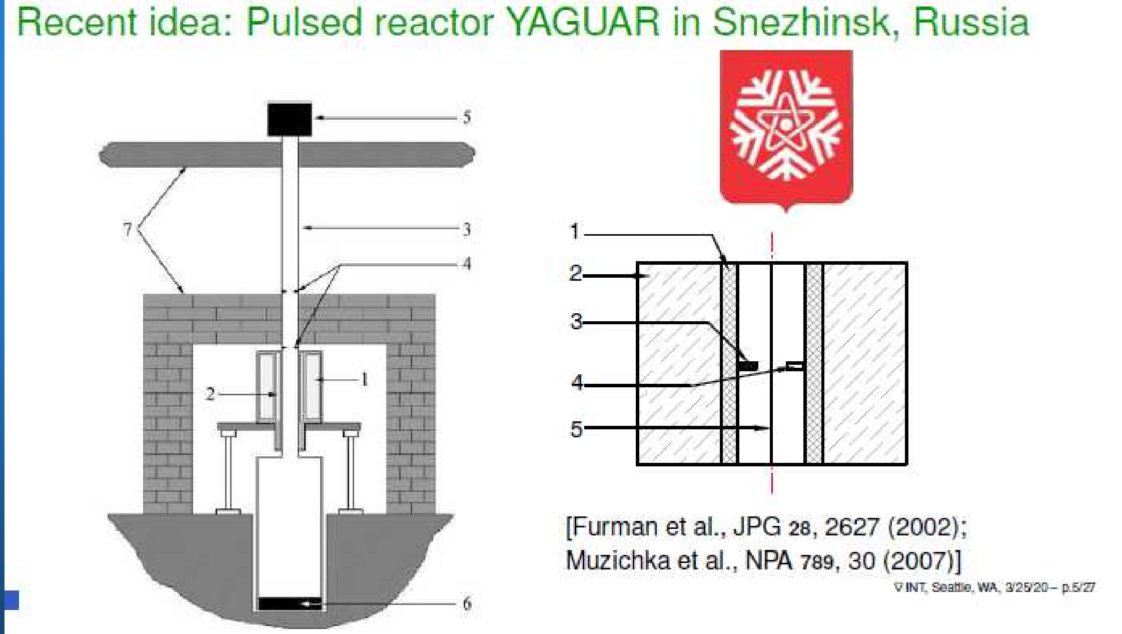
Properties of the Neutron

- Properties
  - Neutron in strong interactions
  - Electromagnetic interactions
  - Weak interaction
  - Neutron and Gravity
  - Other forces

Neutron in strong interaction

- Neutron-neutron scattering length

$$a_{nn}^{\mathrm{str}} = -18.9 \pm 0.4 \text{ fm}, \; a_{pp}^{\mathrm{str}} = -17.3 \pm 0.4 \text{ fm}$$



Recent idea: Pulsed reactor YAGUAR in Snezhinsk, Russia

[Furman et al., JPG 28, 2627 (2002);
Muzichka et al., NPA 789, 30 (2007)]

∇INT, Seattle, WA, 3/25/20 – p.5/27

- Neutron-nucleus interactions

Electromagnetic interaction (I)

- Neutral particle

PDG value −0.2±0.8 (10^{-21} e)

- Radius of the neutron (measurement of the EM FF)

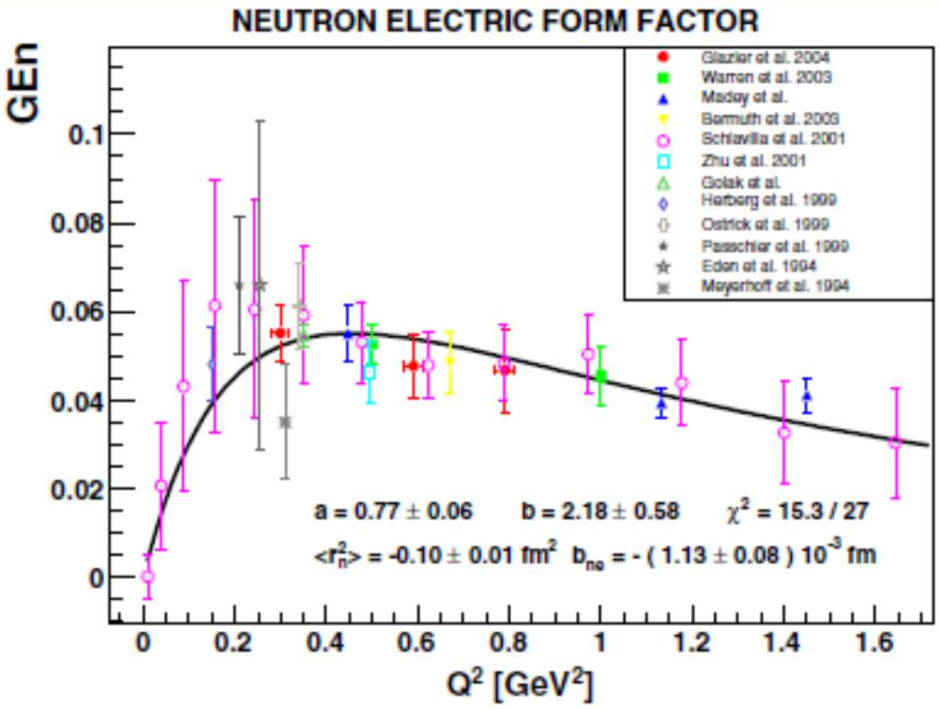


FIG. 4 (color online). The neutron form factor $G_E(\mathbf{q}^2)$ as a function of the momentum transferred $\mathbf{q}^2$. The experimental data are taken from [29]; the solid curve is a two parameter fit using formula (19).

