中性子を用いた素粒子物理学実験

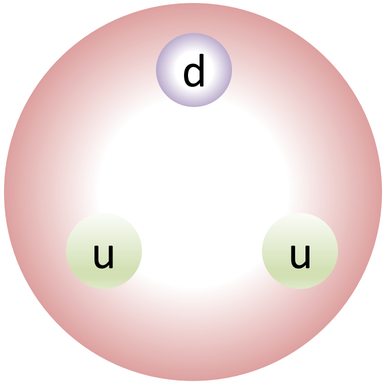
大阪大学 核物理研究センター
三島　賢二

素粒子物理学の進展2025 (PPP2025), September 1st, 2025,
パナソニックホール, 京都大学基礎物理学研究所

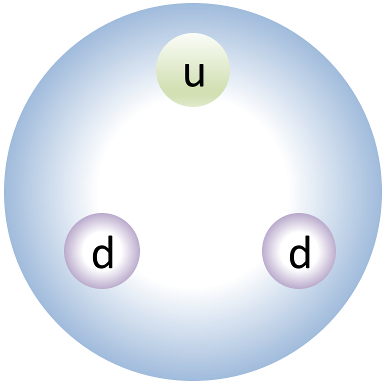
中性子とは

- 陽子と共に原子核を構成する核子のひとつで、そのうち電荷のないもの。
- 1932年にチャドウィックが発見。
- 単体では不安定で、ほぼ原子核に束縛された状態で存在している。

