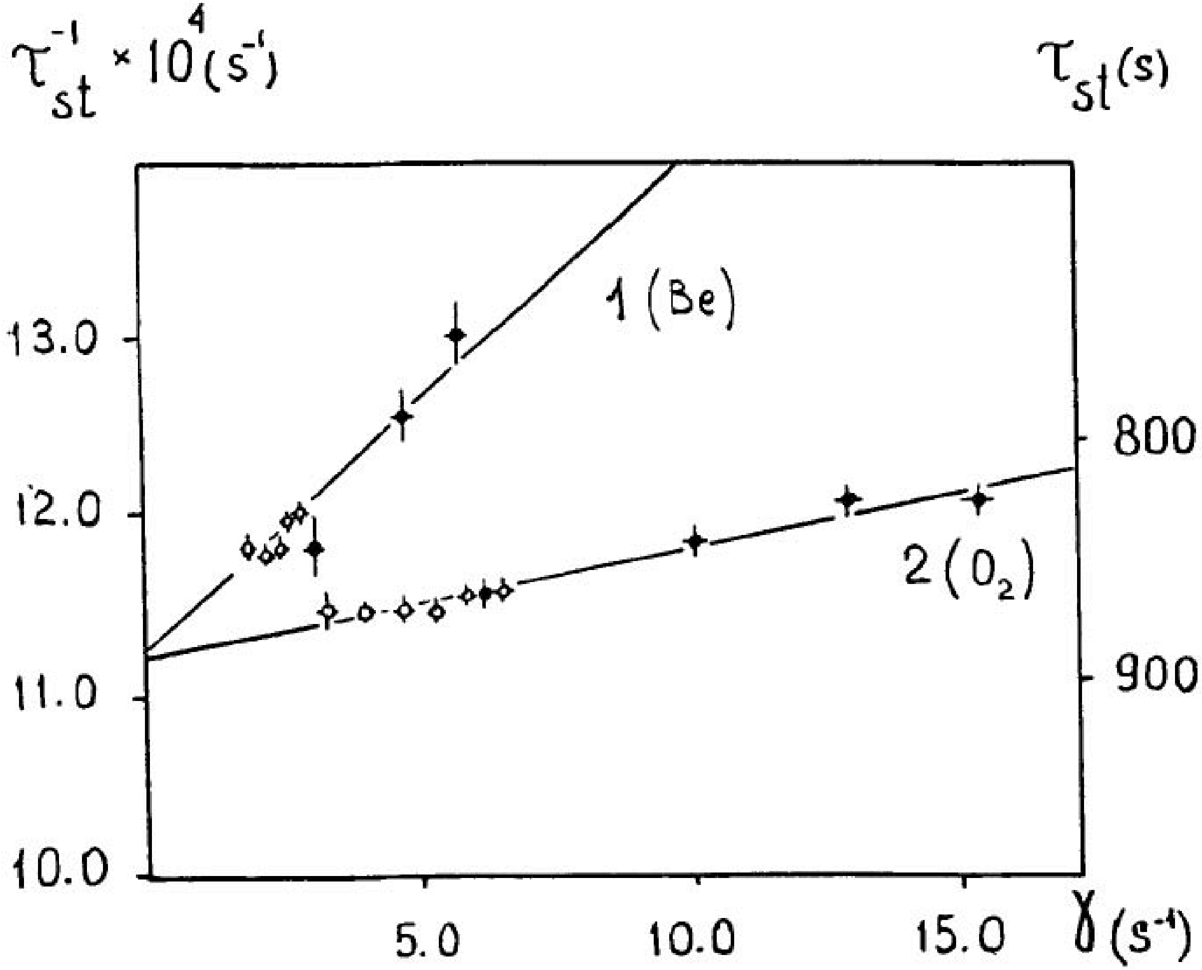
Rotating Gravitational Bottle



V. Nesvizhevsky *et al.*, JETP 75(3) (1992) 405

Rotating Gravitational Bottle

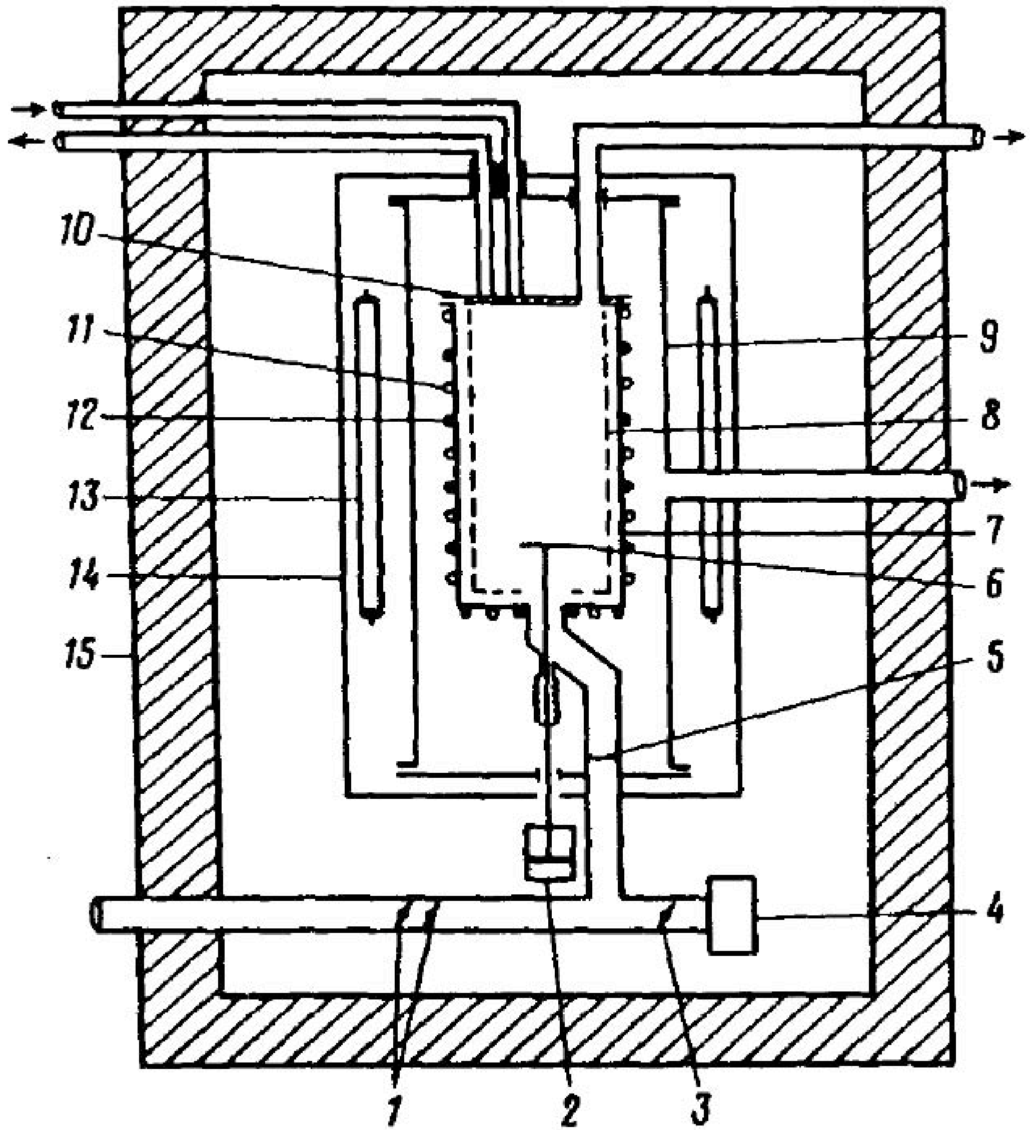




$\tau_n = 888.4 \pm 3.3\ s$

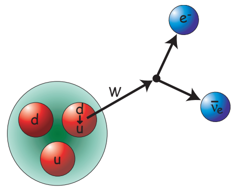
V. Nesvizhevsky *et al.*, JETP 75(3) (1992) 405

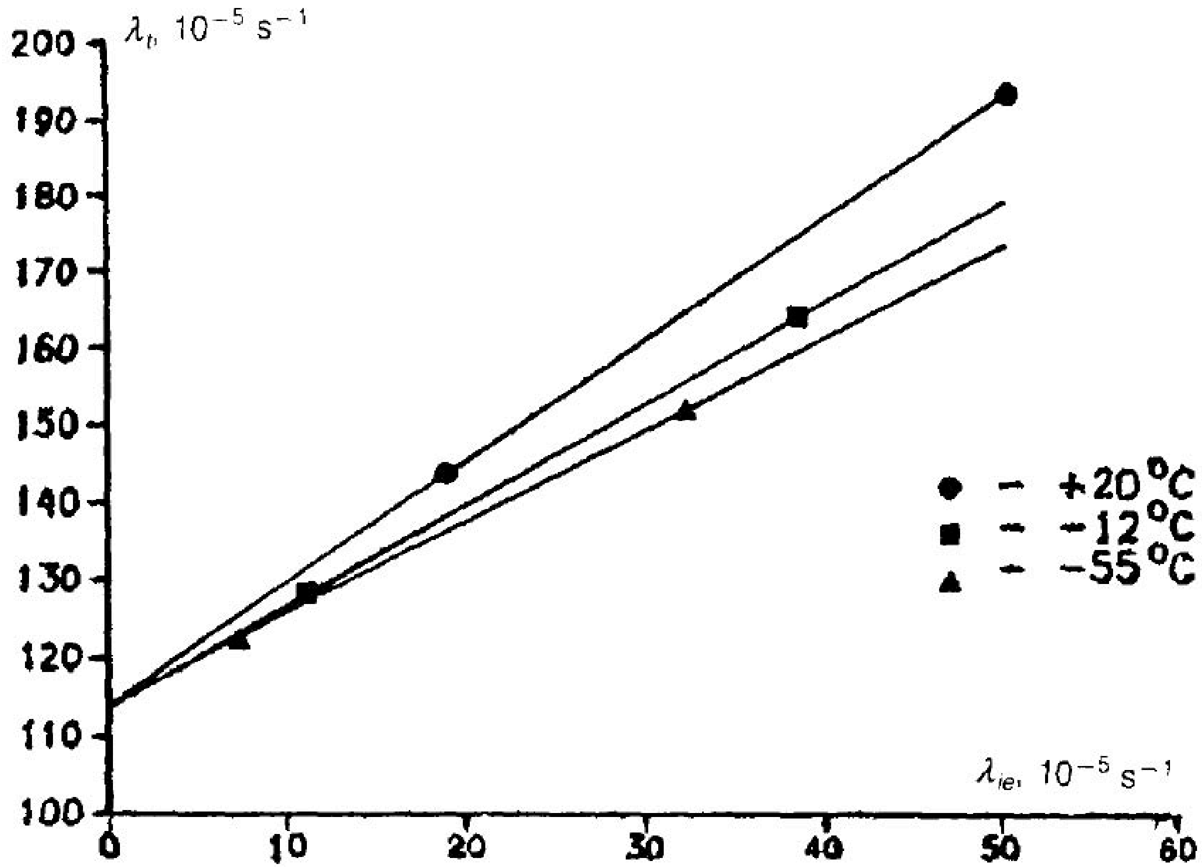
Bottle w/Upscattering



W. Mampe *et al.*, JETP Lett, 57 (1993) 82

Bottle w/Upscattering

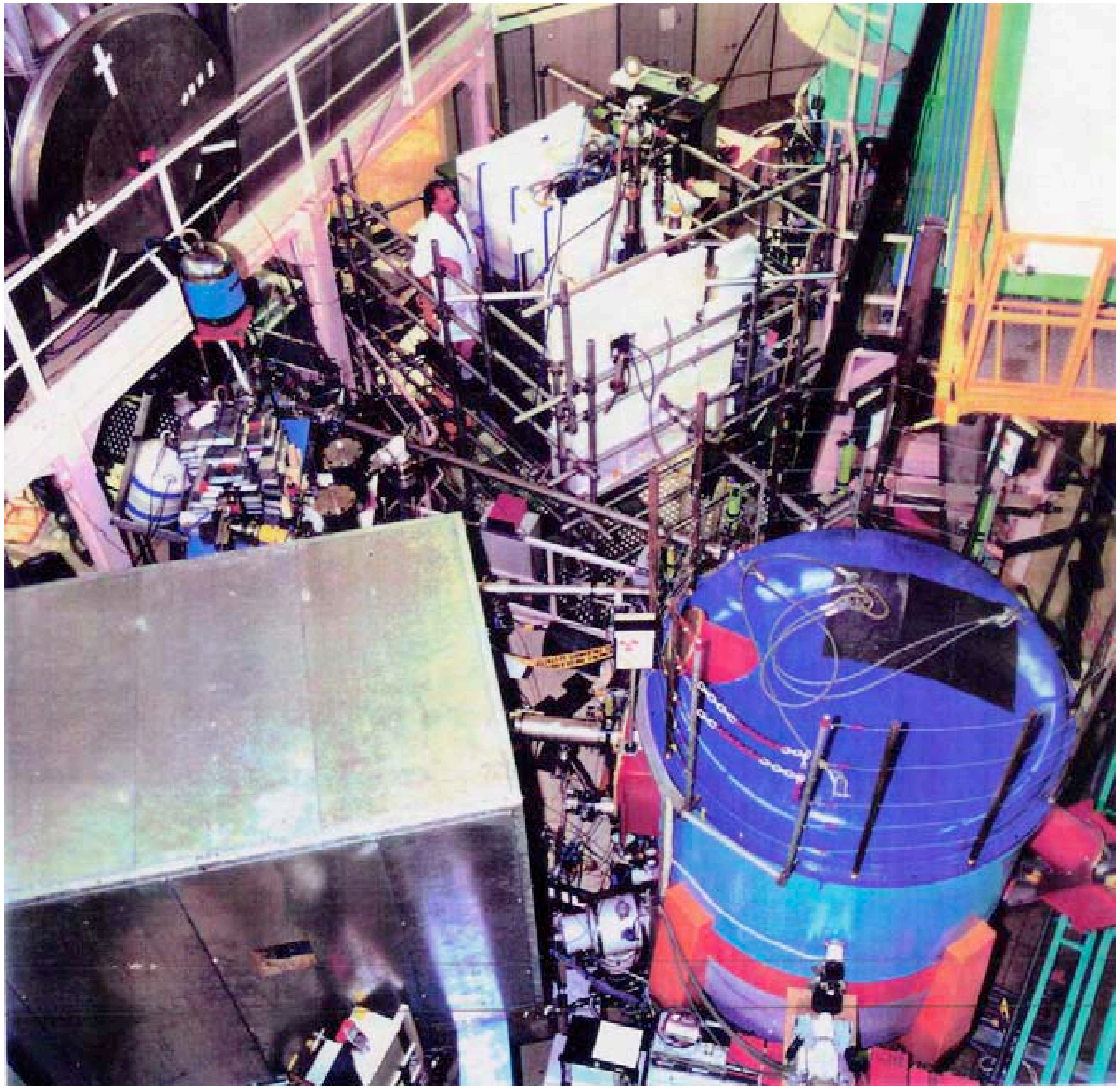




$$\tau_n = 882.6 \pm 2.7\ s$$

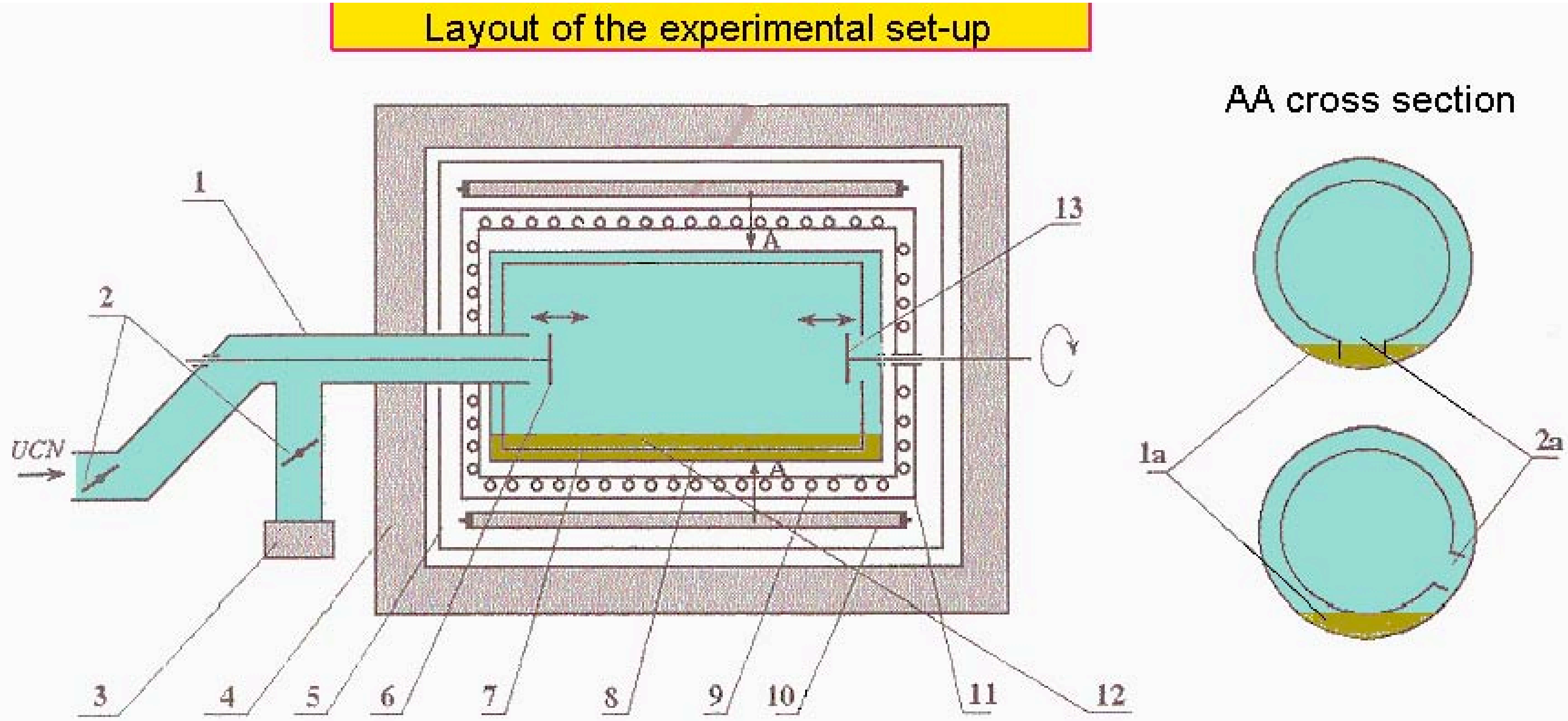
W. Mampe *et al.*, JETP Lett, 57 (1993) 82

ILL Bottle Lifetime



Arzumanov *et al.*, Phys. Lett. B483 (2000)