Electromagnetic interaction (II)

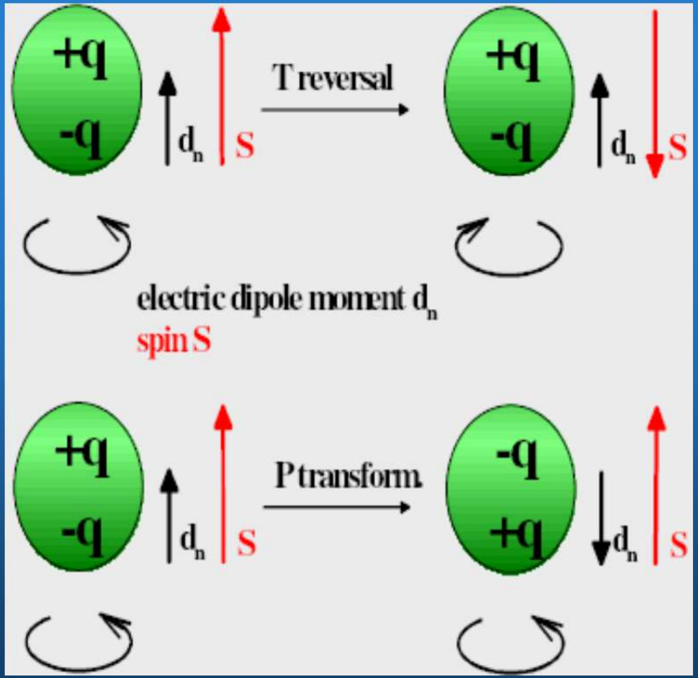
- Magnetic moment

PDG value $-1.91304272 \pm 0.00000045$ in nm

- Electric dipole moment (EDM)
- …

Neutron Electric Dipole Moment (nEDM) – search for CP violation

$$\overrightarrow{d_n} = e \cdot \vec{r} = d_n \hat{\vec{s}}$$



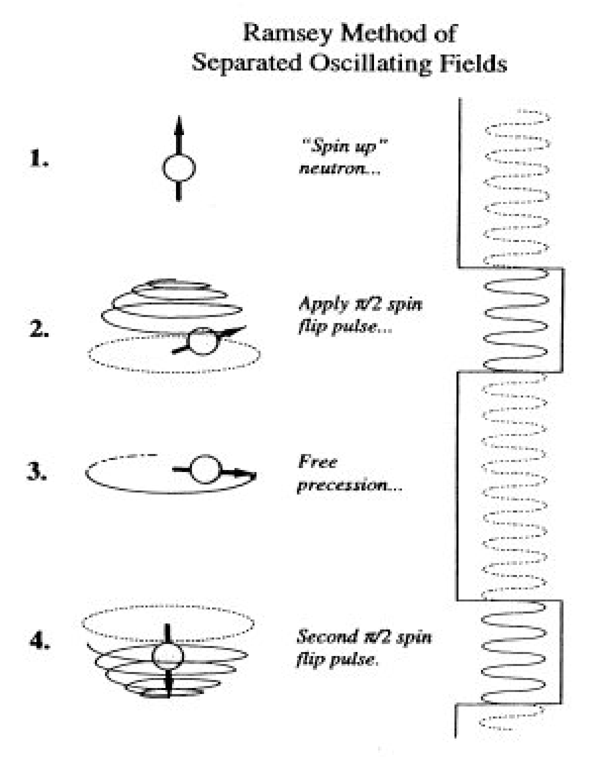
CP violation was observed only in the systems of neutral kaons and B mesons