陽子
Proton



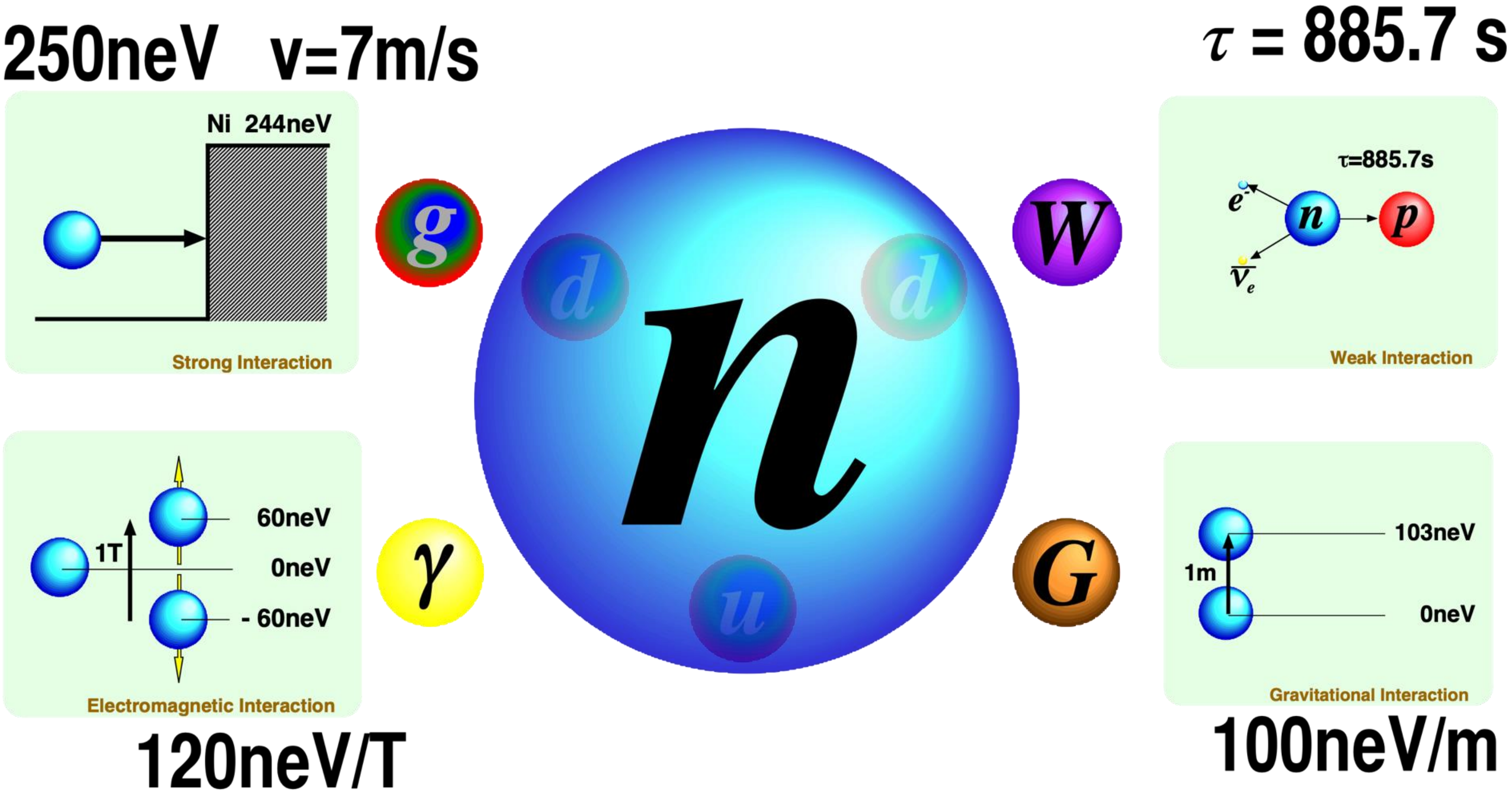
中性子
Neutron



Mass:	938.2720881(29) MeV/c	939.56542052(54) MeV/c
Lifetime:	not detected (>0.9×10^{30}) s	878.4(5) s
Electric charge:	e^+	0 (< 1×10^{-21}) e
Spin	$\hbar/2$	$\hbar/2$

中性子と4つの相互作用

- 強い力、弱い力、電磁気、重力の4つの相互作用がちょうどいい感じな粒子である。

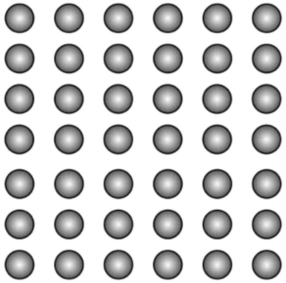


名古屋大清水氏提供

中性子と量子性

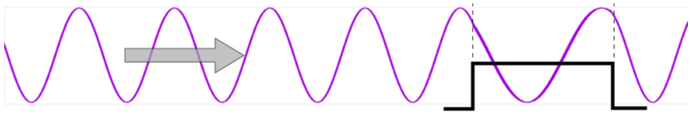
- 原子炉や加速器から取り出した中性子は散乱して「熱化」する。
  - 室温(300 K)ならば25 meVのボルツマン分布に。
- その時の中性子の波長は1.8Åと、原子間距離と同程度となる。
  - 粒子というより波としての性質が顕著に現れる。
- この性質から古くから量子力学の研究に用いられてきた。
  - また、物質の性質を調べるのによく用いられている。
  - 陽子は電荷があるのであまり都合が良くない。
- さらに冷却することで超冷中性子(UCN)にすると、箱の中に閉じ込めることが可能になる。