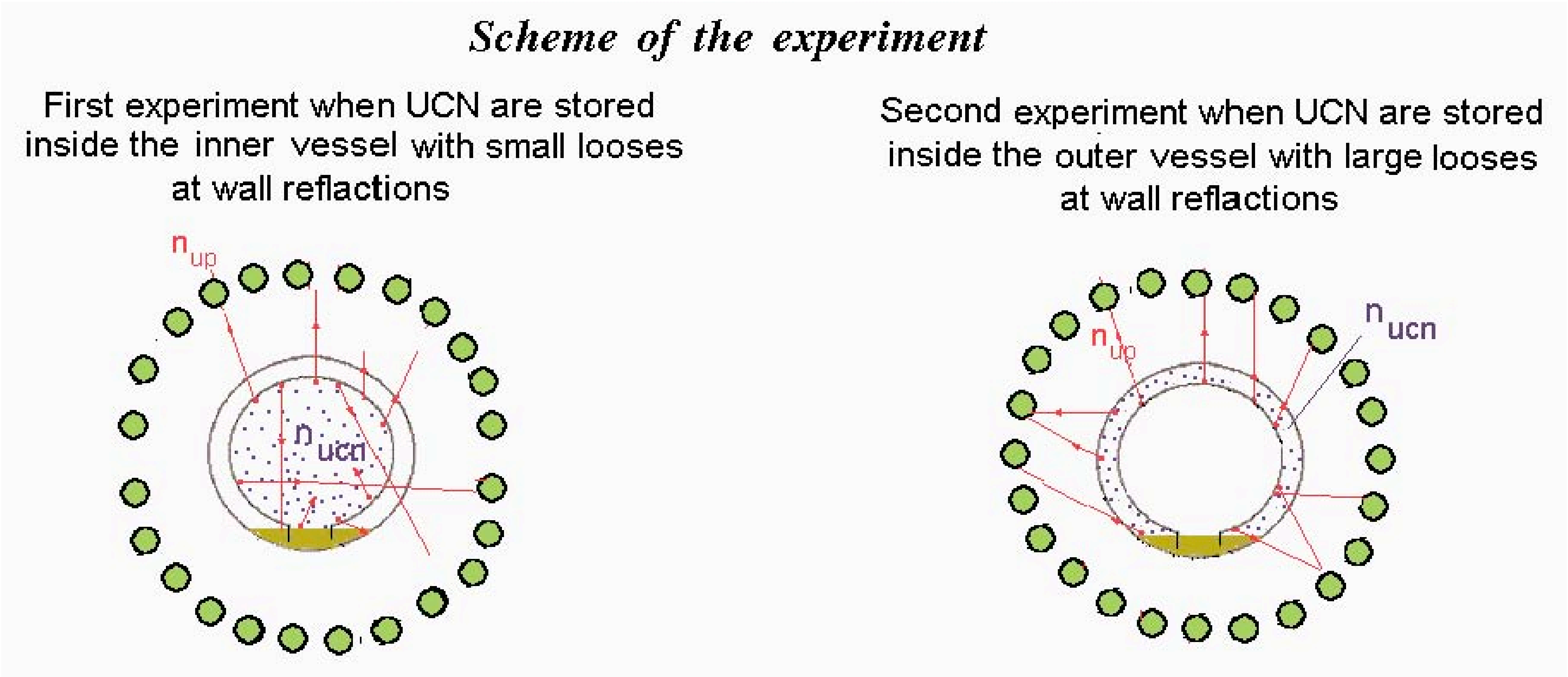
ILL Bottle Lifetime



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

Arzumanov *et al.*, Phys. Lett. B483 (2000)

ILL Bottle Lifetime



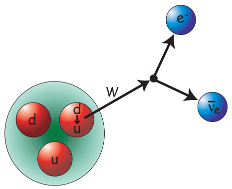
V = 65 l

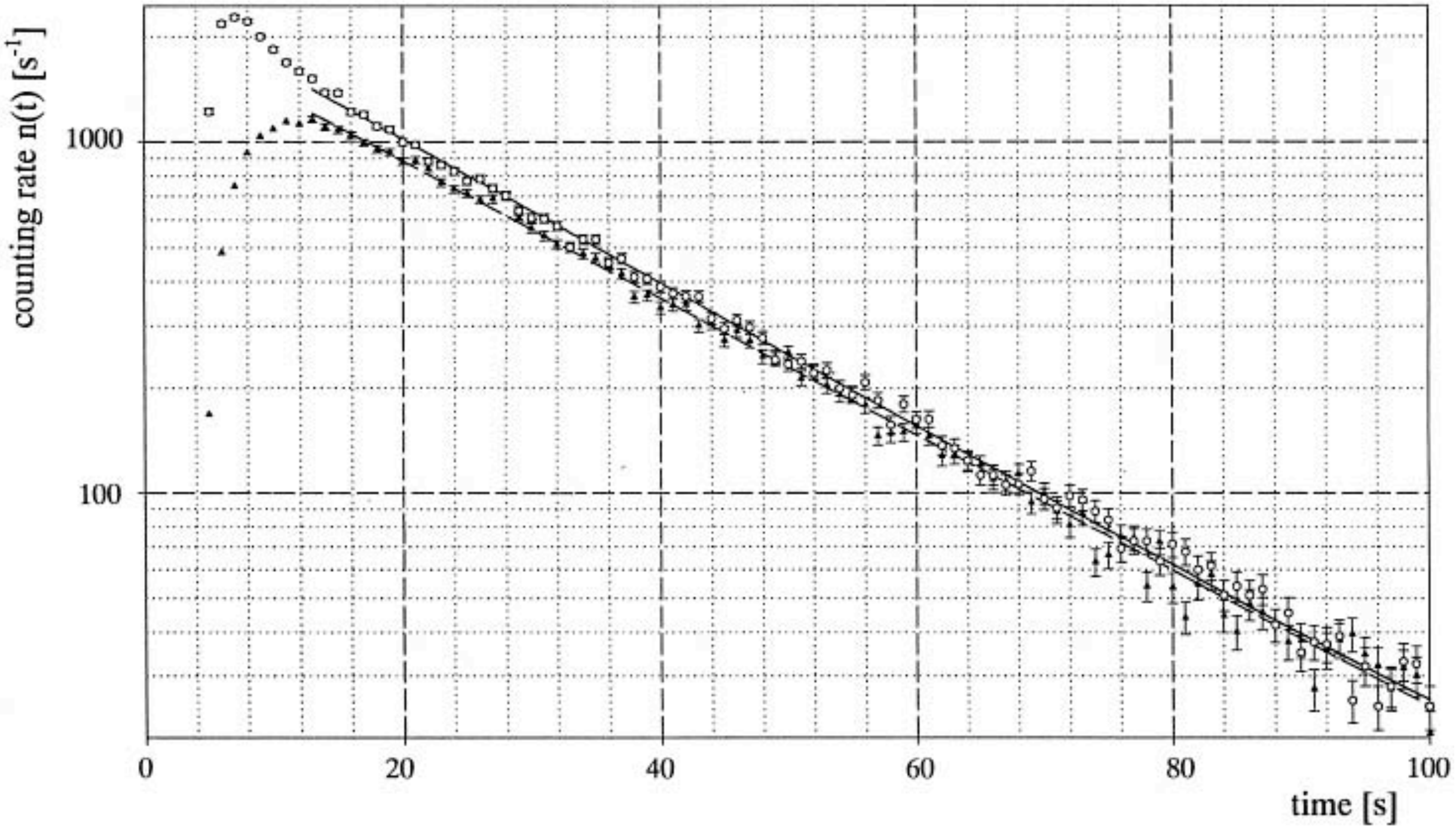
T = 300 K
= –9 °C
= –26 °C

V = 20 l

Arzumanov *et al.*, Phys. Lett. B483 (2000)

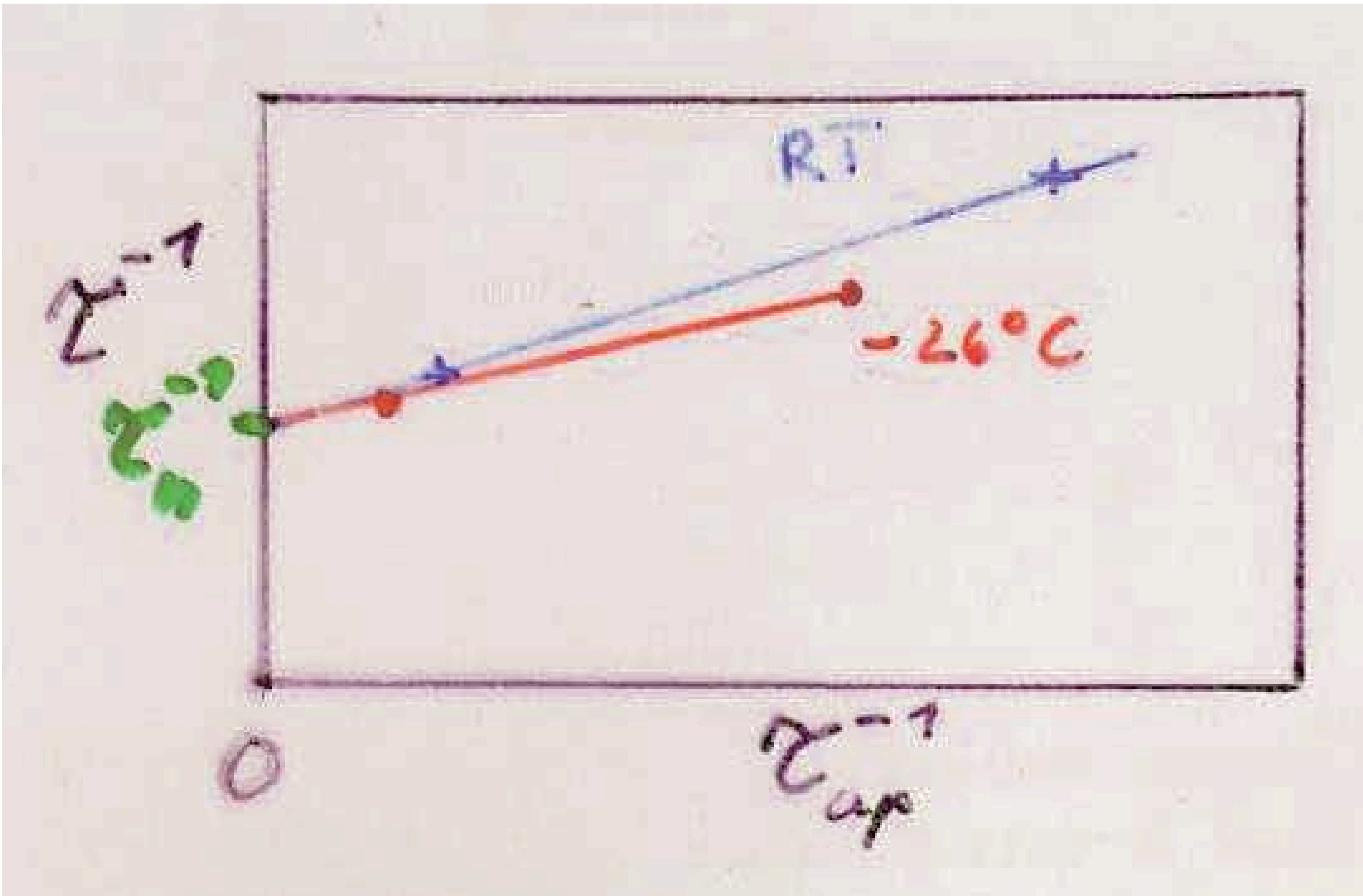
ILL Bottle Lifetime





circles - inner chamber
triangles - outer chamber

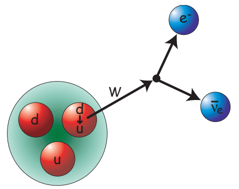
ILL Bottle Lifetime

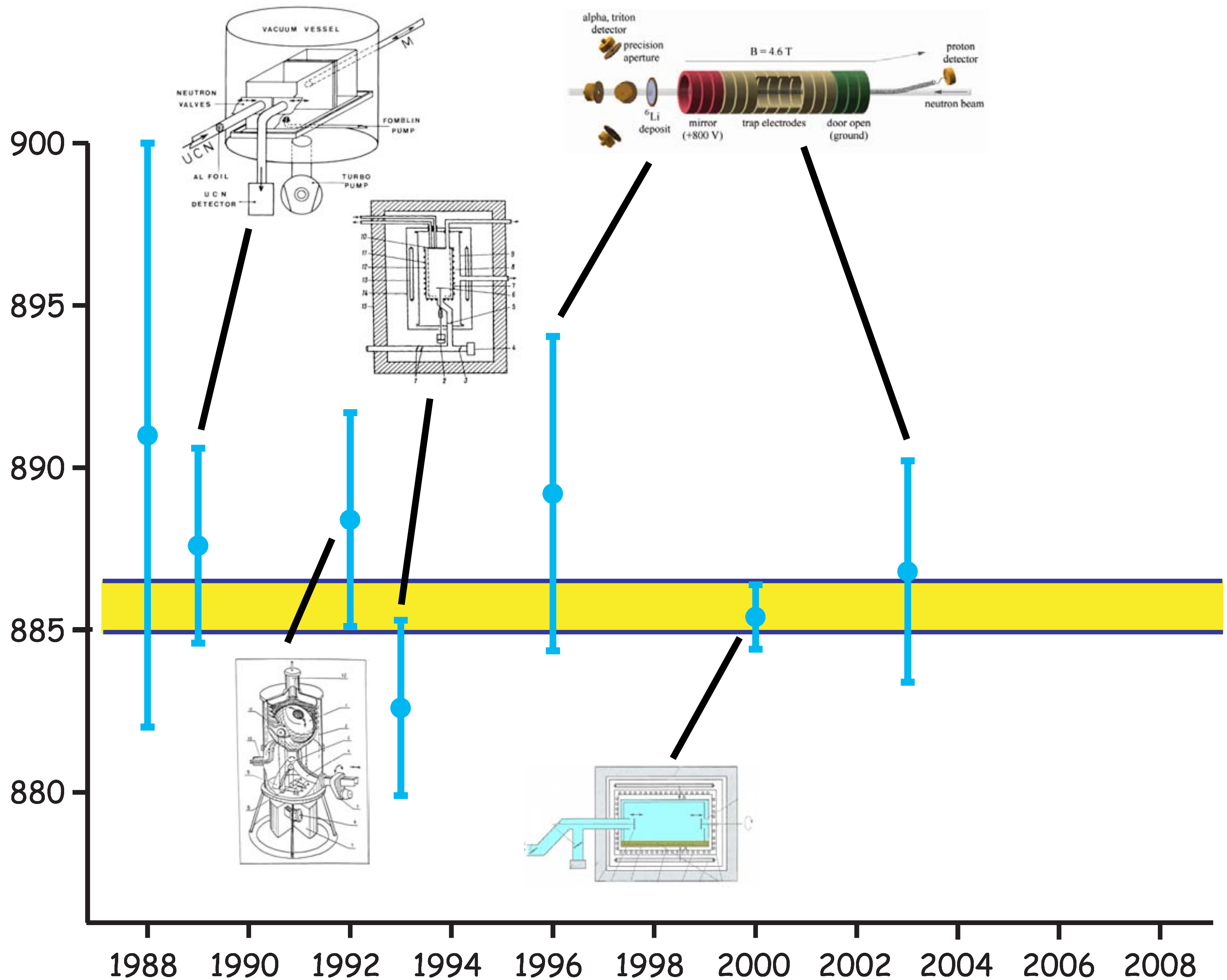


$$\tau_n = 885.4 \pm 0.9 \pm 0.4\ s$$

Arzumanov *et al.*, Phys. Lett. B483 (2000)