Existence of the nEDM ≠ 0 means

violation of **P and of T**

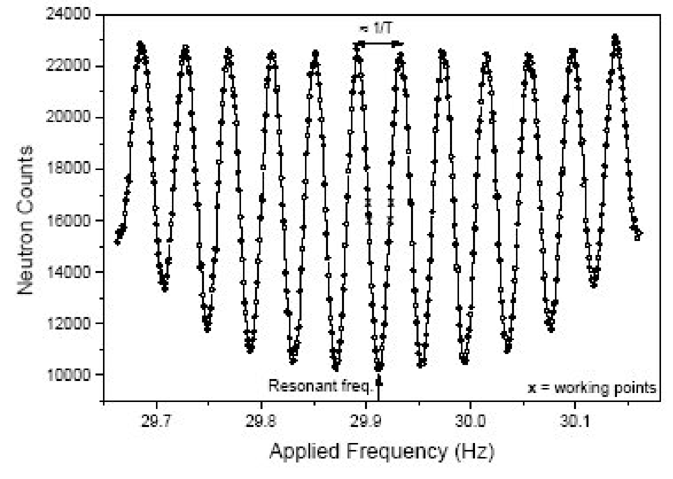
CPT Theorem → **CP** violation

Ramsey’s Method

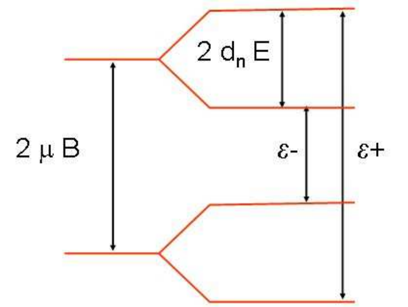


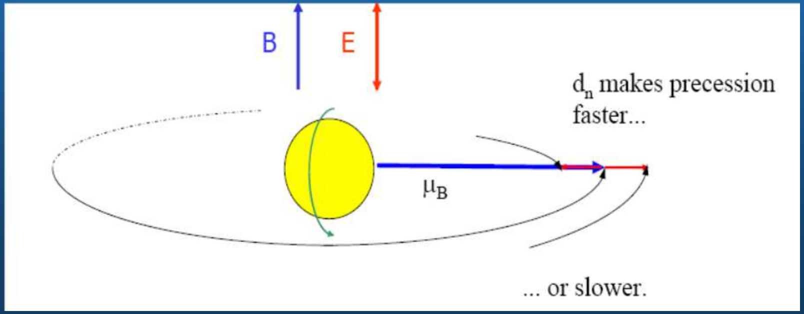
T

N ↑



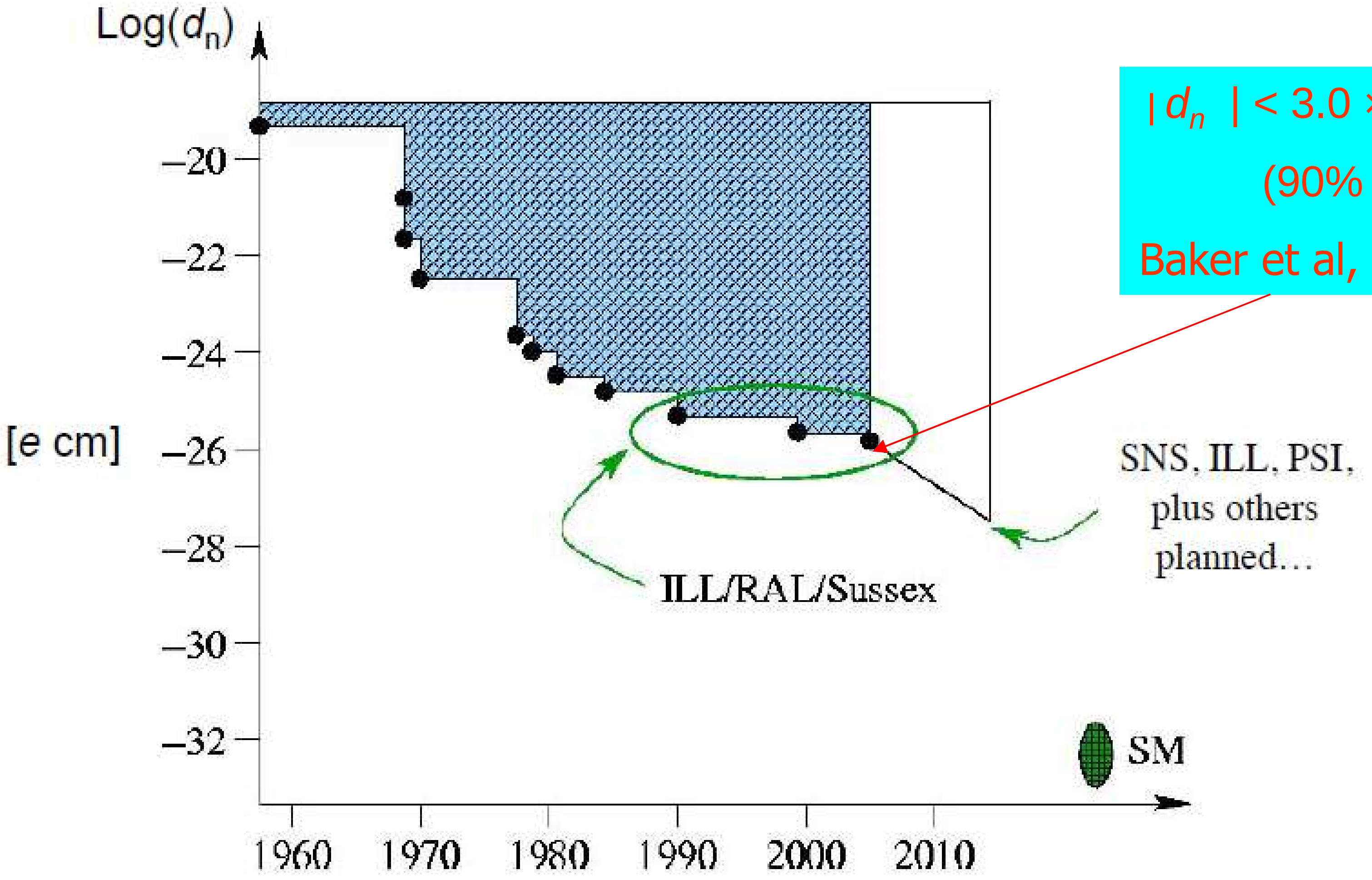
$$H = -2(\mu_n \vec{I}.\vec{B} + d_n \vec{I}.\vec{E})$$





$$\Delta\nu = 4 d_n E / h$$

Progress in the neutron EDM bound



$|d_n| < 3.0 \times 10^{-26}$ ecm

(90% C.L.)