物体

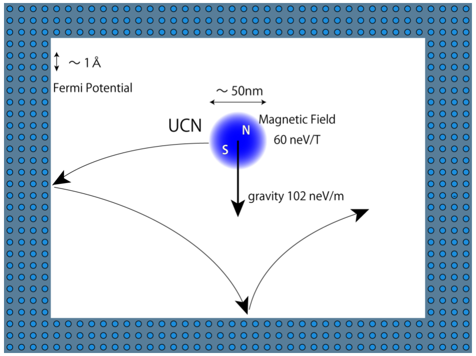


個々の原子核との相互作用というより

10 nm ~ 0.01 nm



平均ポテンシャルを感じる



今日の内容

- 普段はJ-PARCで実験をしています。
- 中性子を使った物理とその実験背景をの紹介します。
  - ➢ おおよそ学生さん向け

1. 中性子と元素合成
2. 量子と重力を使った実験
3. 時間反転対称性探索
4. 中性子反中性子振動

- J-PARC@茨城県東海村

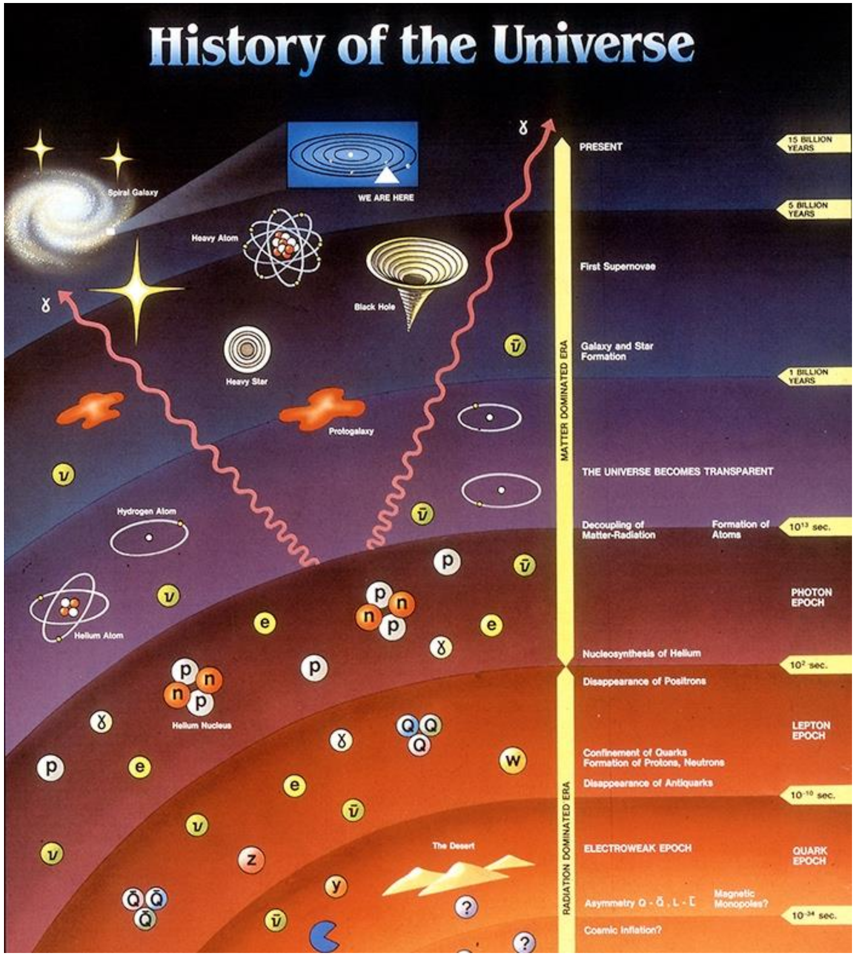
中性子と元素合成

宇宙の歴史

- 宇宙は高密度の熱い火の玉から始まった(ビッグバン)

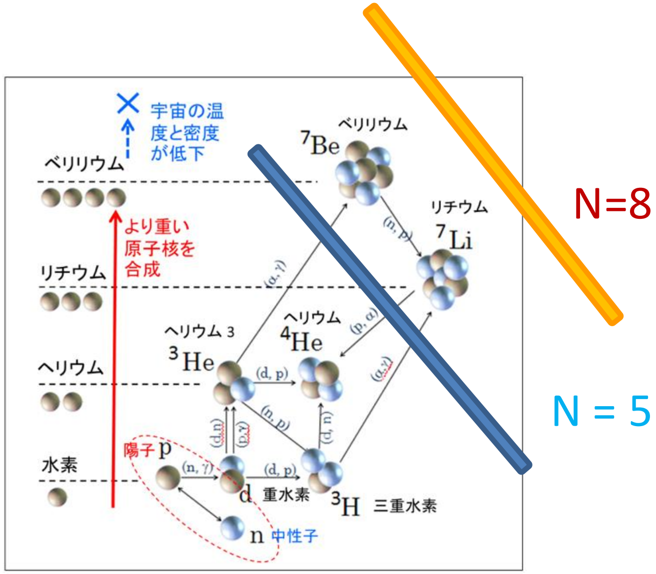
Alpher, Bethe, and Gamow, Phys. Rev. 73 (1948) 803
"The Origin of Chemical Elements"
https://doi.org/10.1103/PhysRev.73.803

- その後、宇宙は拡張しながら冷却されていく。
- 1マイクロ秒後、宇宙の温度が1 GeVを切るあたりで陽子と中性子が生成される。
- 中性子はβ崩壊するので、ちょっとずつ陽子になっていく。
  - この値は中性子の寿命で決まる。

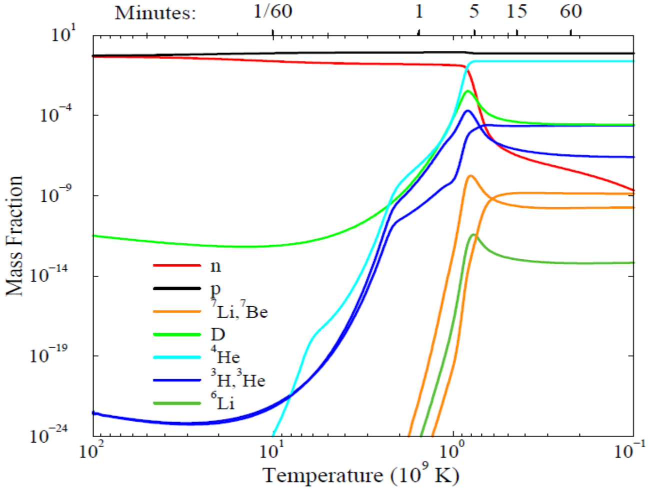


https://www.exploratorium.edu/explore/origins/big-bang

ビッグバン元素合成(BBN)