Measurement Summary

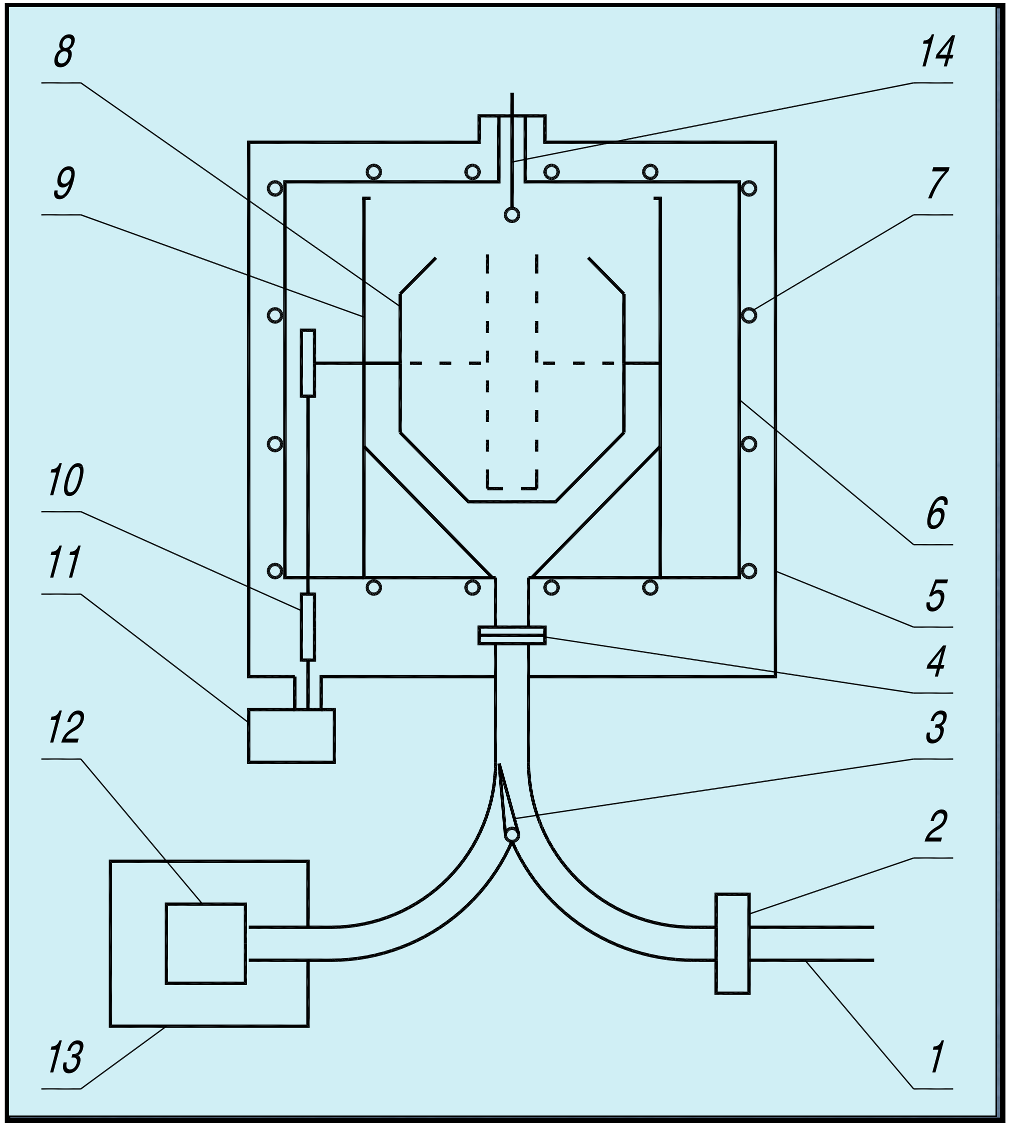




ILL Gravitrap

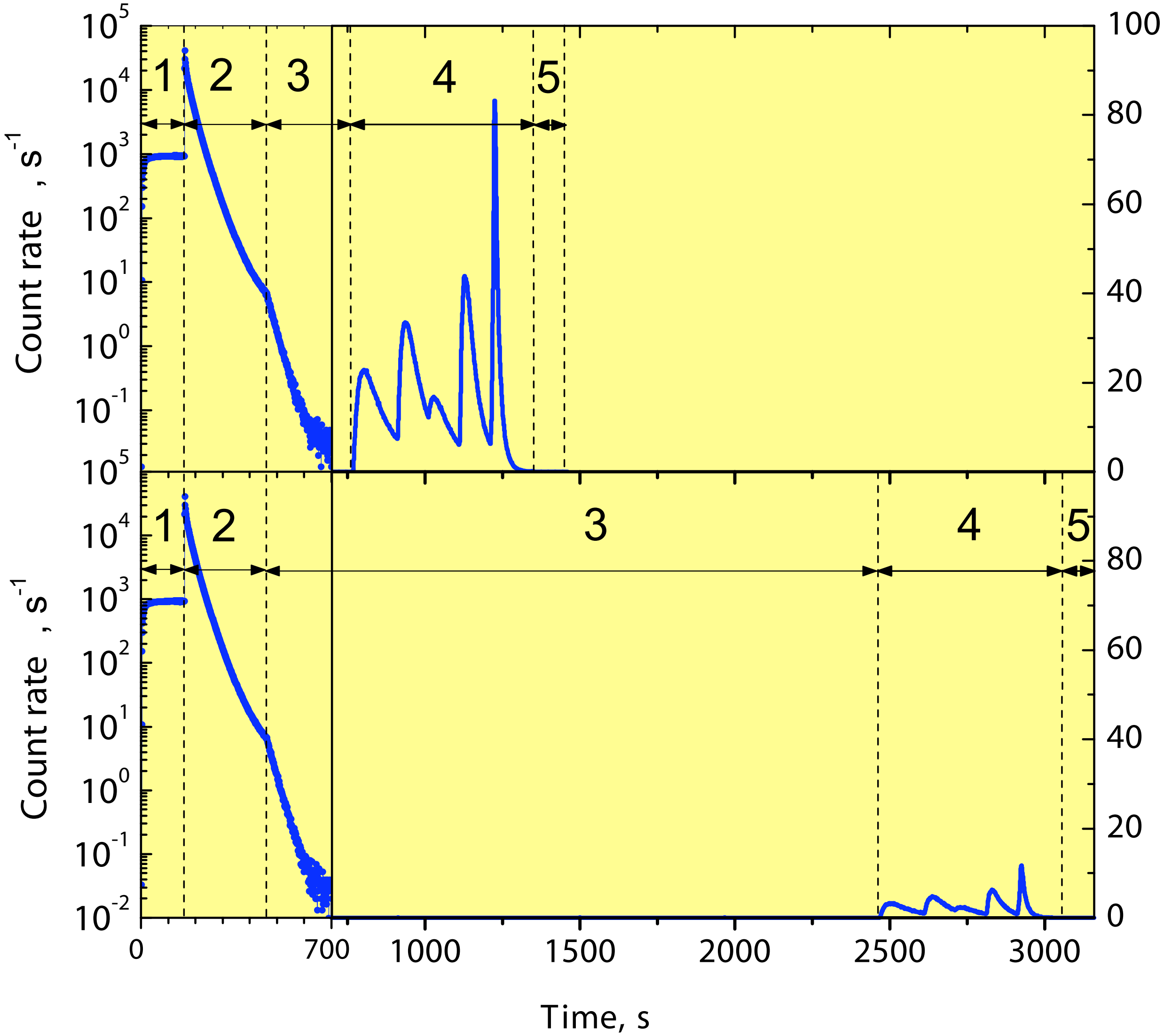
A. Serebrov *et al.*, Phys. Lett. B605 (2005) 72

ILL Gravitrap



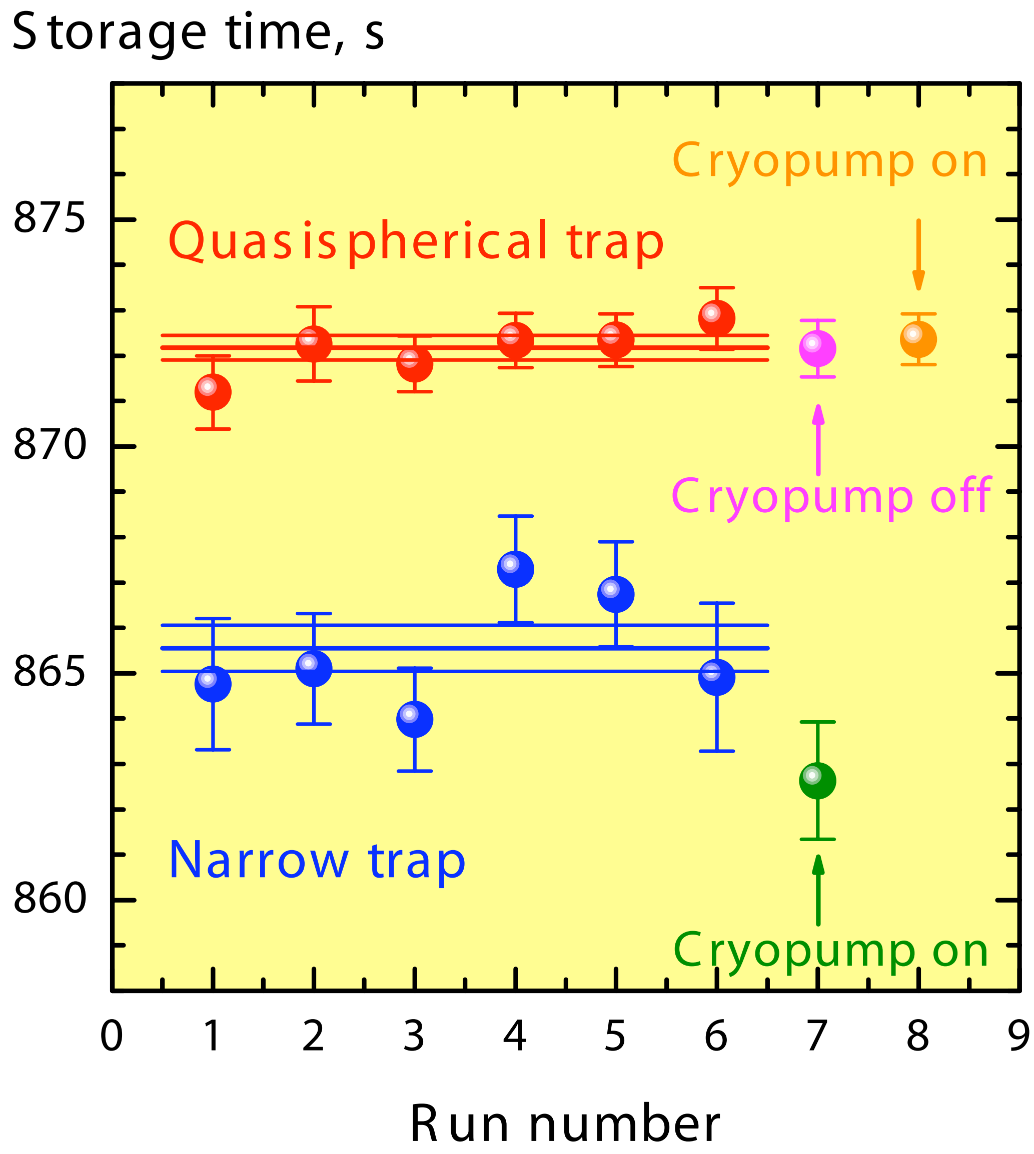
A. Serebrov *et al.*, Phys. Lett. B605 (2005) 72

ILL Gravitrap



A. Serebrov *et al.*, Phys. Lett. B605 (2005) 72

ILL Gravitrap

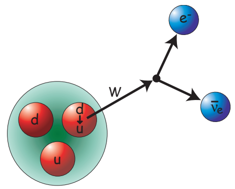


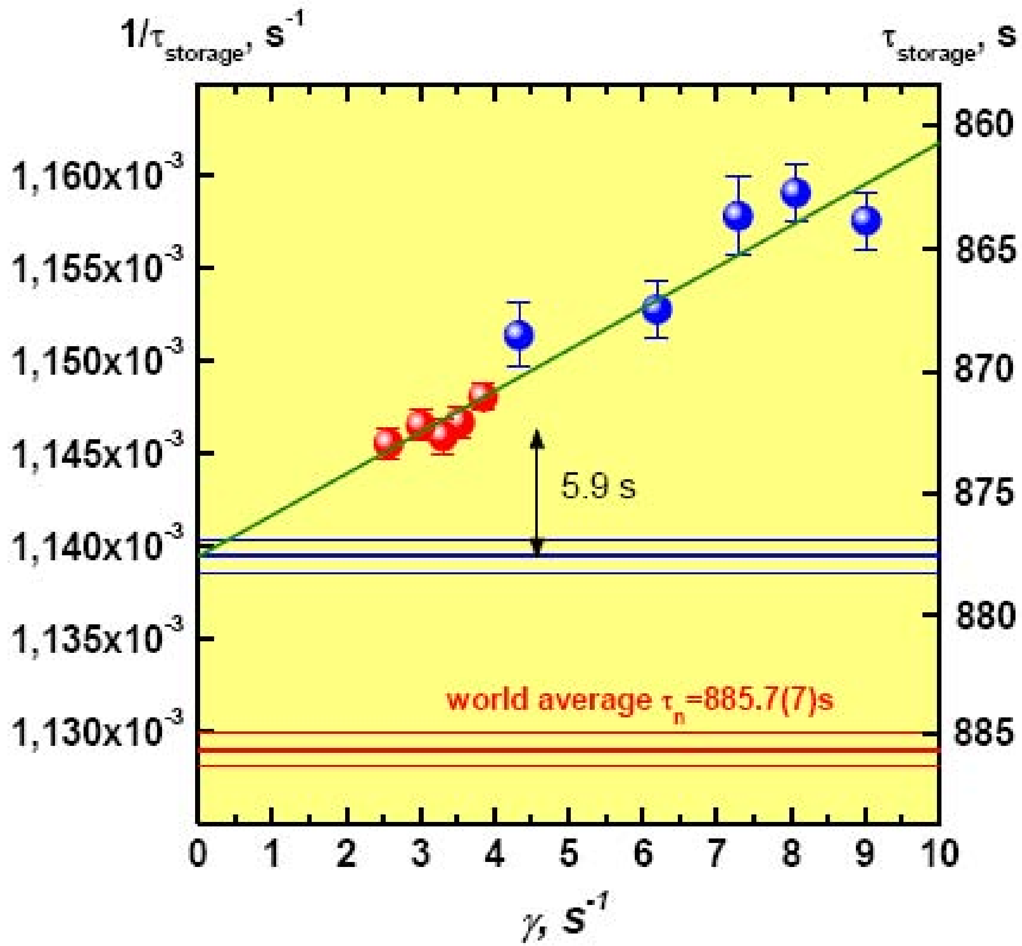
τ_{st} = 872.2 ± 0.3 s

τ_{st} = 865.6 ± 0.6 s

A. Serebrov *et al.*, Phys. Lett. B605 (2005) 72

Gravitrap

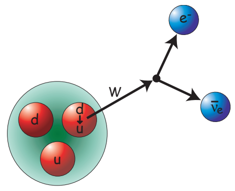


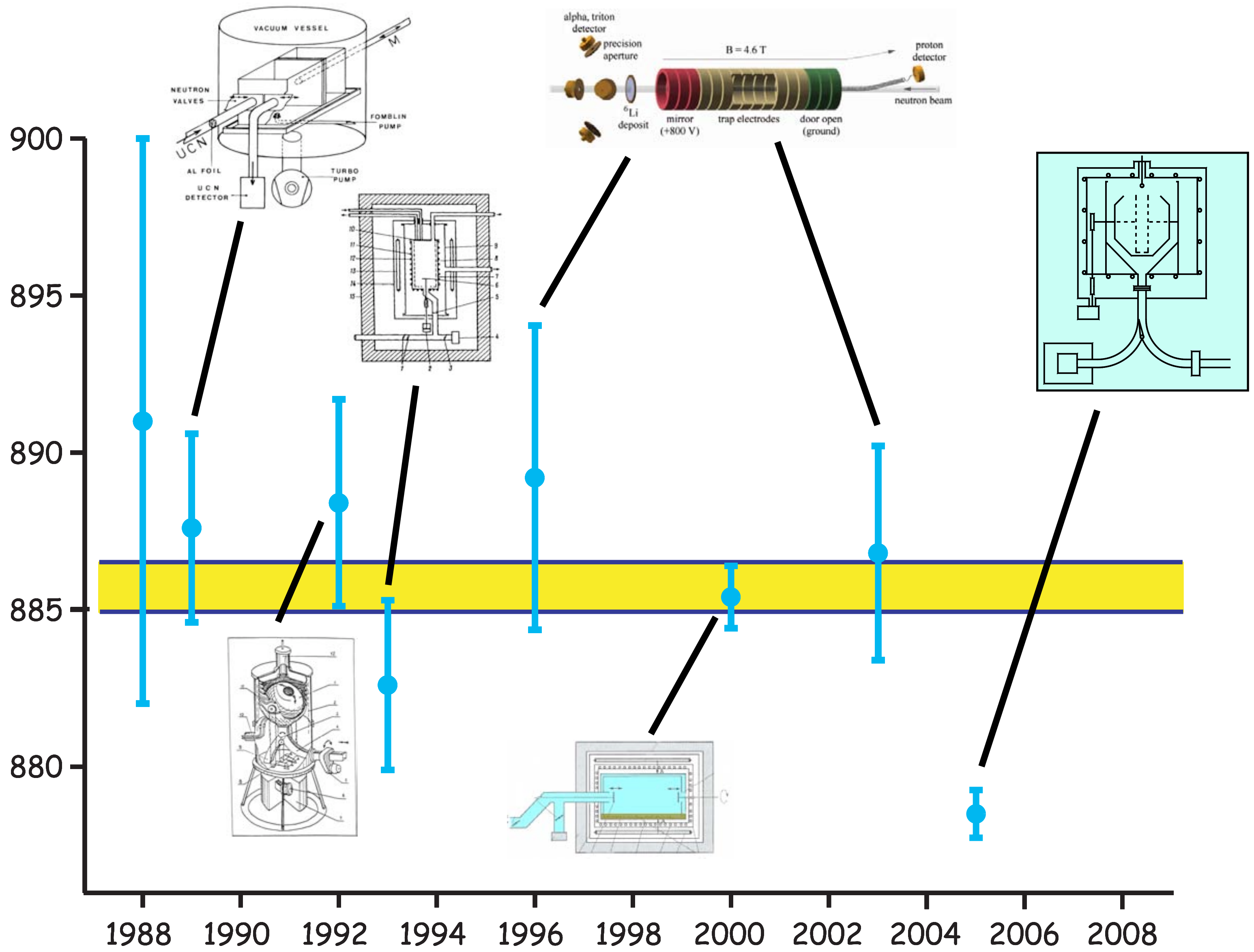


$\tau_n = 878.5 \pm 0.7 \pm 0.3\ s$

A. Serebrov *et al.*, Phys. Lett. B605 (2005) 72

Measurement Summary





n MEAN LIFE

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

The most recent result, that of SEREBROV 05 (for a more detailed account, see SEREBROV 08A), is so far from other results that it makes no sense to include it in the average. It is up to workers in this field to resolve this issue. Until this major disagreement is understood our present average of 885.7 ± 0.8 s must be suspect.

For recent reviews of neutron physics, see NICO 05A and SEVERIJNS 06.

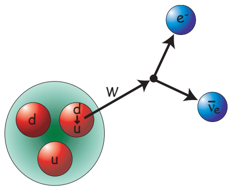
Limits on lifetimes for *bound* neutrons are given in the section "*p* PARTIAL MEAN LIVES."

VALUE (s)	DOCUMENT ID		TECN	COMMENT
885.7± 0.8 OUR AVERAGE				
886.3± 1.2± 3.2	NICO	05	CNTR	In-beam *n*, trapped *p*
885.4± 0.9± 0.4	ARZUMANOV	00	CNTR	UCN double bottle
889.2± 3.0± 3.8	BYRNE	96	CNTR	Penning trap
882.6± 2.7	[10] MAMPE	93	CNTR	Gravitational trap
888.4± 3.1± 1.1	NESVIZHEV...	92	CNTR	Gravitational trap
887.6± 3.0	MAMPE	89	CNTR	Gravitational trap
891 ± 9	SPIVAK	88	CNTR	Beam
• • • We do not use the following data for averages, fits, limits, etc. • • •				
878.5± 0.7± 0.3	[11] SEREBROV	05	CNTR	Gravitational trap
886.8± 1.2± 3.2	DEWEY	03	CNTR	See NICO 05
888.4± 2.9	ALFIMENKOV	90	CNTR	See NESVIZHEVSKII 92
893.6± 3.8± 3.7	BYRNE	90	CNTR	See BYRNE 96
878 ±27 ±14	KOSSAKOW...	89	TPC	Pulsed beam
877 ±10	PAUL	89	CNTR	Storage ring
876 ±10 ±19	LAST	88	SPEC	Pulsed beam
903 ±13	KOSVINTSEV	86	CNTR	Gravitational trap
937 ±18	[12] BYRNE	80	CNTR	
875 ±95	KOSVINTSEV	80	CNTR	
881 ± 8	BONDAREN...	78	CNTR	See SPIVAK 88
918 ±14	CHRISTENSEN	72	CNTR	

[10] IGNATOVICH 95 calls into question some of the corrections and averaging procedures used by MAMPE 93. The response, BONDARENKO 96, denies the validity of the criticisms.

[11] This SEREBROV 05 result is 6.5 standard deviations from our average of previous results and 5.6 standard deviations from the previous most precise result (that of ARZUMANOV 00).

[12] This measurement has been withdrawn (J. Byrne, private communication, 1990).

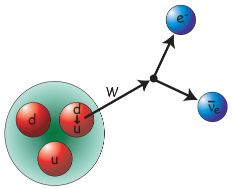


C. Amsler *et al.*
(Particle Data Group),
PL B667, 1 (2008)
and 2009 partial update
for the 2010 edition
(URL: http://pdg.lbl.gov)

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

The most recent result, that of Serebrov *et al.*, is so far from other results that it makes no sense to include it in the average.

Reanalyses



- Recent reanalysis by Fomin and Serebrov
- Incorporated quasi-elastic scattering from the walls
- Shifted the MamBo value down by 7.3 ± 1.6 s
- Also reanalyzed Mampe '93 result, which also shifts lifetime to a lower value.