Baker et al, PRL (2006)

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

Weak interaction

- Neutron lifetime
- Asymmetry coefficients in neutron decay

$$dW(\sigma, \mathbf{p}_e, \mathbf{p}_{\bar\nu}) \propto F(E_e) d\Omega_e d\Omega_{\bar\nu} \{1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_{\bar\nu}}{E_e E_{\bar\nu}} + \frac{b m_e}{E_e} +$$

$$+ \langle \sigma_n \rangle (A \frac{\mathbf{p}_e}{E_e} + B \frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + D \frac{\mathbf{p}_e \times \mathbf{p}_{\bar\nu}}{E_e E_{\bar\nu}} + R \frac{\sigma_e \times \mathbf{p}_e}{E_e} + \ldots)\}$$

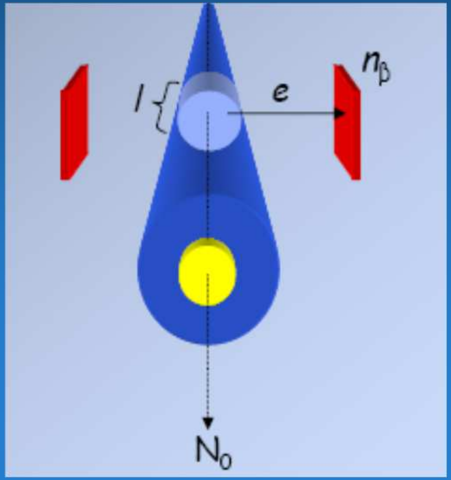
$$\lambda = G_A / G_V$$

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2}, \quad A = -2\frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}, \quad B = 2\frac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2}$$

In flight experiment (CN) :

- To measure the neutron beam radioactivity:

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

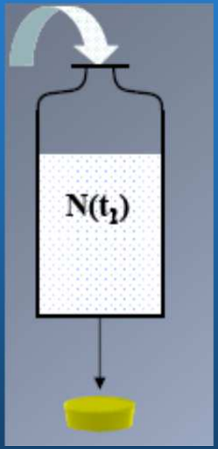


- Two measurements of absolute values

Storage experiment (UCN) :

- To measure directly the decreasing of number of stored neutron s

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



- Two relative measurements, but: $\tau_m^{-1} = \tau_n^{-1} + \tau_{loss}^{-1}$

Neutron lifetime

- Standard Model

$$\left|V_{ud}\right|^2 = \frac{(4908 \pm 4)s}{\tau(1+3\lambda^2)} \qquad \lambda = \frac{g_A}{g_V}$$

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

- Astrophysics
  - Solar cycle
  - neutron stars formation
  - Big Bang nucleosynthesis
  - …

« Typical » experiment with UCN (MamBo I)

Idea :

- Storage volume (V) and its surface (S) are variables
- To measure the storage time as a function of the ration V/S
- Extrapolate to infinite volume

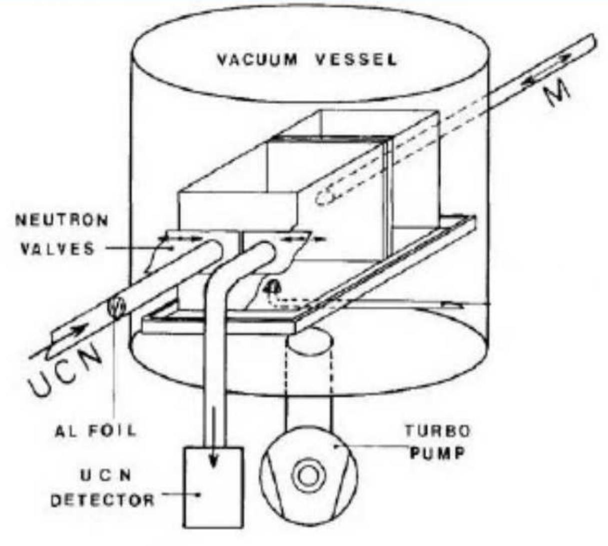


FIG. 1. Sketch of the apparatus.

$$\tau_\beta = (887.6 \pm 3)\,\text{s}$$

Neutron Lifetime Measured with Stored Ultracold Neutrons
W. Mampe et al, Phys. Rev. Letters **63** (1989) 6