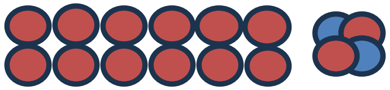


ビッグバンの3-20分後、リチウムまでの原子核が合成される。

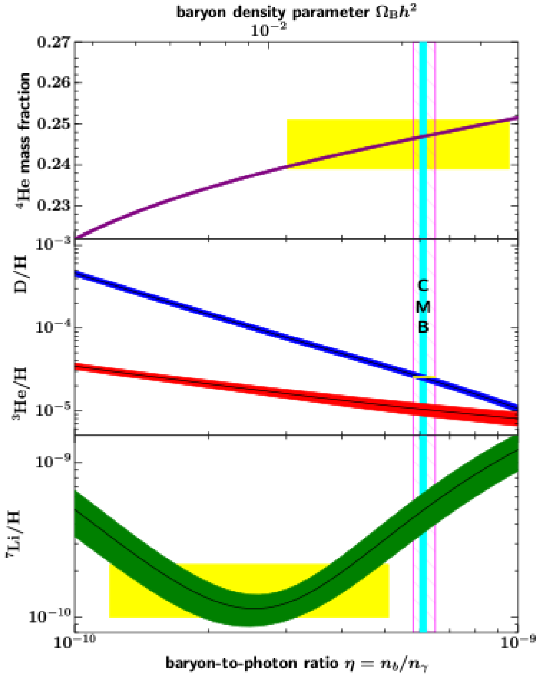


天文学辞典 > ビッグバン元素合成
https://astro-dic.jp/big-bang-nucleosynthesis/

陽子が7個、中性子が1個の割合なので、核子16個のうち、水素が12、ヘリウムが1



質量比でいうとYp=He/(He+H)が25%
初期宇宙ヘリウムの観測量と予想が一致
これがビッグバンの根拠となった。

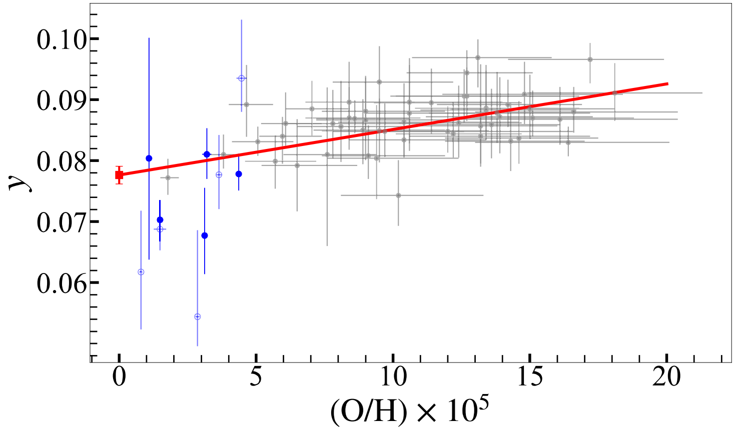


R.L. Workman et al. (Particle Data Group),
Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