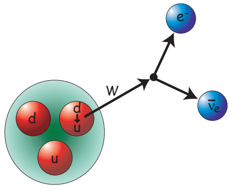
$$\tau_n = 880.3 \pm 3 \text{ s}$$

$$\tau_n = 881.5 \pm 2.4 \text{ s}$$

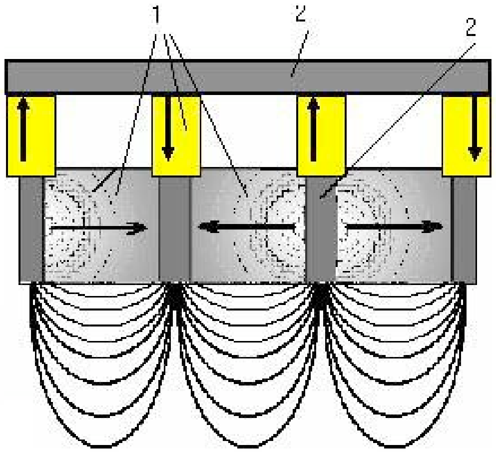
Fomin and Serebrov, 7th UCN Workshop (2009)

Gravitational-Magnetic Trap

Permanent Magnet Trap

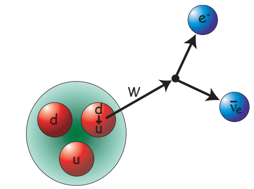


- Permanent magnets (1 T at surface)
- Filled from either below or on top
- Depolarization characterized by coating inner walls with Fomblin to retain spin-flipped neutrons
- Estimate 0.5 s in 50 days at ILL

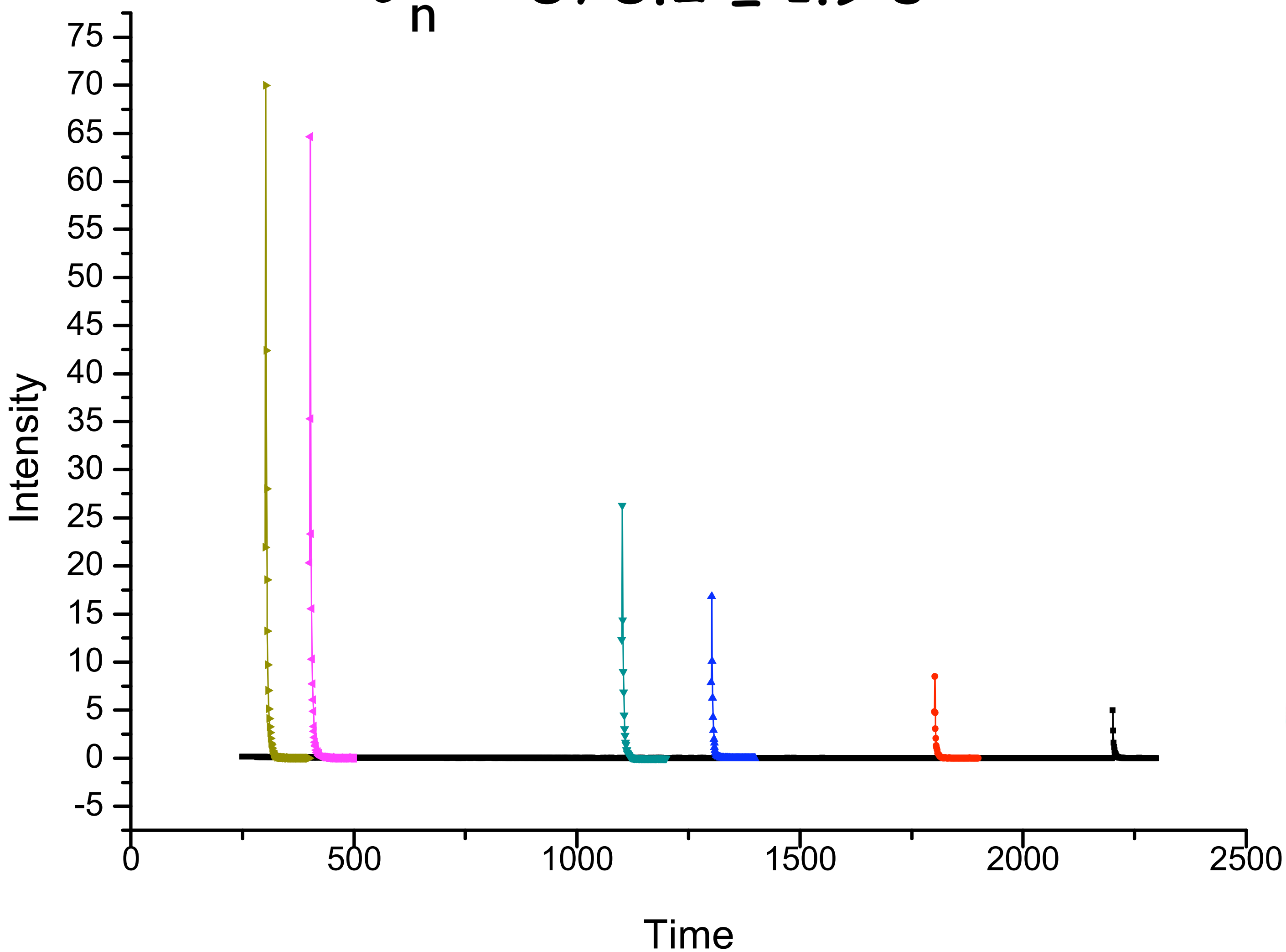


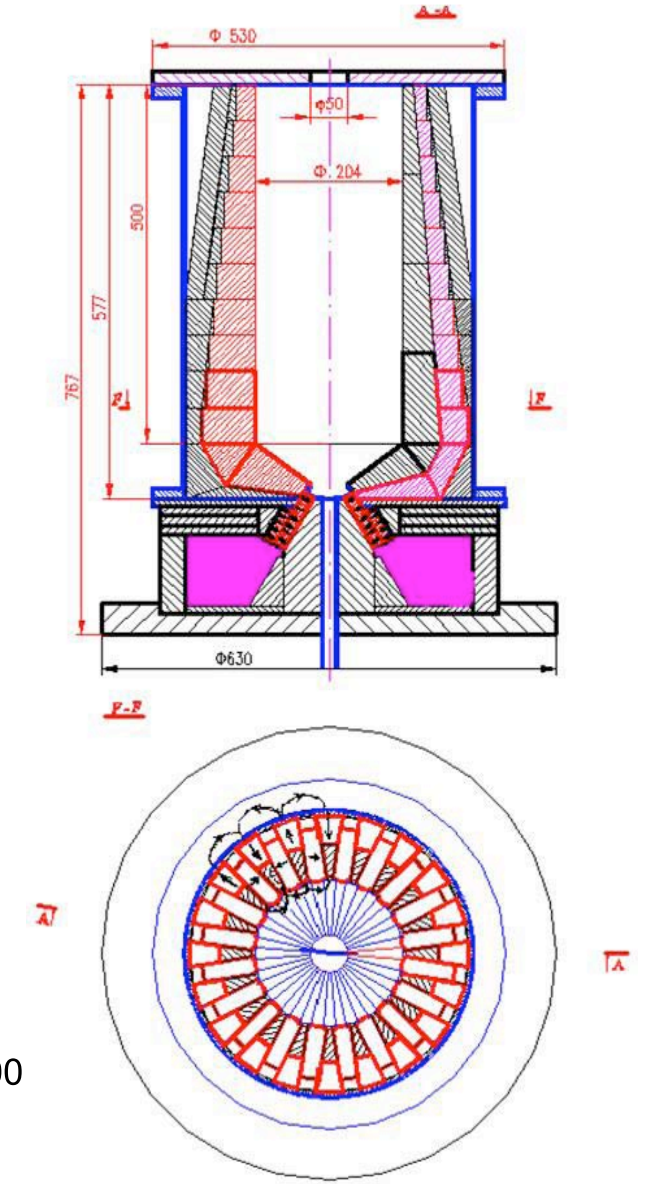
V.F. Ezhov, 7th UCN Workshop (2009)

Permanent Magnet Trap



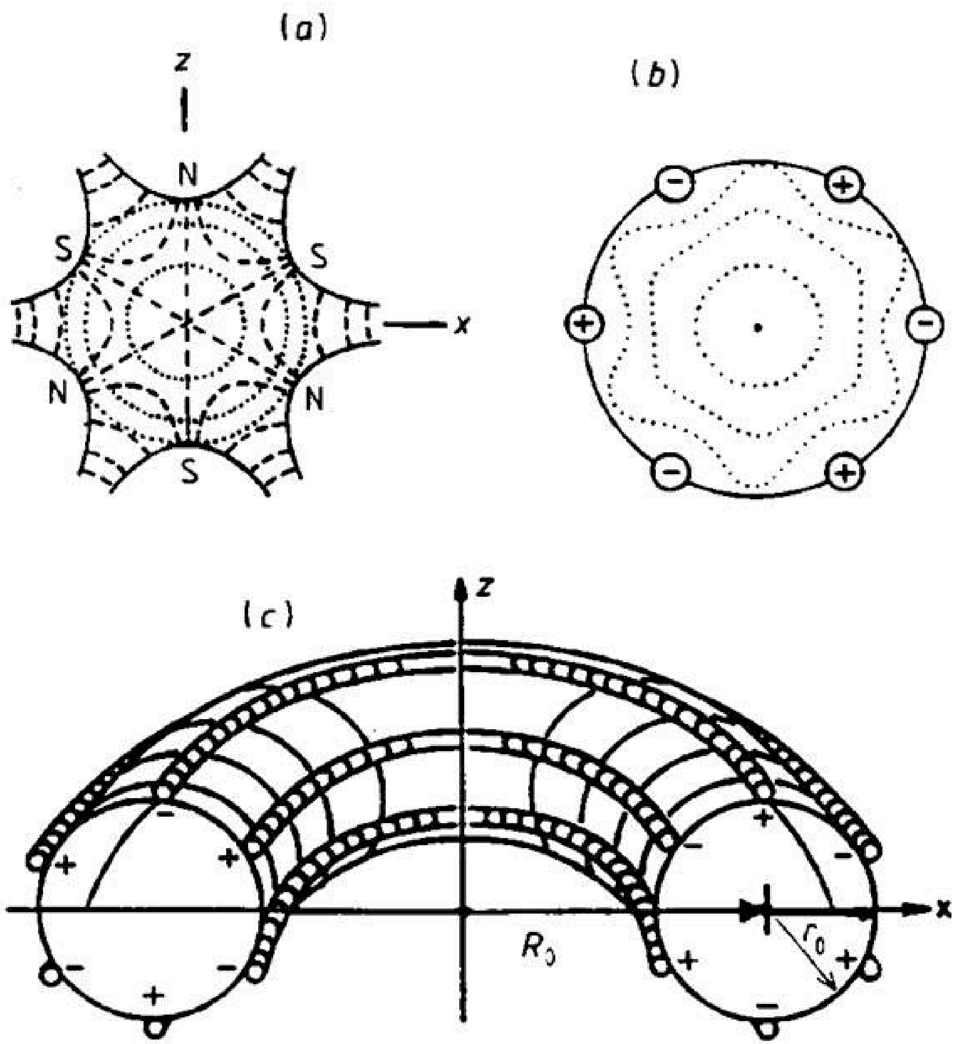
$$\tau_n = 878.2 \pm 1.9 \text{ s}$$

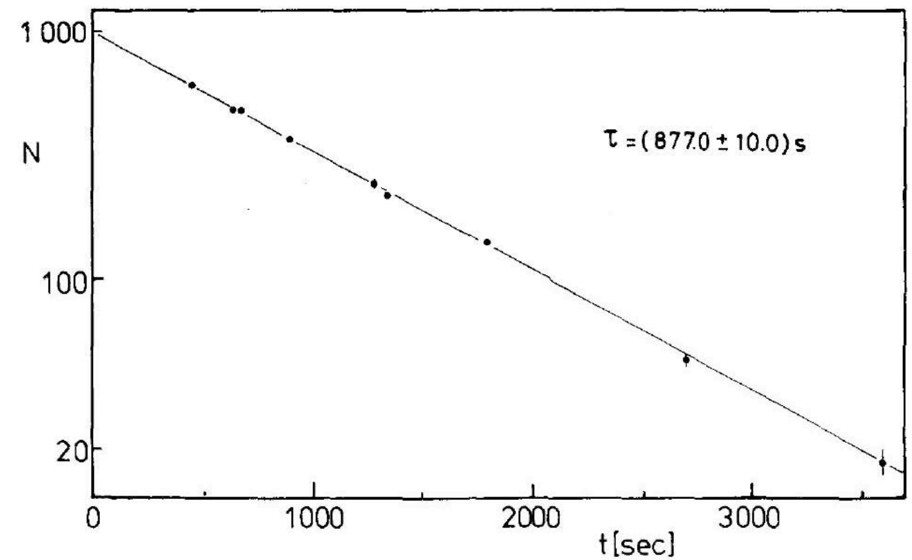




V.F. Ezhov, 7th UCN Workshop (2009)

Magnetic Storage Ring

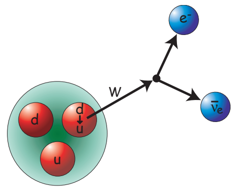


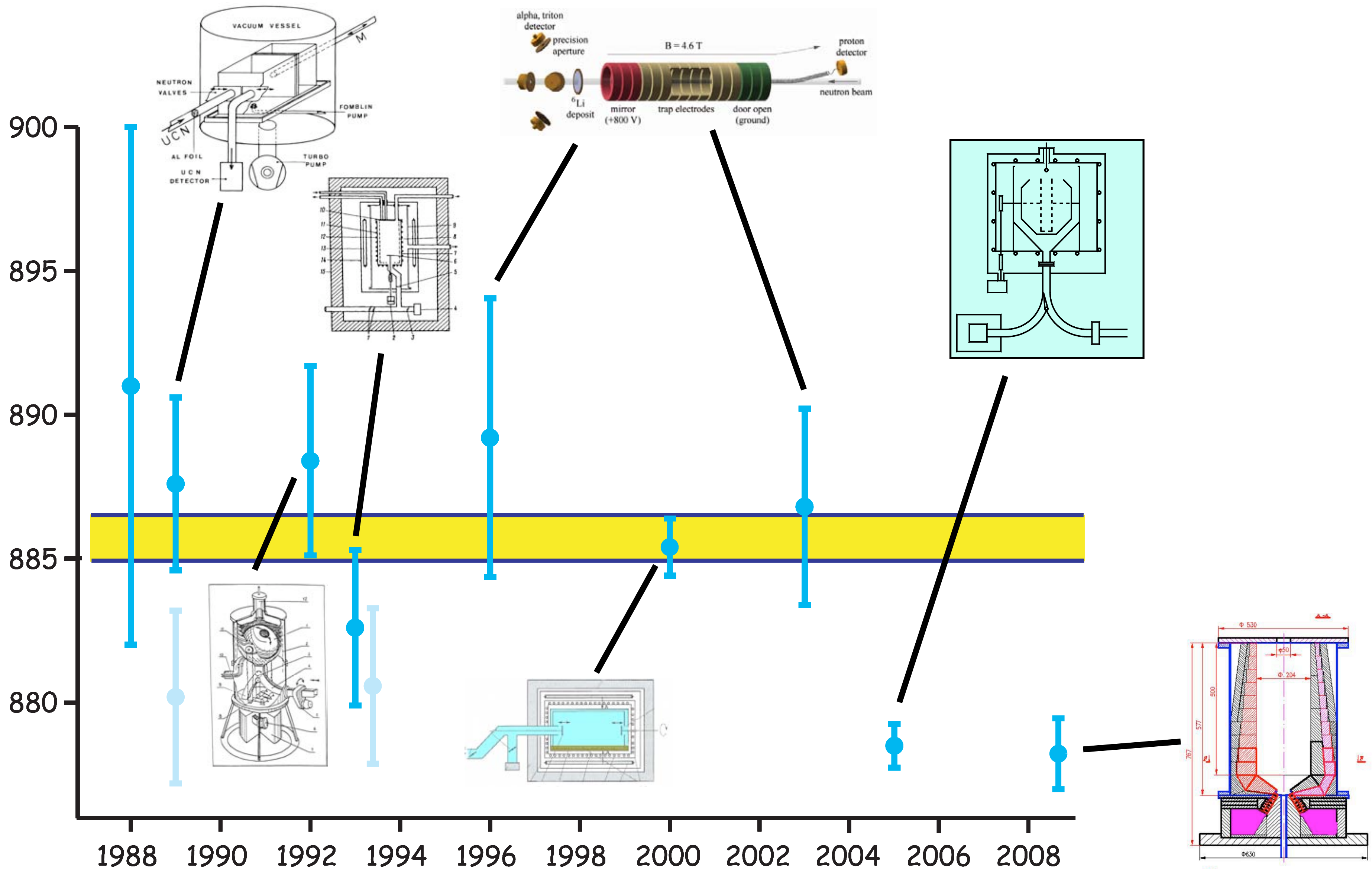


$\tau_n = 877 \pm 10\ s$

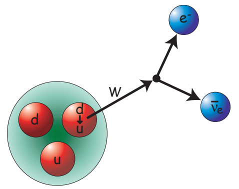
W. Paul *et al.*, Z Physics C, 45 (1989) 25