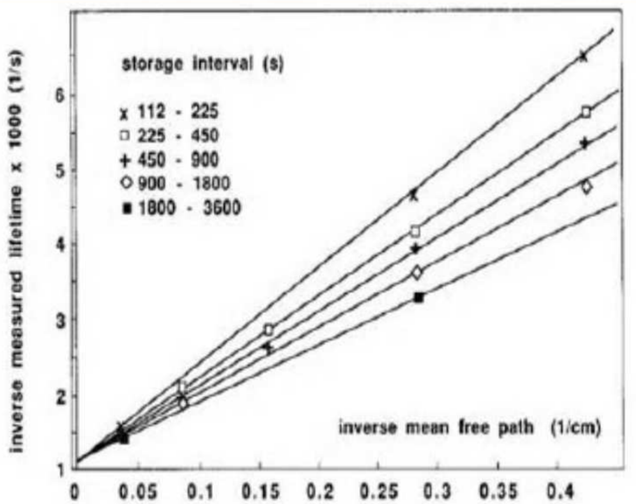
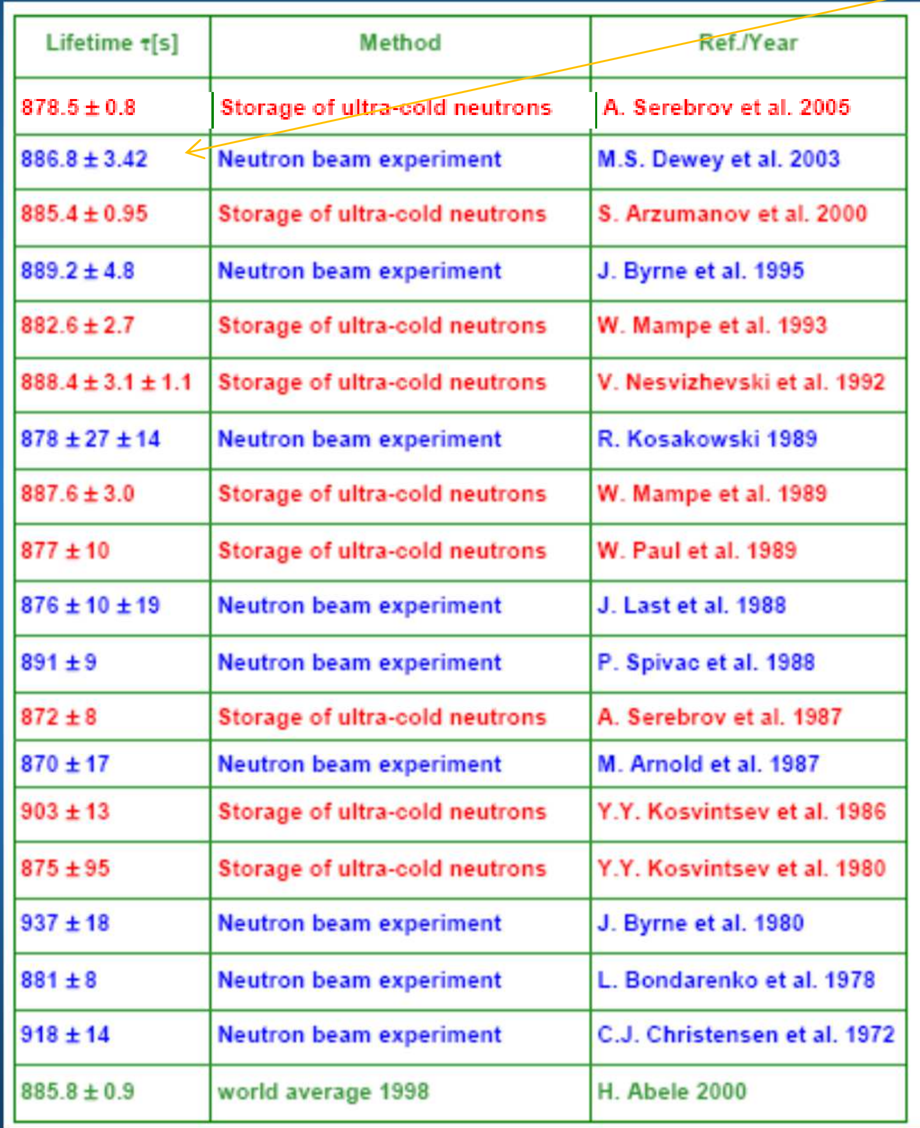


FIG. 2. Measured inverse bottle lifetimes as a function of the bottle inverse mean free path and for different storage intervals, from a 10-d run. The error bars are smaller than the data points.

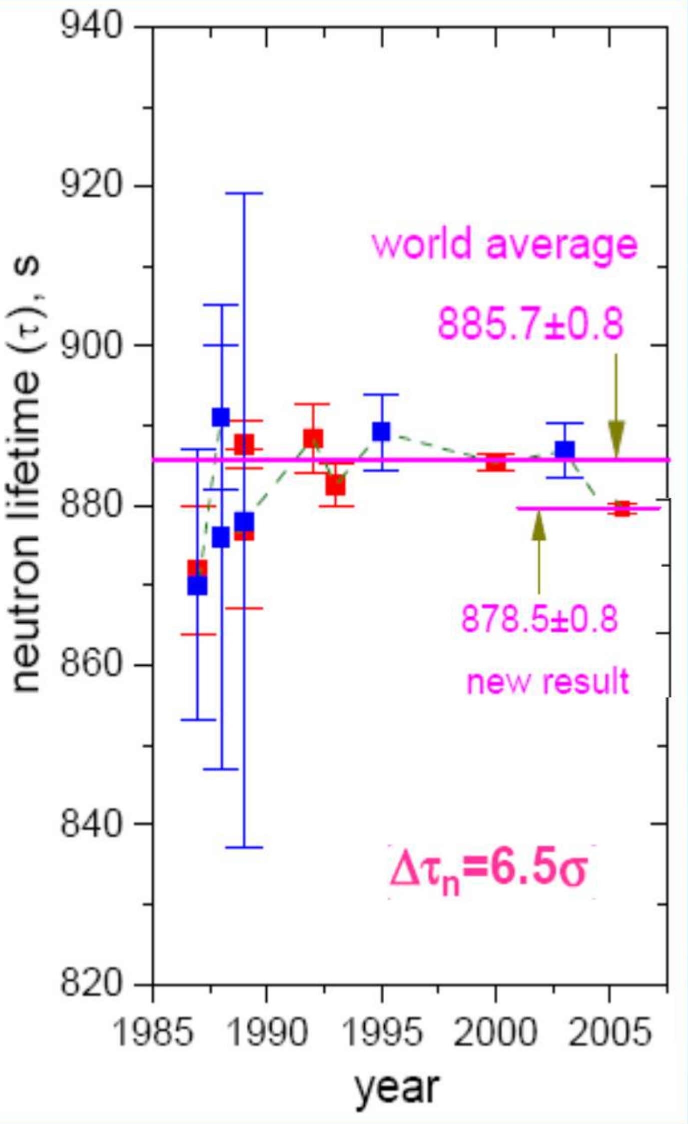
$$\tau_n = (887.7 \pm 1.2\,[\mathrm{stat}] \pm 1.9\,[\mathrm{syst}])\ \mathrm{s.}$$