Measurement Summary



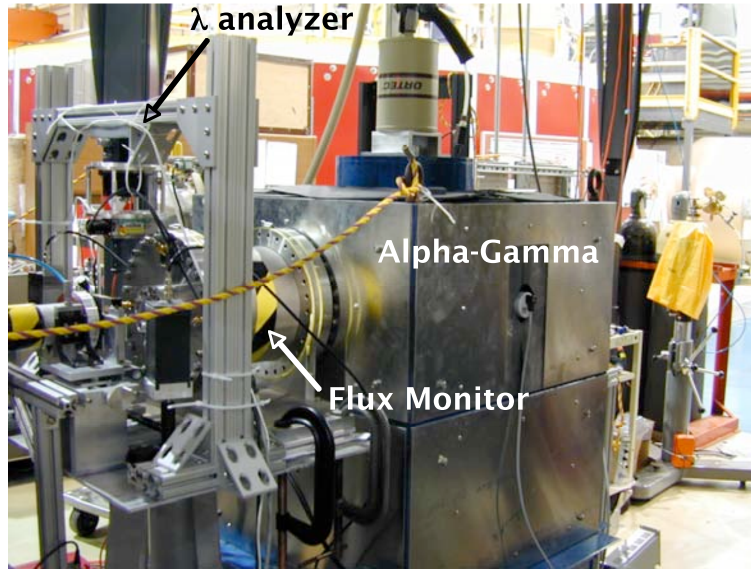


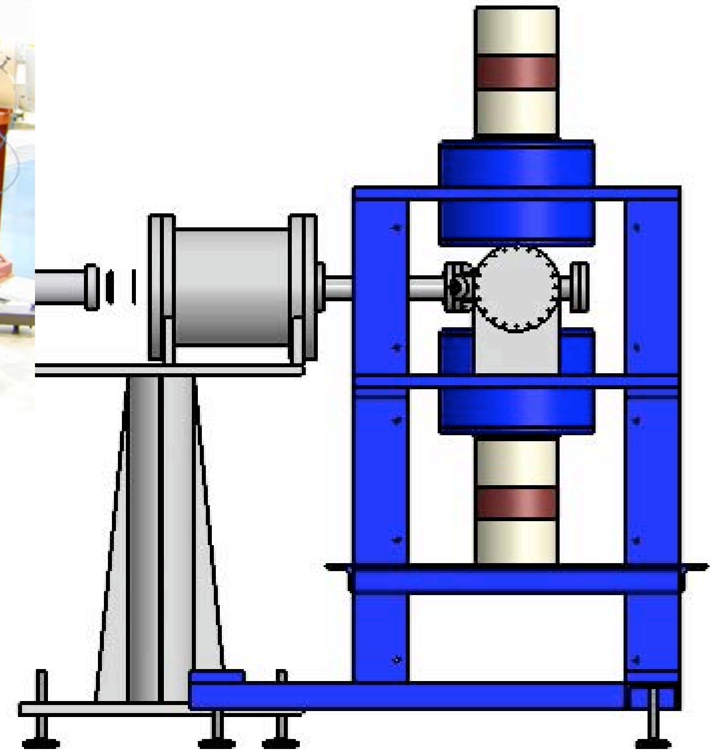
Planned Experiments

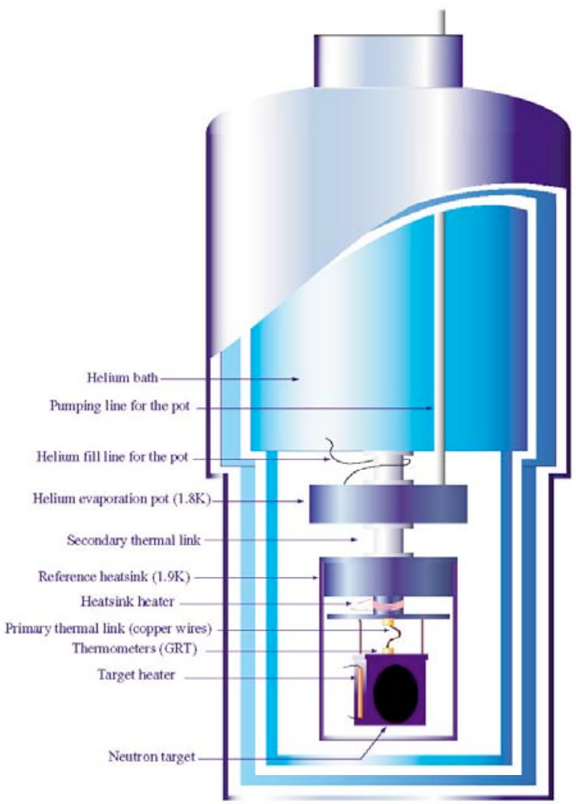


- Beam
  - Improved flux measurement for NIST expt. (Nico et al.)
  - J-Parc ion chamber (Otono et al.)
- Material Bottle
  - Accordion Bottle (Steryl et al.)
  - Updated gravitational trap (Serebrov et al.)
- Magnetic Trapping (Magneto-Gravitational)
  - PENeLOPE (Picker et al.)
  - LANL permanent magnet (Bowman et al.)
- Magnetic Trapping (4π magnetic confinement)
  - Halback octupole magnet (Zimmer et al.)
  - NIST Ioffe trap (Mumm et al.)

NIST Neutron Fluence





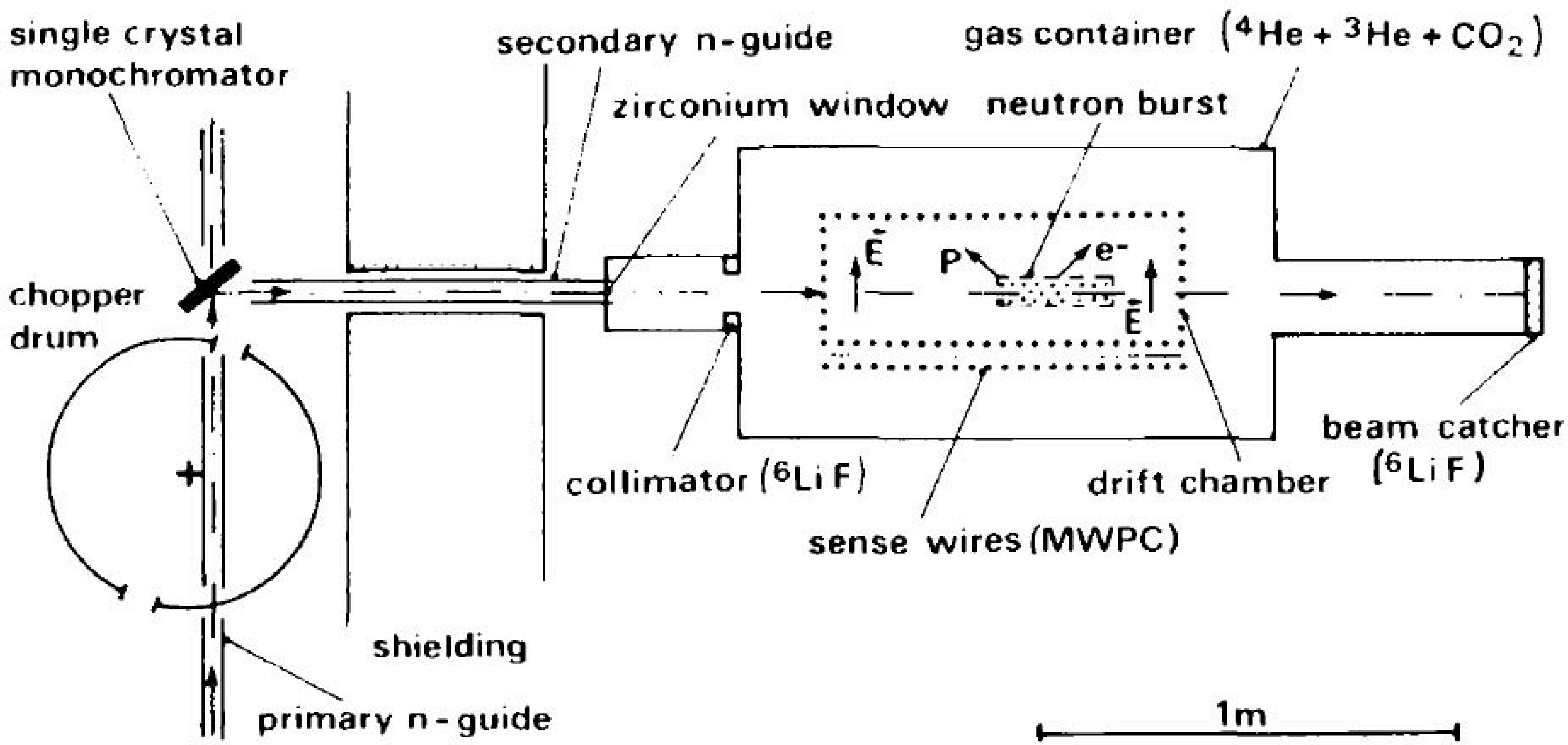


estimated accuracy

of τ_n will be ± ~2.2 s

± 1.5 s with increased running

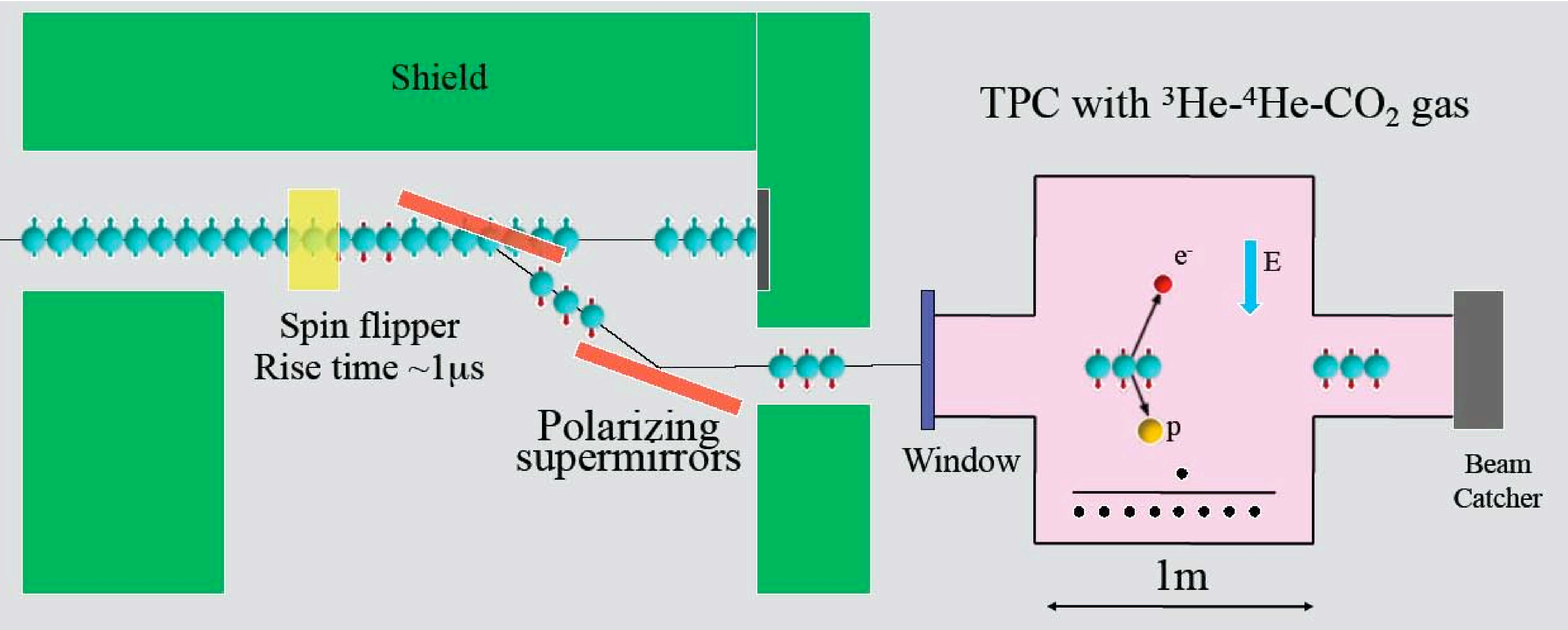
Beam Ion-Chamber



$$\tau_n = 878 \pm 31\ s$$

R. Kossakowski *et al.*, Nucl. Physics A503 (1989) 473

Ion-Chamber

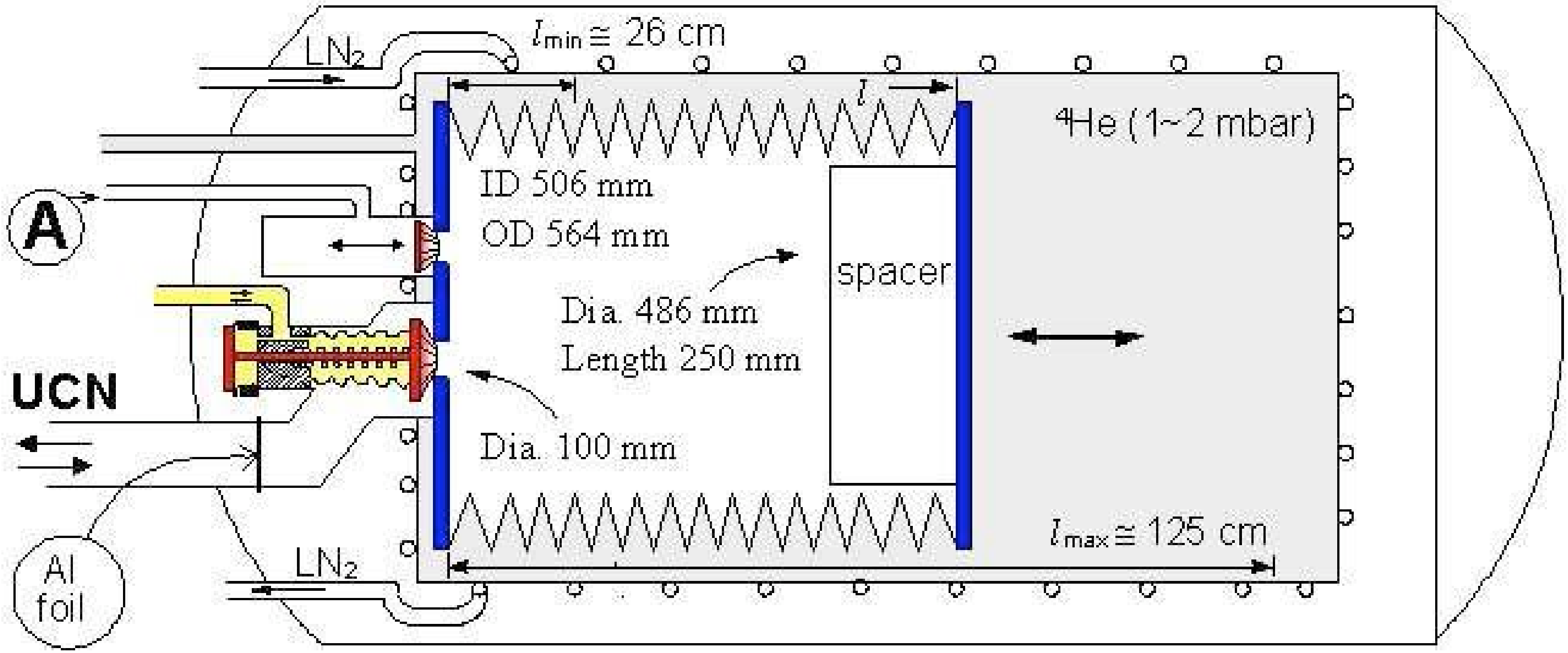


$$\tau_n^{-1} = \frac{N_e/\varepsilon_e}{N_p/\varepsilon_p}\rho_{^3He}\sigma_{^3He}(v_0)v_0$$

goal: 0.1% measurement

H. Shimizu, 7th UCN Workshop (2009)

Accordion Bottle

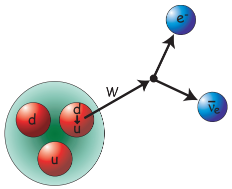


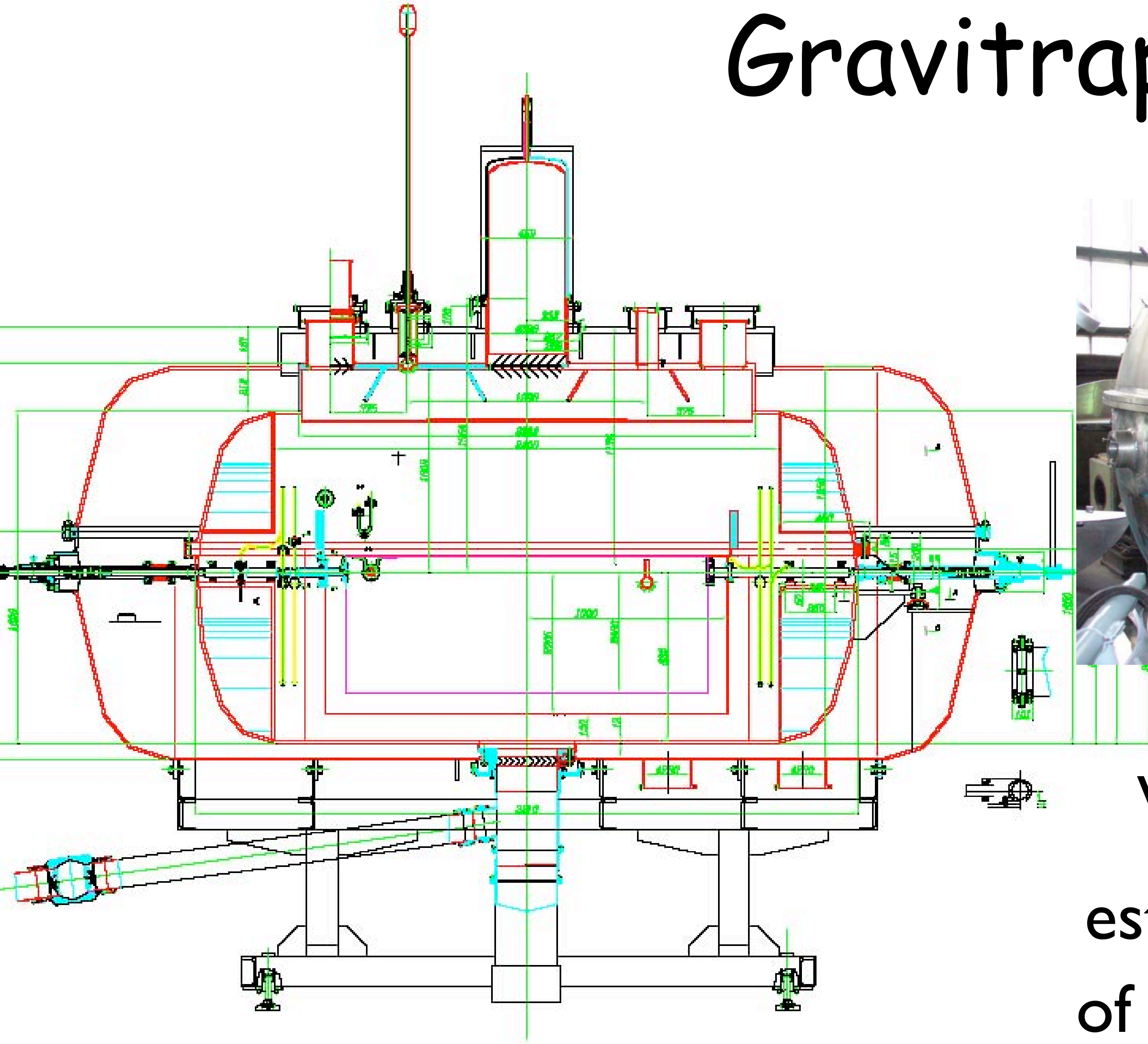
estimated accuracy

of τ_n will be $\pm$ 1 s

Albert Steryl, private communication (2008)

Gravitrap II



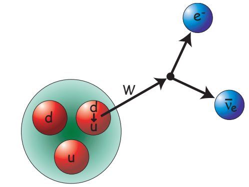


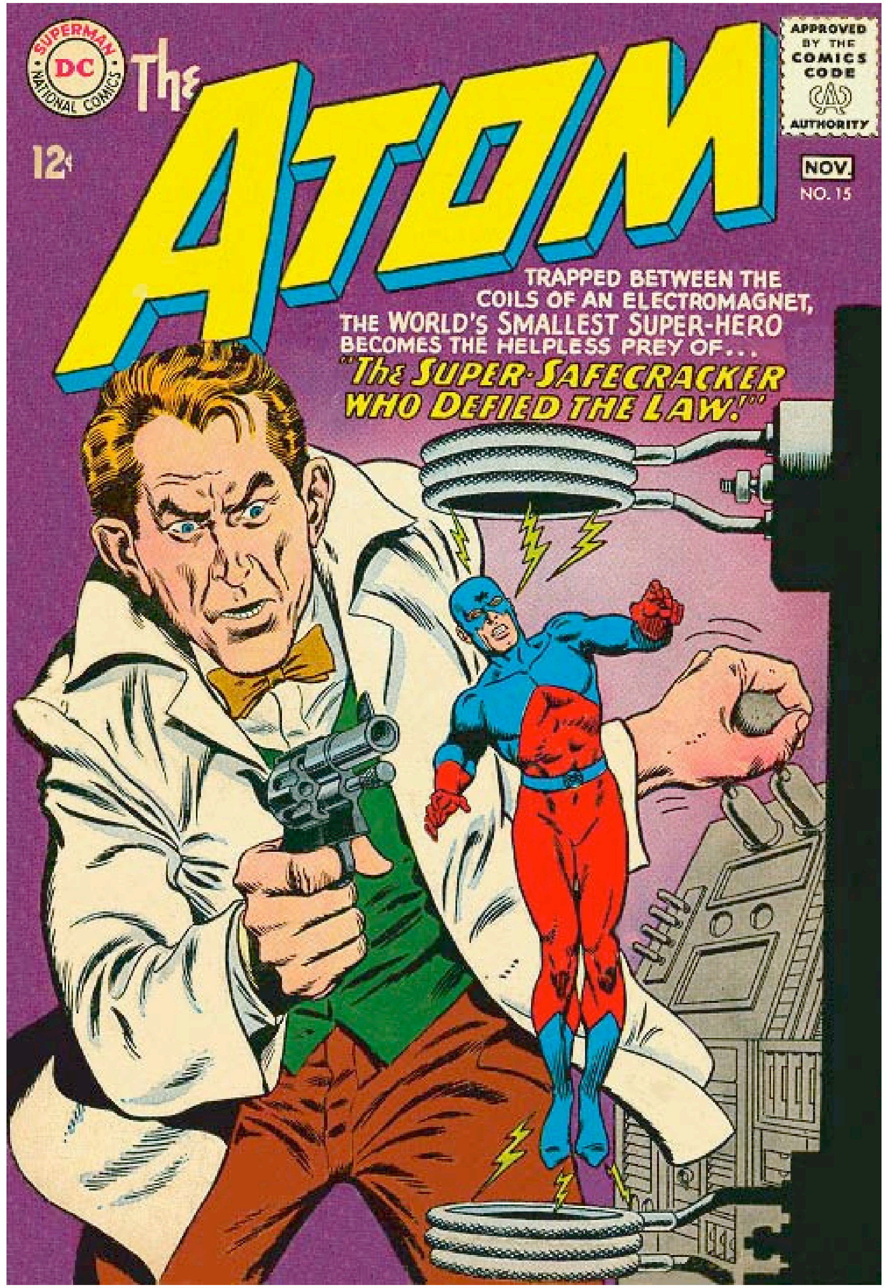
Will run at PF2

estimated accuracy of τ_n will be ± 0.2 s

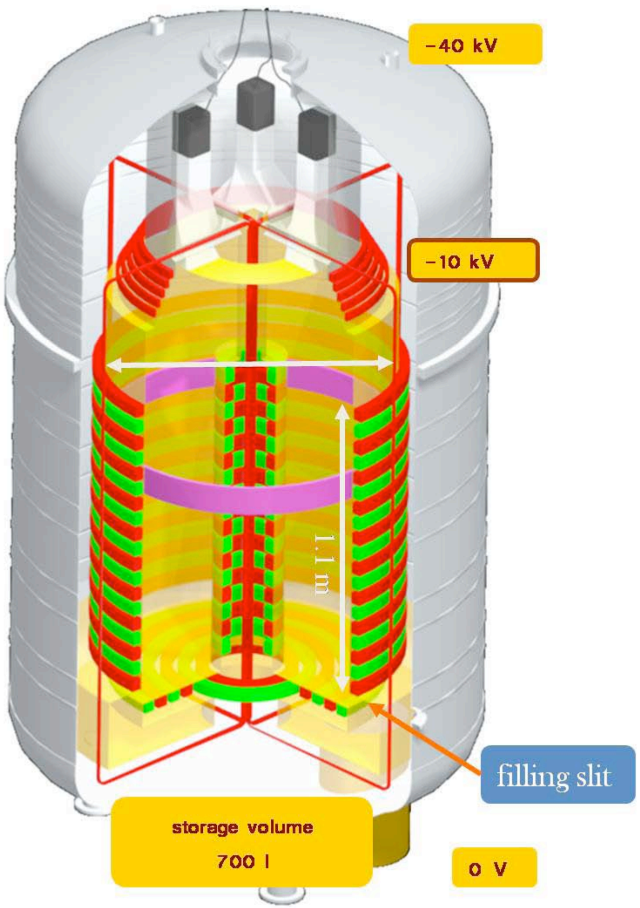
Serebrov, 7th UCN Workshop (2009)

Magnetic Trapping



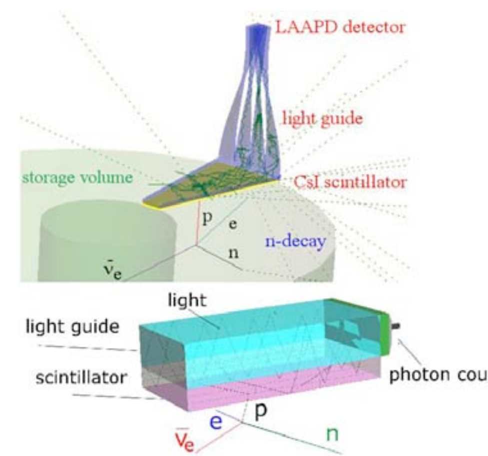


PENeLOPE



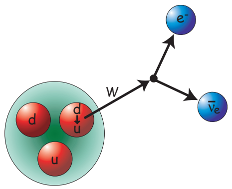
PENeLOPE

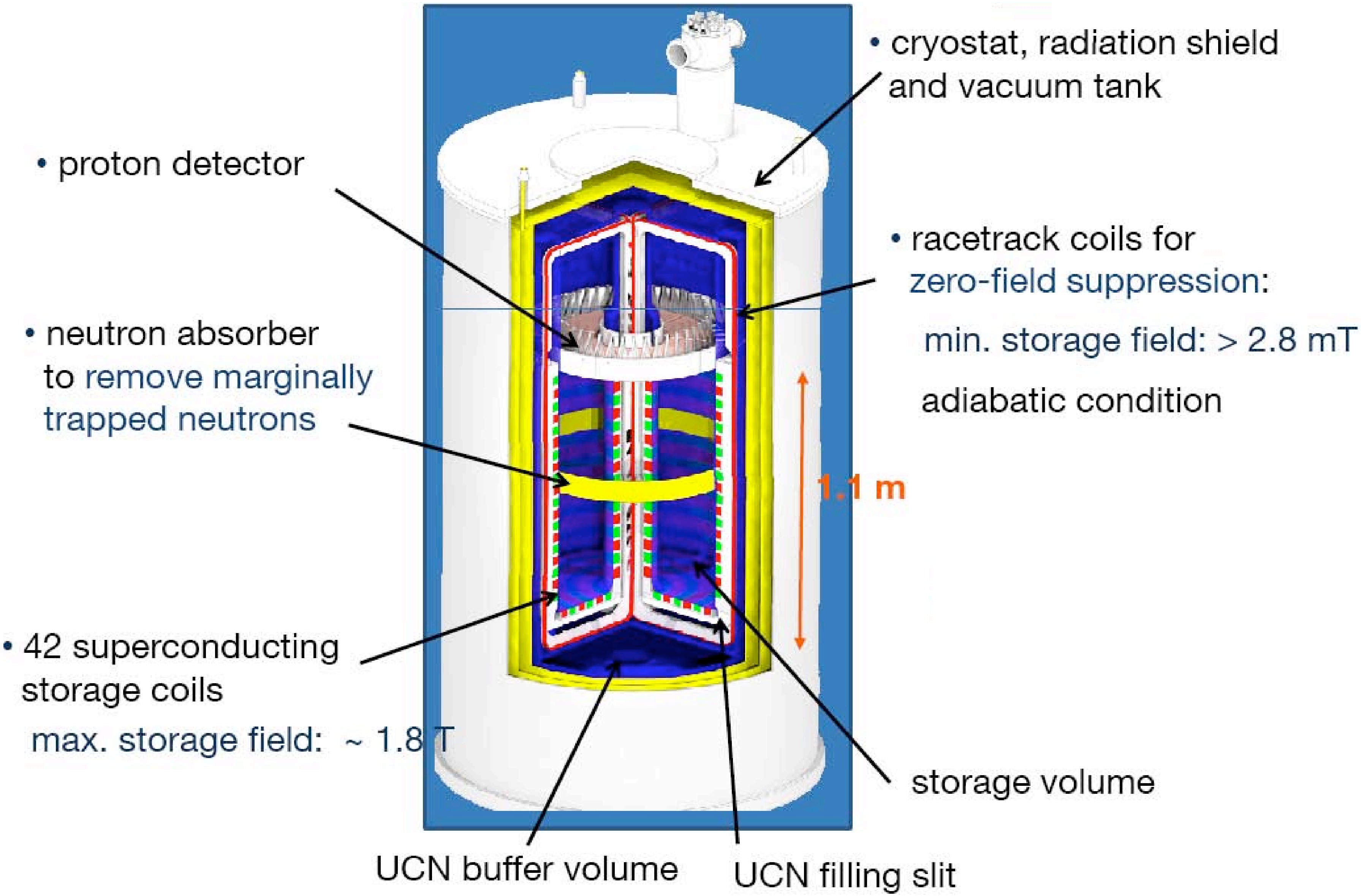
- Superconducting analog to permanent magnet trap (2 T at wall)
- Rings alternate in current sense
- Decay protons guided to scintillator
- Marginally trapped neutrons and Majorana spin-flips are a problem



S. Materne, 7th UCN Workshop (2009)

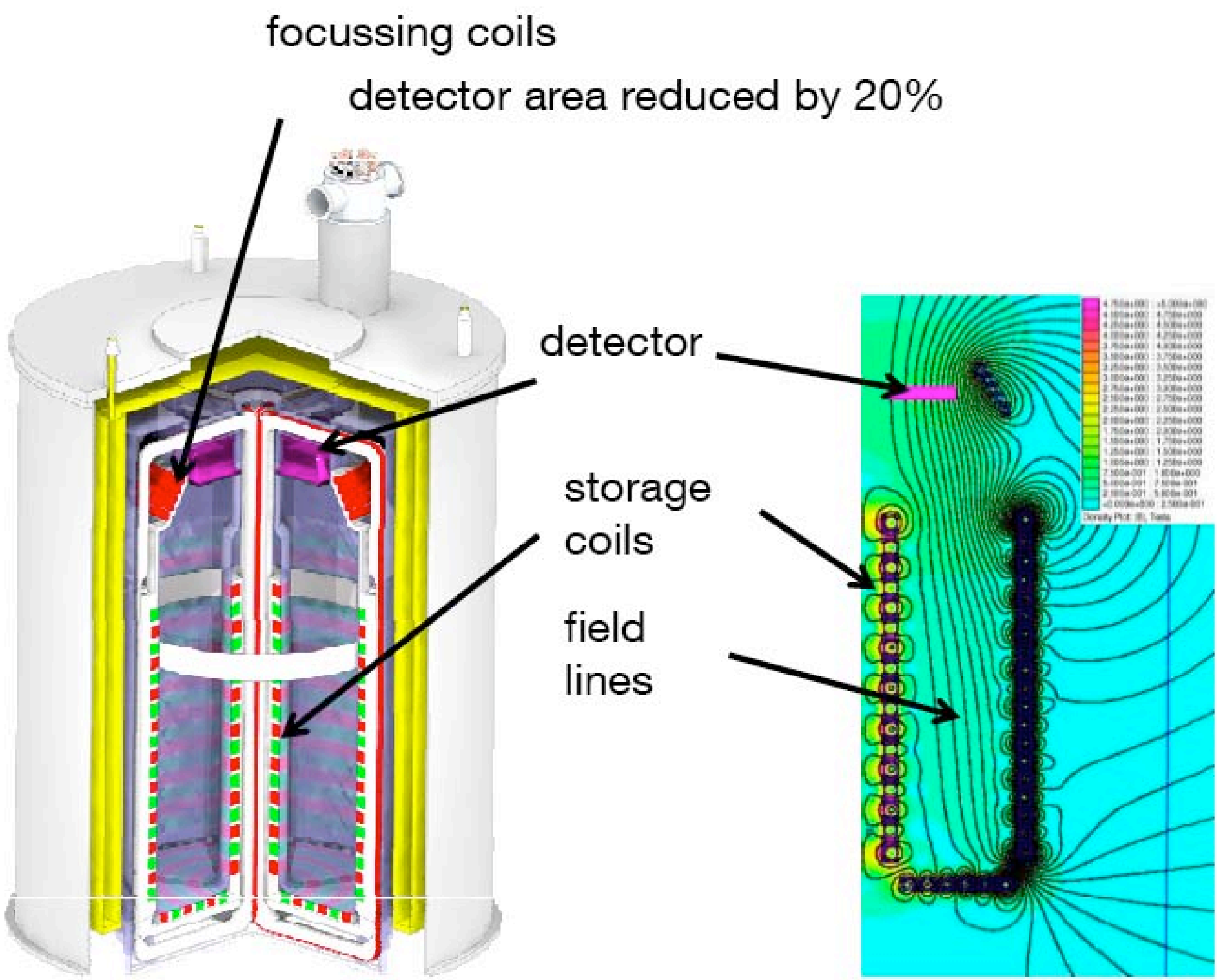
PENeLOPE





S. Materne, 7th UCN Workshop (2009)

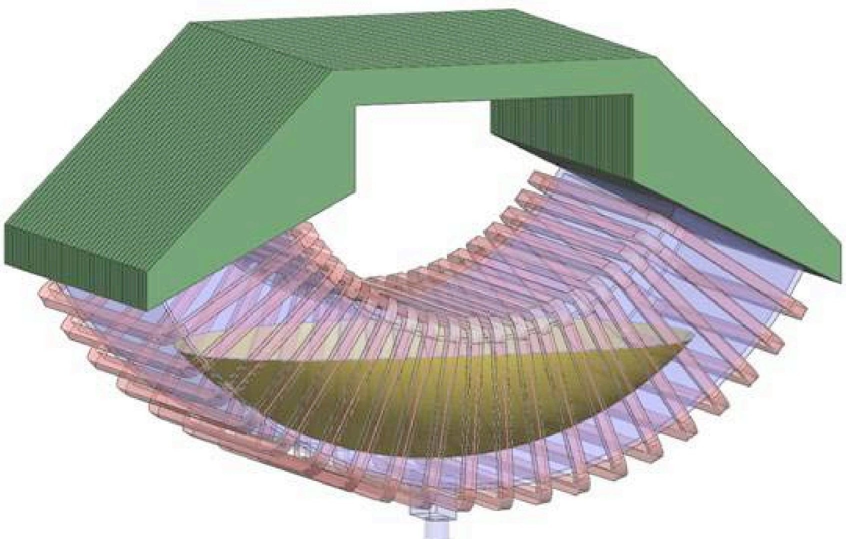
PENeLOPE

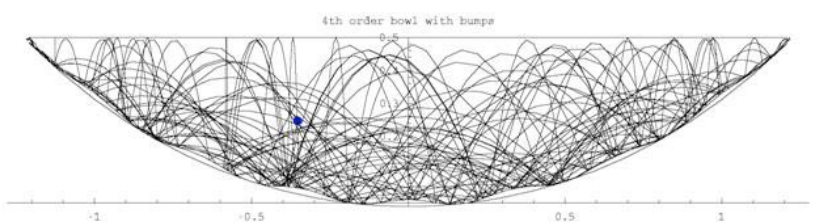


- anticipated statistical precision: ~ 0.1 s

S. Materne, 7th UCN Workshop (2009)

Halback Gravitational



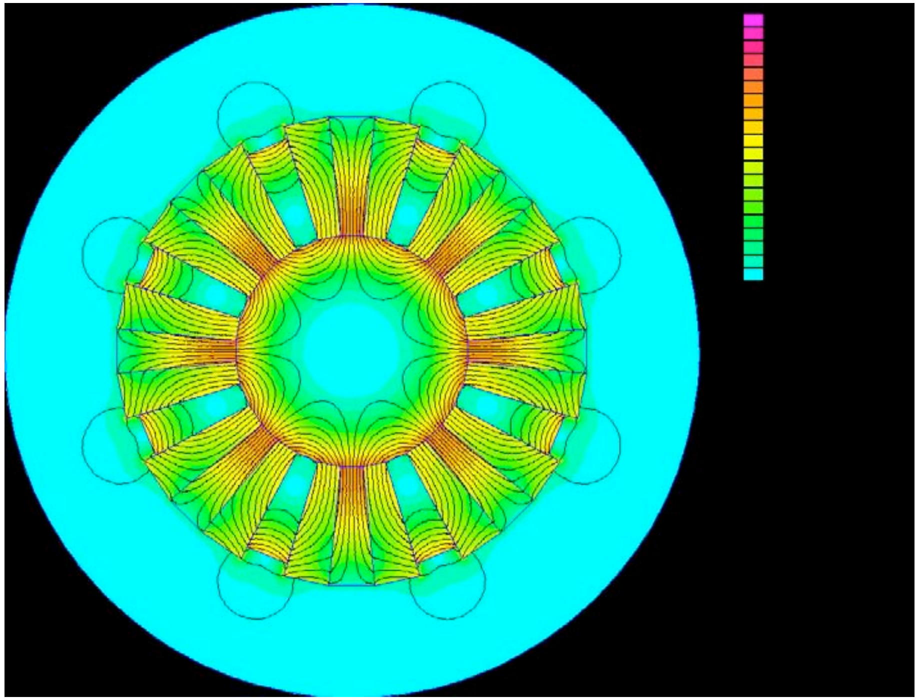


- Shallow Halbach array + gravity for trap, trap door loading
- Guide field for decay betas
- Marginally trapped neutrons experience chaotic orbits and are ejected rapidly
- Goal precision ± 0.1 s
- Presently under construction