PRL (2013)

Neutron lifetime

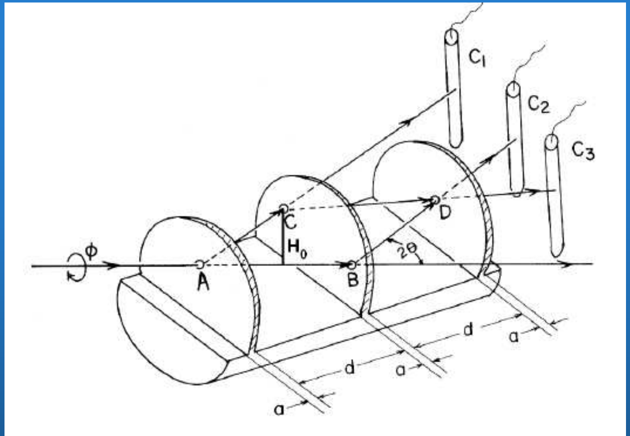


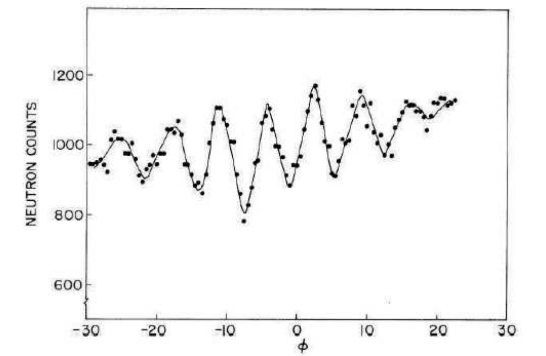
Lifetime τ[s]	Method	Ref./Year
878.5 ± 0.8	Storage of ultra-cold neutrons	A. Serebrov et al. 2005
886.8 ± 3.42	Neutron beam experiment	M.S. Dewey et al. 2003
885.4 ± 0.95	Storage of ultra-cold neutrons	S. Arzumanov et al. 2000
889.2 ± 4.8	Neutron beam experiment	J. Byrne et al. 1995
882.6 ± 2.7	Storage of ultra-cold neutrons	W. Mampe et al. 1993
888.4 ± 3.1 ± 1.1	Storage of ultra-cold neutrons	V. Nesvizhevski et al. 1992
878 ± 27 ± 14	Neutron beam experiment	R. Kosakowski 1989
887.6 ± 3.0	Storage of ultra-cold neutrons	W. Mampe et al. 1989
877 ± 10	Storage of ultra-cold neutrons	W. Paul et al. 1989
876 ± 10 ± 19	Neutron beam experiment	J. Last et al. 1988
891 ± 9	Neutron beam experiment	P. Spivac et al. 1988
872 ± 8	Storage of ultra-cold neutrons	A. Serebrov et al. 1987
870 ± 17	Neutron beam experiment	M. Arnold et al. 1987
903 ± 13	Storage of ultra-cold neutrons	Y.Y. Kosvintsev et al. 1986
875 ± 95	Storage of ultra-cold neutrons	Y.Y. Kosvintsev et al. 1980
937 ± 18	Neutron beam experiment	J. Byrne et al. 1980
881 ± 8	Neutron beam experiment	L. Bondarenko et al. 1978
918 ± 14	Neutron beam experiment	C.J. Christensen et al. 1972
885.8 ± 0.9	world average 1998	H. Abele 2000



Neutron and Gravity

- (Used in the UCN production)
- Interference experiments (m_i vs m_g)
  Collela, Overhauser, and Werner (1975)