P.L Walstron *et al.*, NIMA, 599 (2009) 82

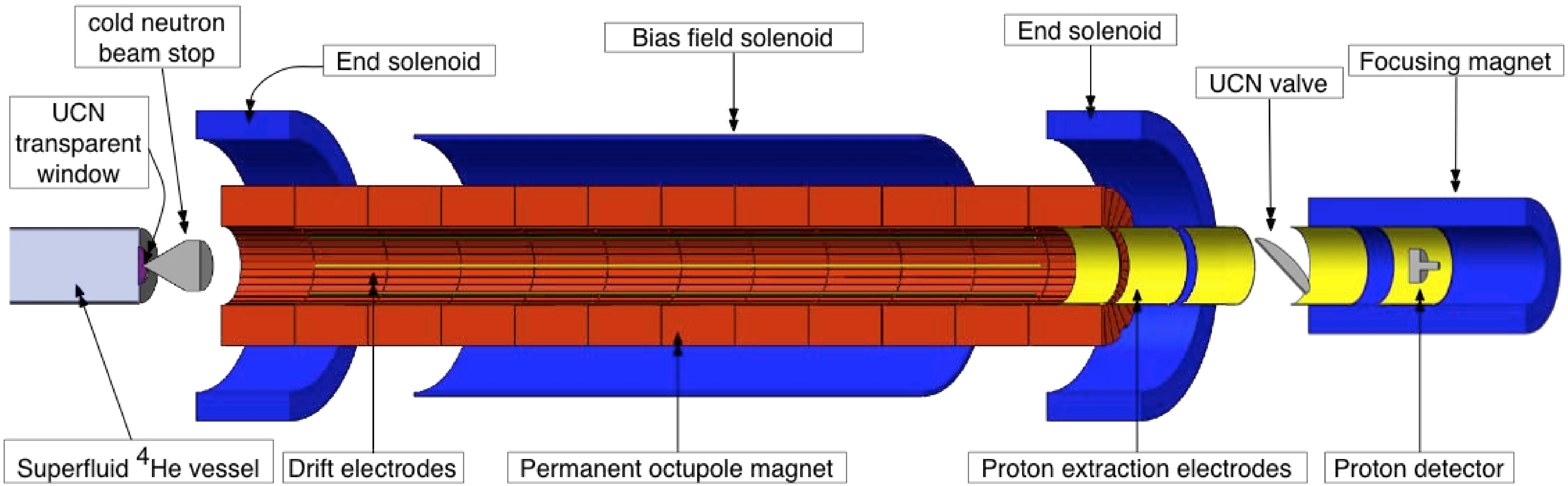
4π Magnetic Confinement

- Halbach Octupole PErmanent (H.O.PE.) magnetic trap
- 1.3 T at surface, 8 l volume

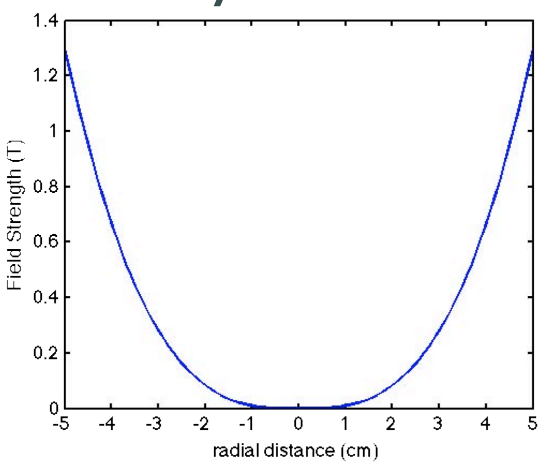


K. Leung, 7th UCN Workshop (2009)

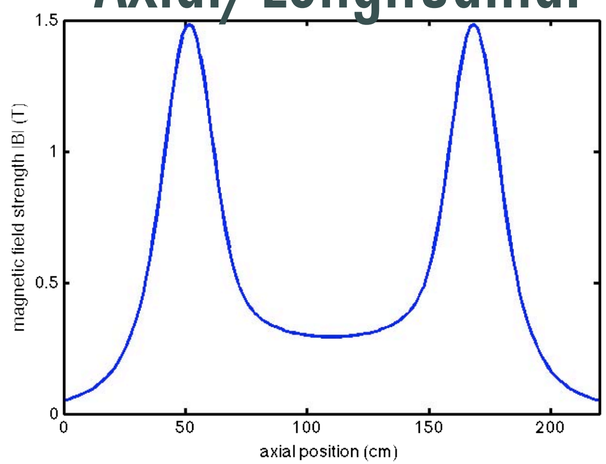
H.O.PE.



Radial/Transverse



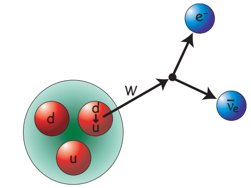
Axial/Longitudinal

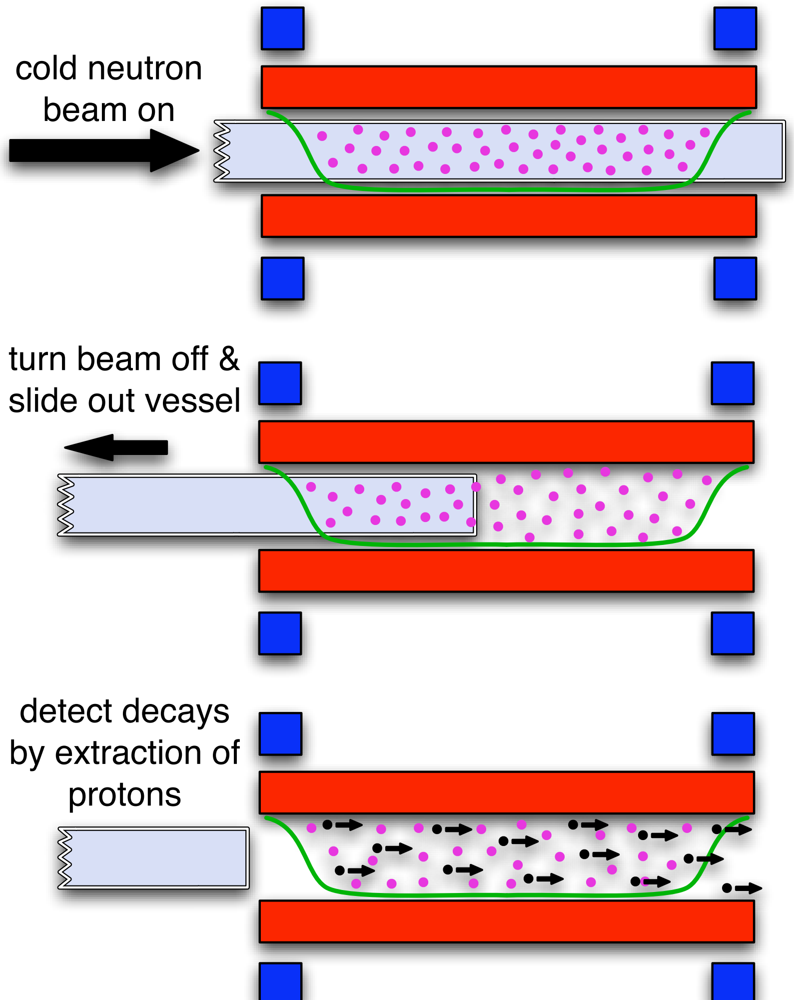


- Permanent octupole magnets
- Superconducting coils
- Proton extraction electrodes

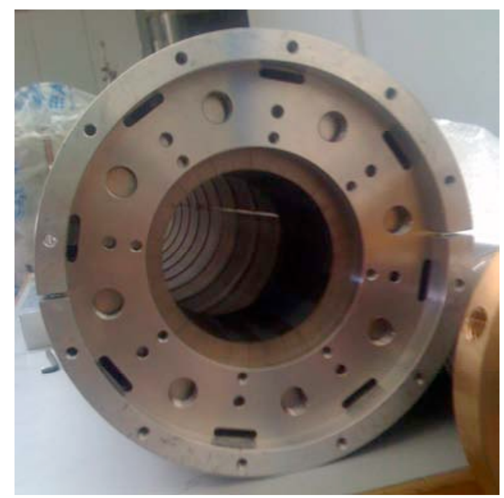
K. Leung, 7th UCN Workshop (2009)

H.O.P.E.



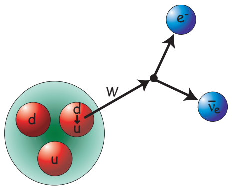


- Initial testing to begin soon, aim to begin measurement in 2010
- anticipated statistical precision: < 0.5 s

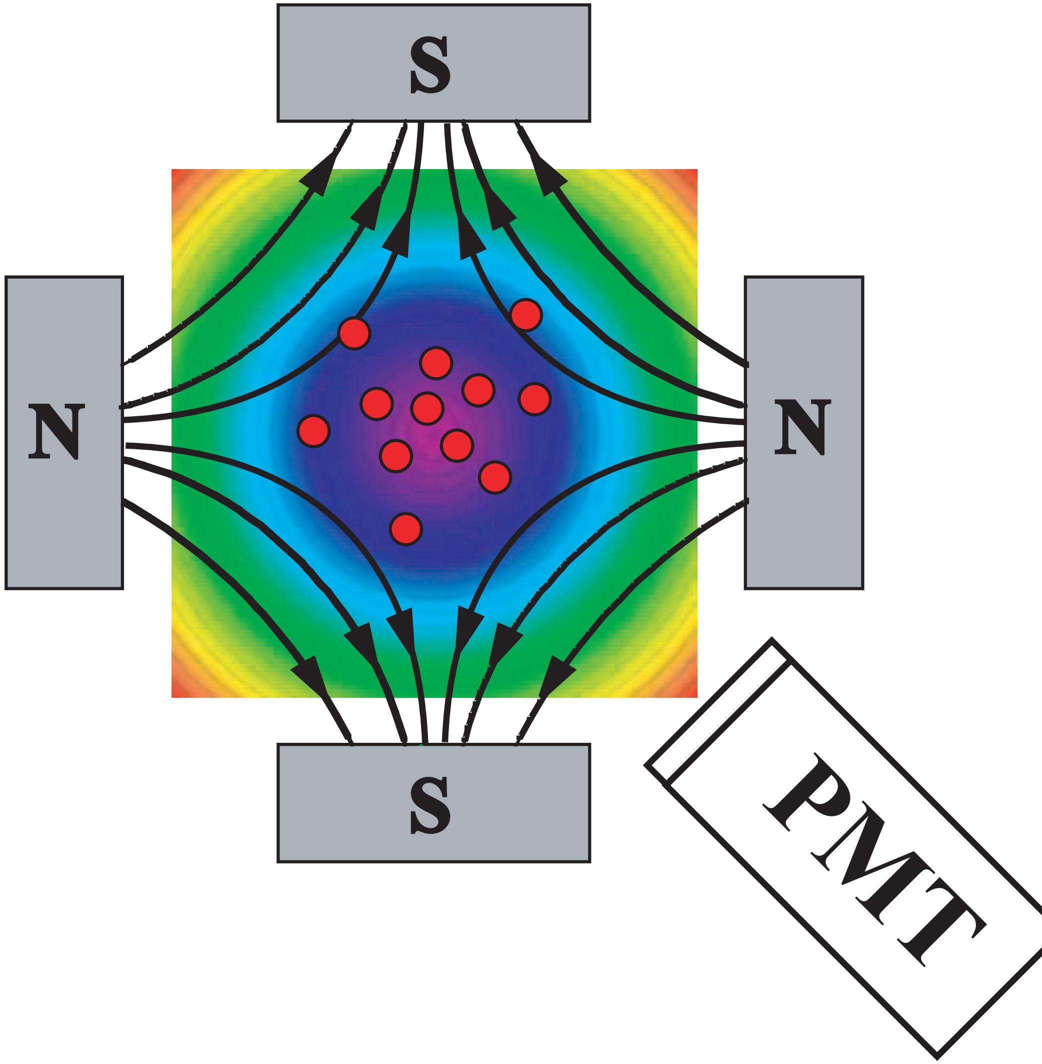


K. Leung, 7th UCN Workshop (2009)

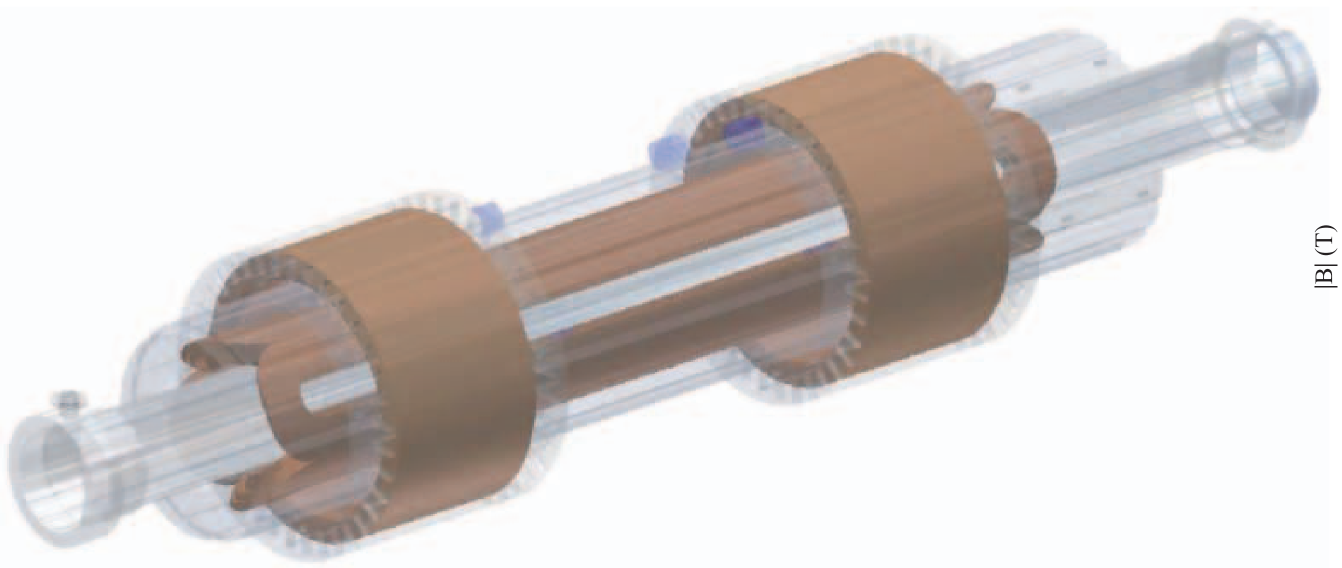
NIST UCN Lifetime

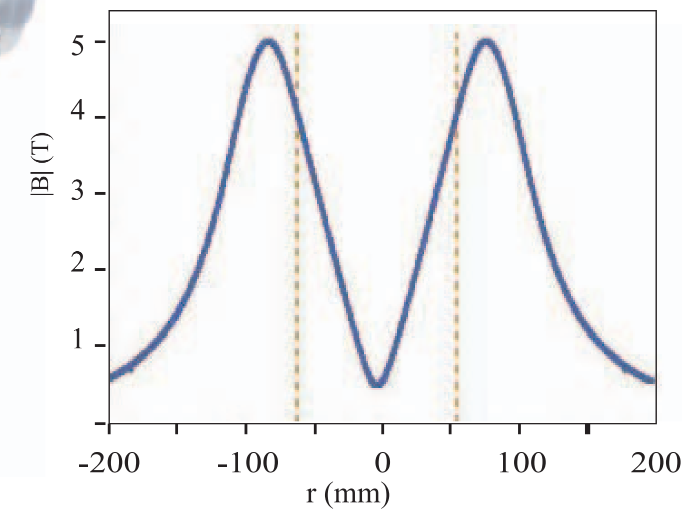


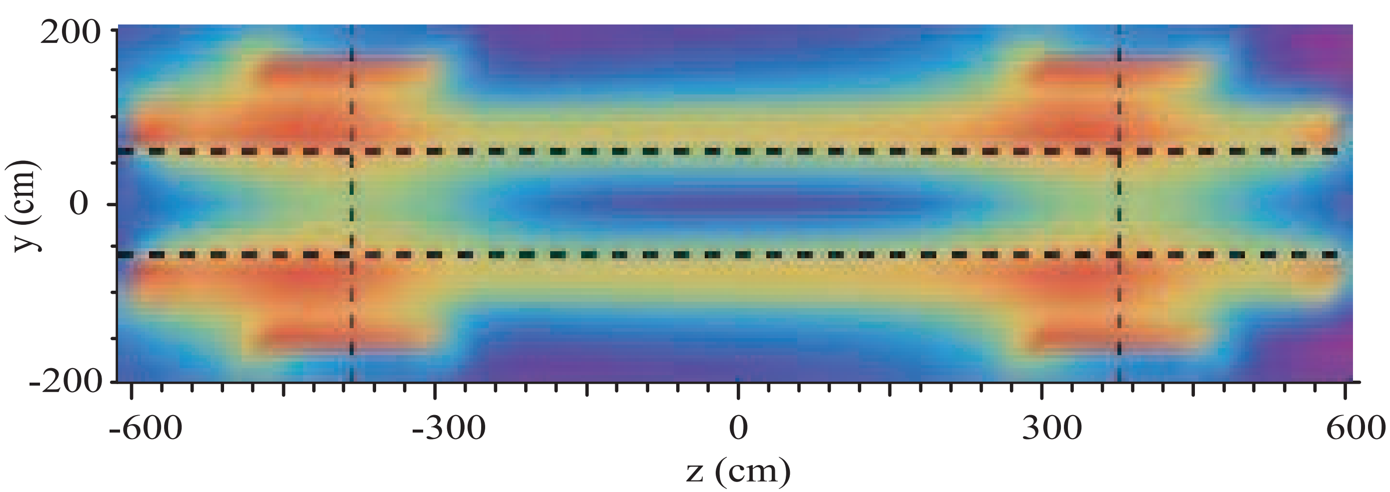
- Produce UCN using the "superthermal" technique
- Confine low field seekers within a magnetic bottle
- Detect each neutron as it decays using scintillation techniques

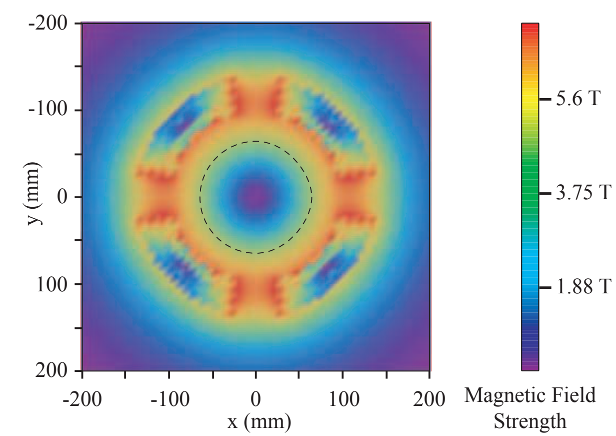


Ioffe-Type Magnetic Trap



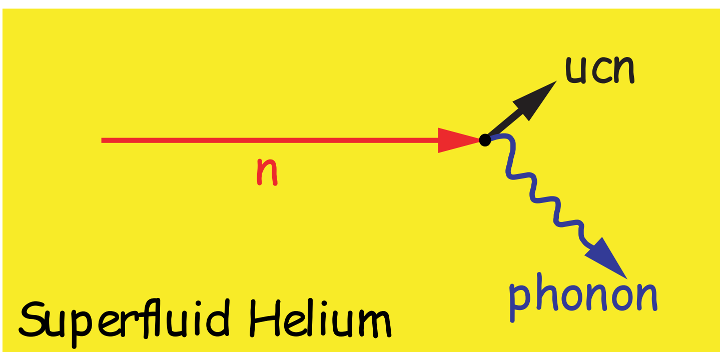




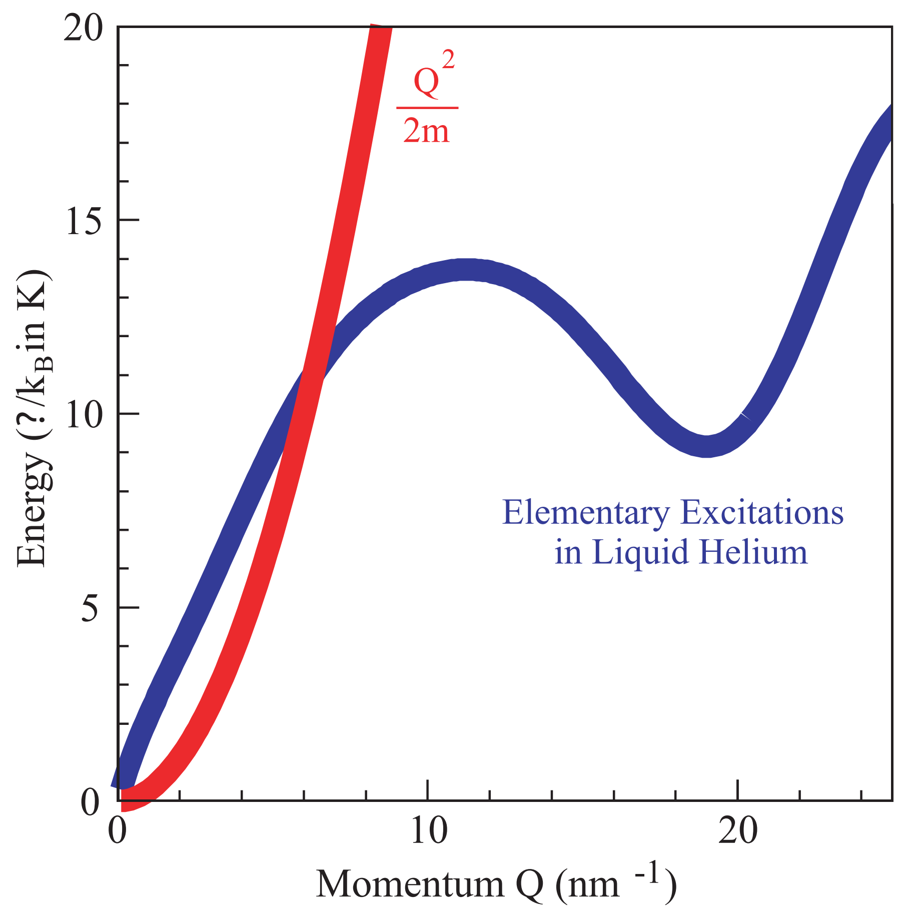


Energy Dissipation: Superthermal Process

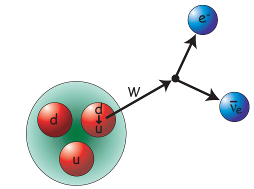
- 0.89 nm (12 K or 0.95 meV) neutrons can scatter in liquid helium to near rest by emission of a single phonon.