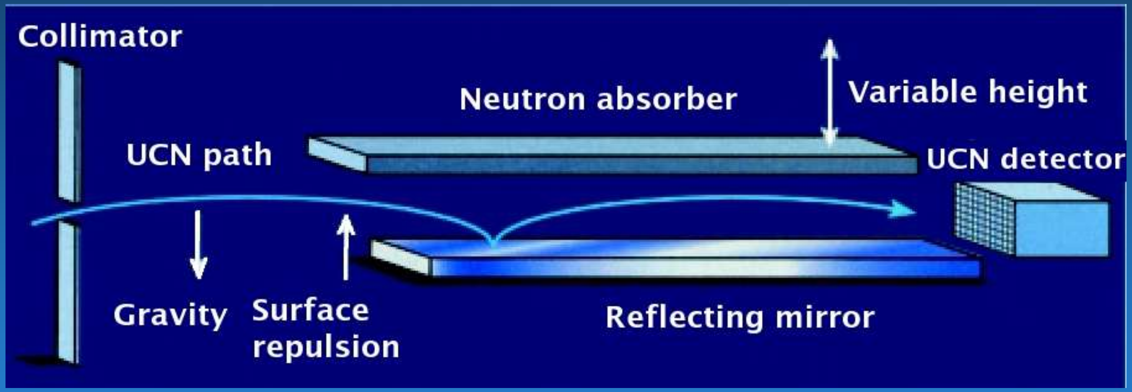
- Quantum states in gravity field

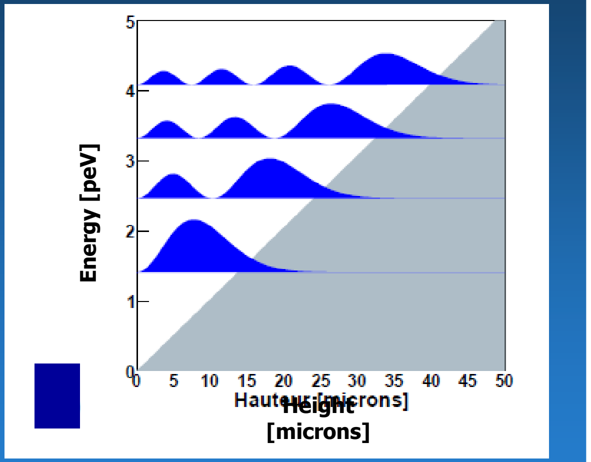
"Let us consider another possibility, an atom held together by gravity alone. For exemple, we might have two neutrons in a bound state. When we calculate the Bohr radius of such an atom, we find that it would be 10^8 light years, and that the atomic binding energy would be 10^{-70} Rydbergs. There is then little hope of ever observing gravitational effects on systems which are simple enough to be calculable in quantum mechanics."

Brian Hatfield, in "Feynman Lectures on Gravitation" ;
R.P. Feynman, F.B. Morinigo, W.G. Wagner, Ed. Brian Hatfield

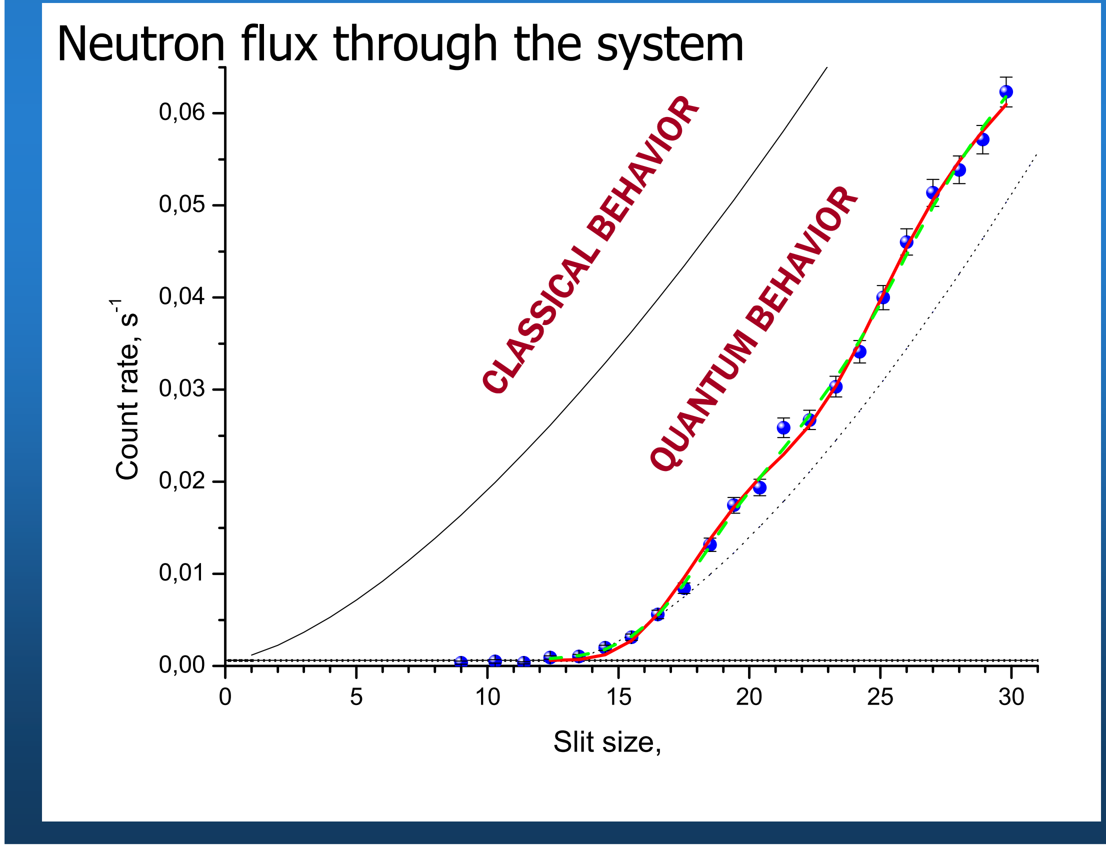
Addison-Wesley Publishing Company, 1995, p. 11

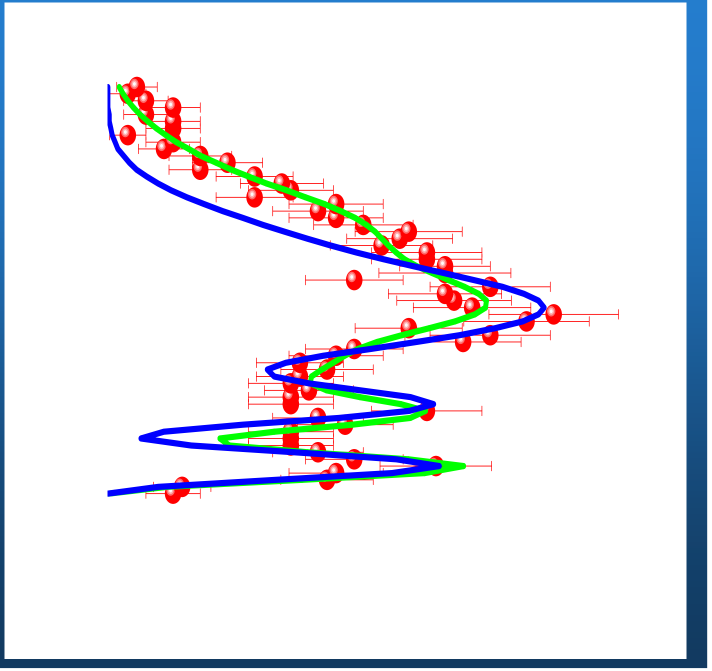
Quantum System: Neutron in a Gravity Field





First « photo » of the wave function


Neutron flux through the system



Neutron in all interactions

- Strong interaction
- Weak interaction
- Electromagnetic interaction
- Gravitational interaction

What else ?

- Search for other interactions

Search for “5th force”

Scattering amplitude of slow neutrons on atoms

$$f(\mathbf{q}) = f_{\mathrm{nucl}}(\mathbf{q}) + f_{ne}(\mathbf{q}) + \ldots + f_V(\mathbf{q})$$

$$f_{ne}(\mathbf{q}) = -b_{ne}\left(Z - f(Z,\mathbf{q})\right)$$

constant for low energies

$$b_{ne} = -\frac{2}{B}\frac{m}{m_e}\left.\frac{dG_E(\mathbf{q}^2)}{d\mathbf{q}^2}\right|_{\mathbf{q}^2=0}$$

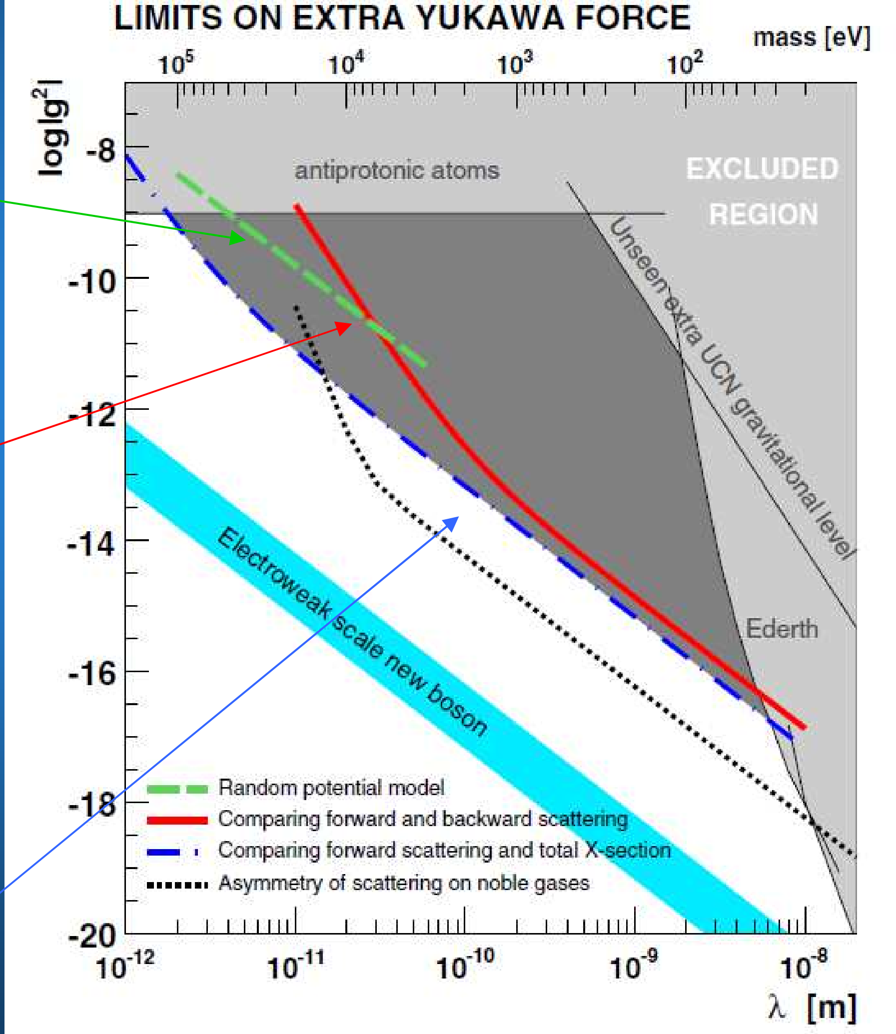
with an unknown contribution induced by a hypothetical interaction

$$V(r) = A\frac{g^2}{4\pi}\frac{\hbar c}{r}e^{-r/\lambda}, \qquad \rightarrow \qquad f_V(q) = -A\frac{g^2}{4\pi}\frac{c}{\hbar}\frac{2m\lambda^2}{1+(q\lambda)^2}$$

Some existing limits

Random potential model

Different methods to determine *b*



Estimation of b_{ne}