- Upscattering (by absorption of a 12 K phonon)
  - ~ Population of 12 K phonons
  - ~ $e^{-12\ K/Tbath}$

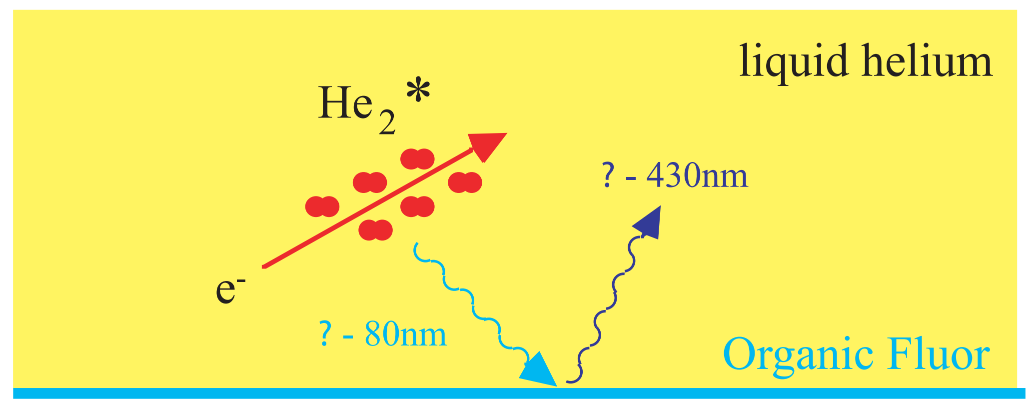


Detection of Decay Events

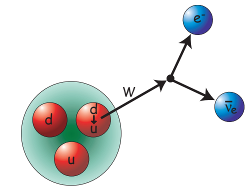


- Recoiling charged particle creates an ionization track in the helium.
- Helium ions form excited He_2^* molecules(ns time scale) in both singlet and triplet states.
- He_2^* singlet molecules decay, producing a large prompt
- (< 20 ns) emission of extreme ultraviolet (EUV) light.
- EUV light (80 nm) converted to blue using the organic fluor (d)TPB (tetraphenyl butadiene).

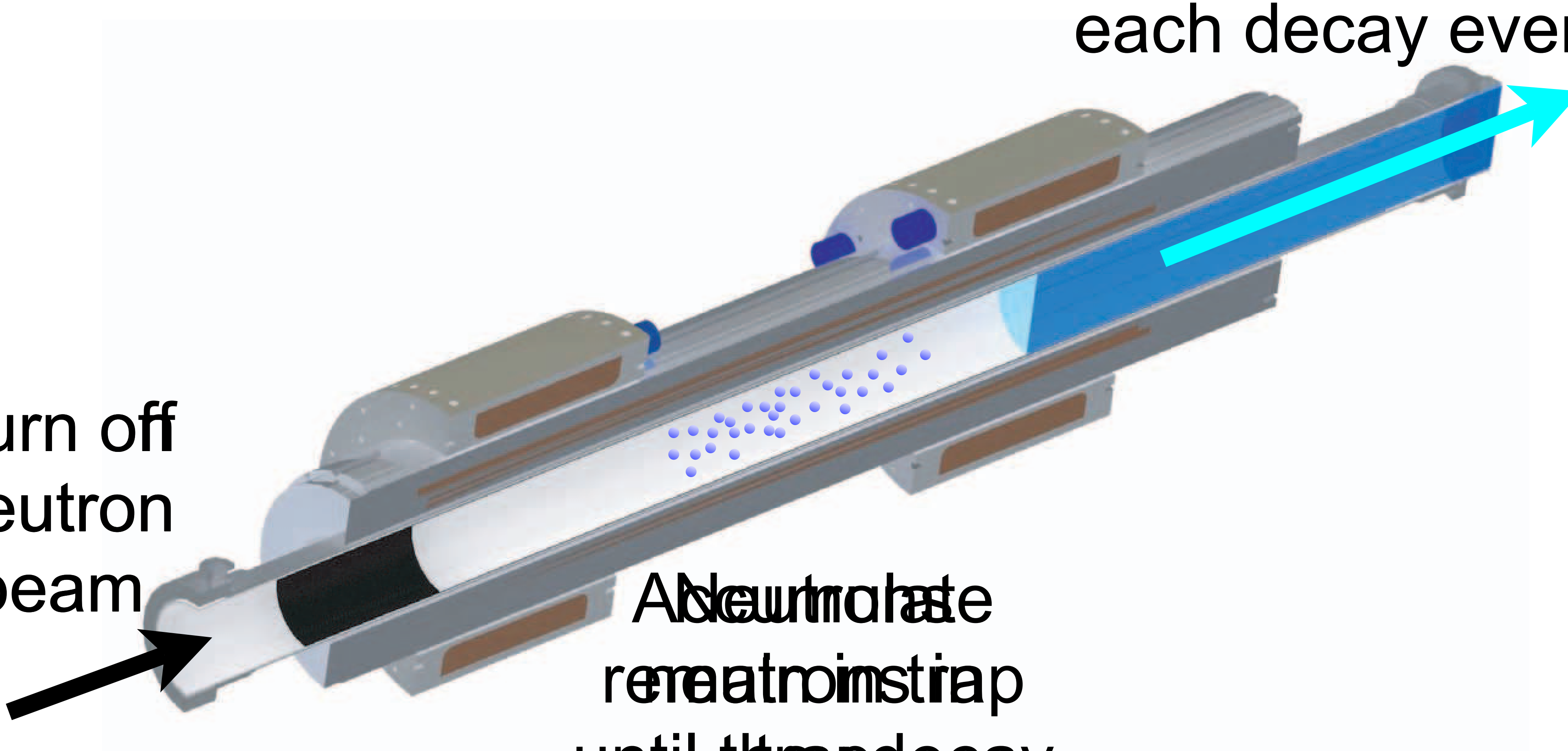
$$n \longrightarrow p^+ + e^- + \bar{\nu}_e + 782 \text{ keV}$$



Experimental Method



Detect pulse of light from each decay event

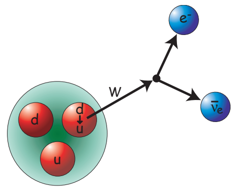


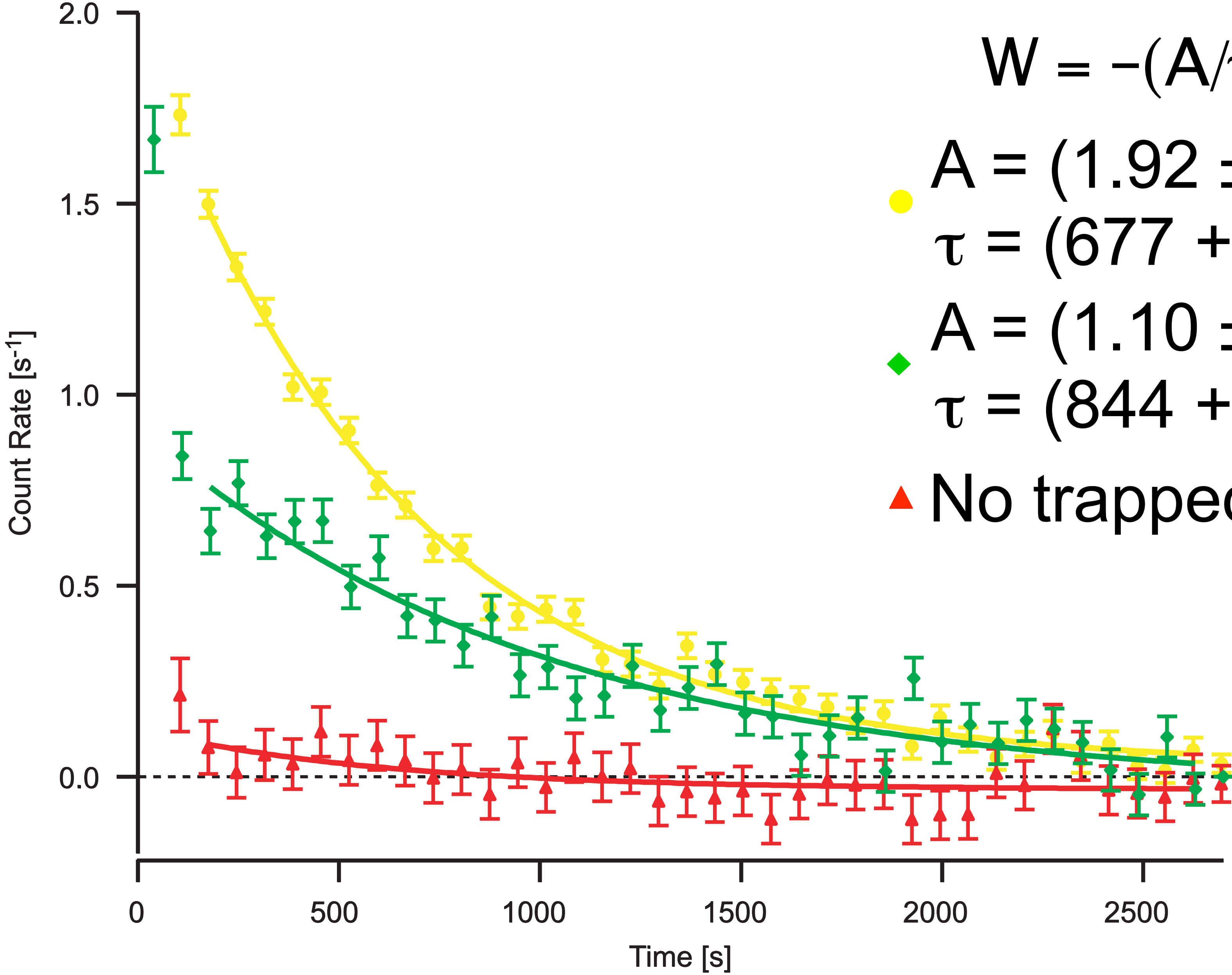
Turn off neutron beam

Neutrons remain in trap until they decay

Accumulate neutrons in trap

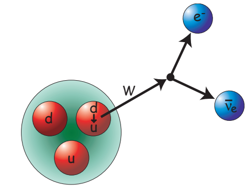
Proof-of-principle Data



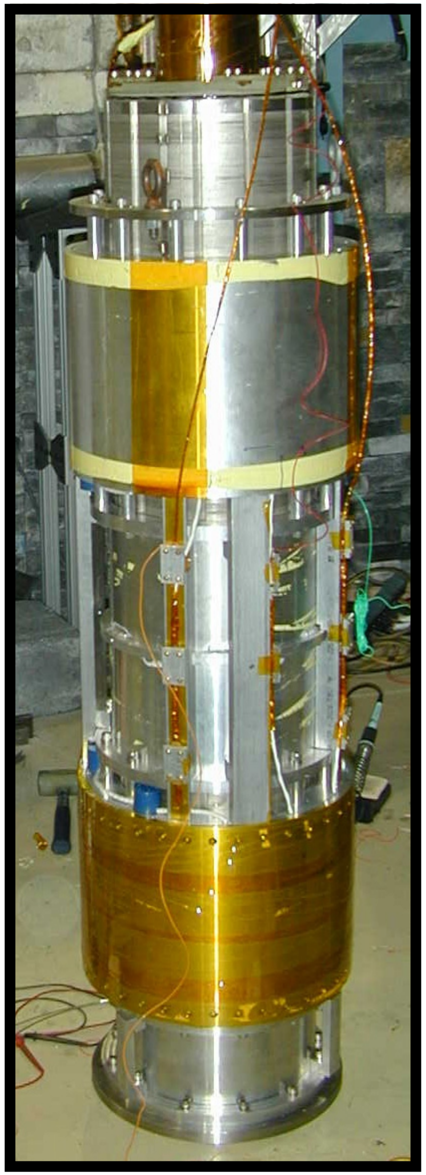


$$W = -(A/\tau)\, e^{-t/\tau}$$

- (yellow circles) $A = (1.92 \pm 0.03)\ s^{-1}$, $\tau = (677\ {+13}/{-12})\ s$
- (green diamonds) $A = (1.10 \pm 0.06)\ s^{-1}$, $\tau = (844\ {+53}/{-47})\ s$
- (red triangles) No trapped neutrons

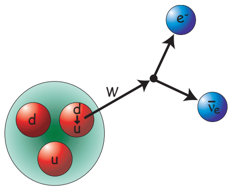


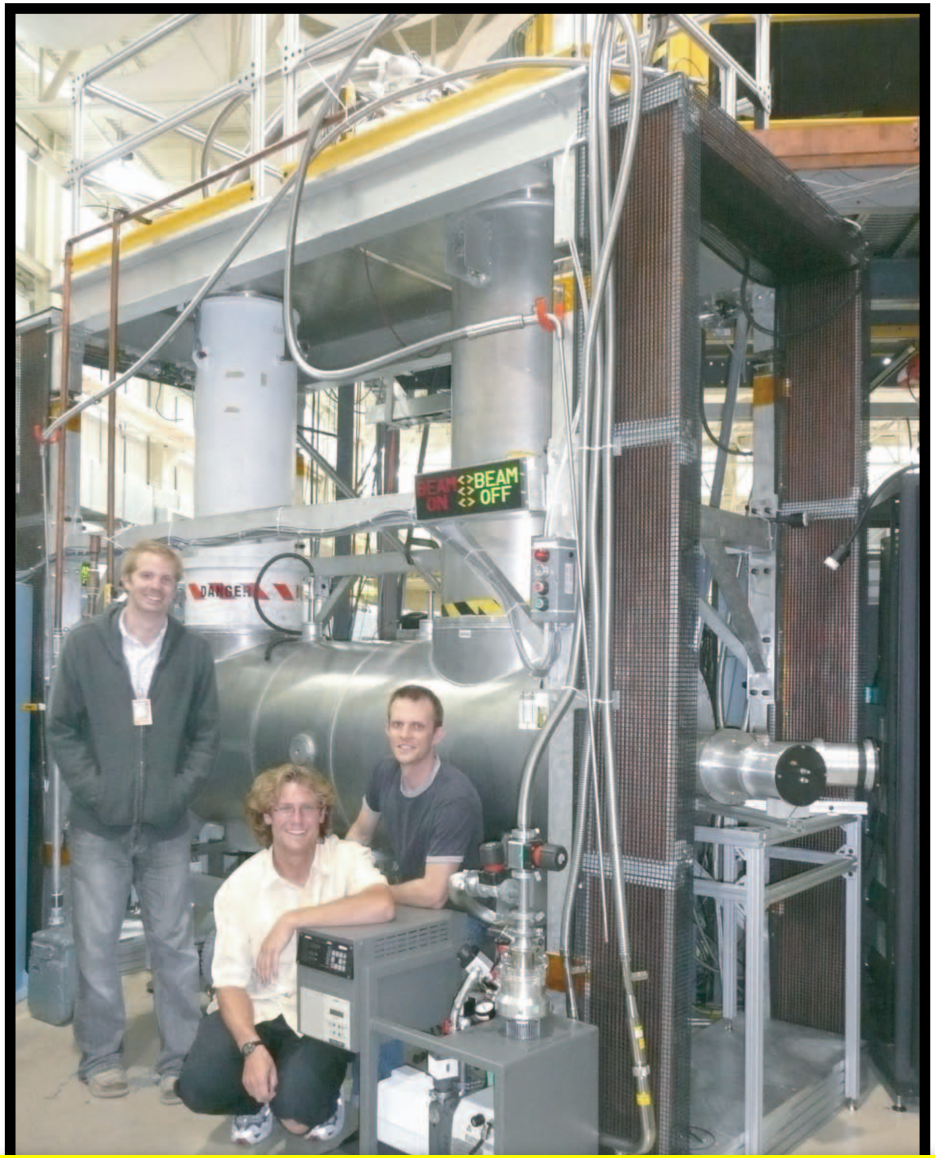
New High-Current Trap



- Quadrupole on loan from the KEK institute, solenoids wound in-house
- Conservative approach:
  - design 30% under load line
- Tested to yield a trap depth and size of:
  - B ≥ 3.0 T, design 3.1 T
  - ø ≥ 11 cm, l ≥ 42 cm
- x20 more trapped neutrons

NIST UCN Summary

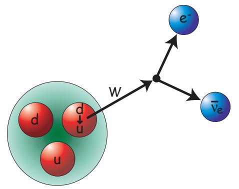




New Dewar on Beamline at NIST

- Apparatus presently ready to take data
- Expect a ± 2 s measurement in ~2yr perios
- < ± 0.5 s measurement possible at upgraded NIST cold source or at the SNS

Summary



- Neutron lifetime is still an important parameter for understanding both the weak interaction and the light element production in BBN
- Experiments are very difficult
- Significant discrepancies in current measurements
- Many experiments are current either in progress or in the planning stages