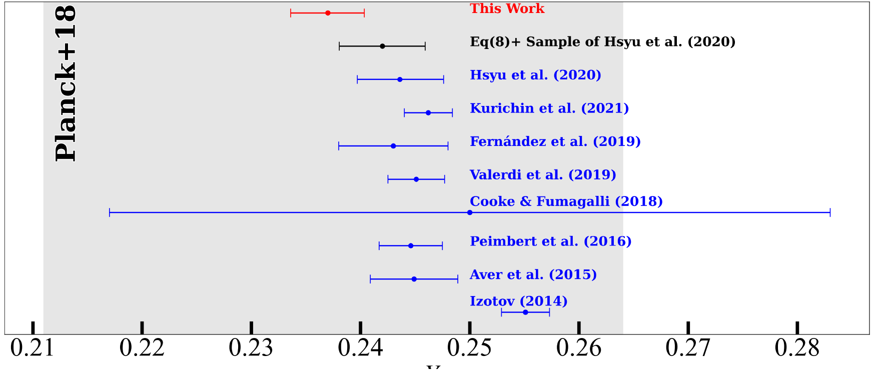
Recent observation by SUBARU telescope

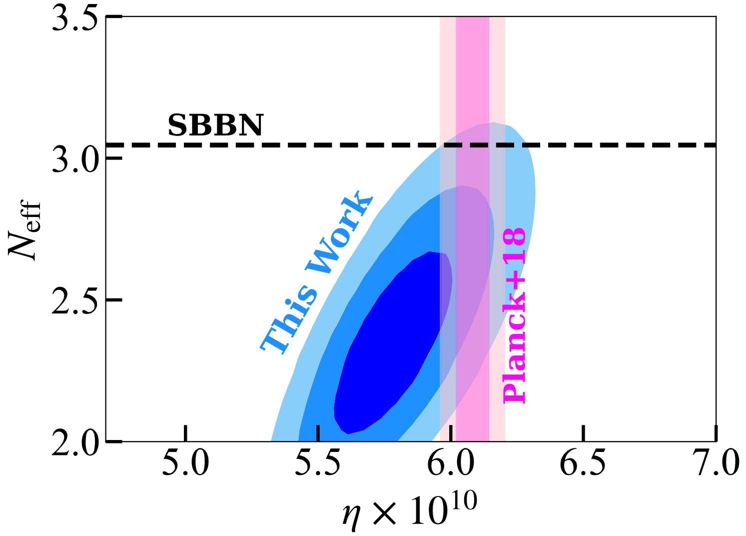
Resent observation from SUBARU telescope gives very small Y_p value.

Correction of Metallicity



Y_p value





$$N_{\rm eff} = 3.11^{+0.34}_{-0.31},$$

$$\eta \times 10^{10} = 6.08^{+0.06}_{-0.06},$$

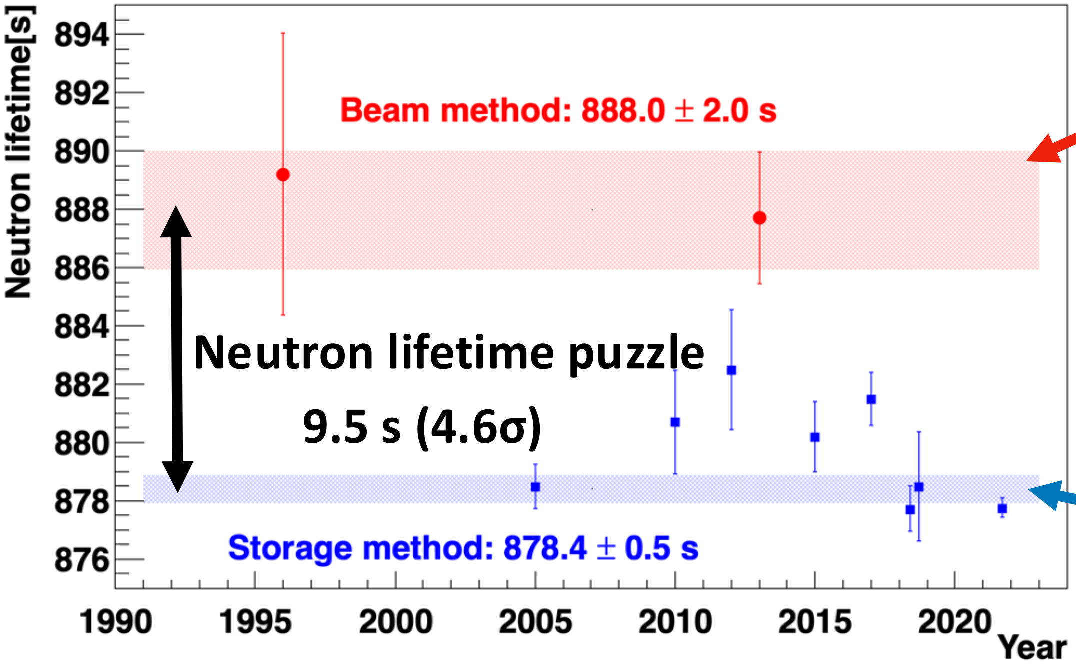
$$\xi_e = 0.05^{+0.03}_{-0.02}.$$

The degeneracy parameter of the electron neutrino ($\nu_e - \overline{\nu}_e$ asymmetry) is non-zero by more than 2σ.

Akinori Matsumoto *et al* 2022 *ApJ* **941** 167, https://doi.org/10.3847/1538-4357/ac9ea1

Neutron lifetime Puzzle

Neutron Lifetime Puzzle



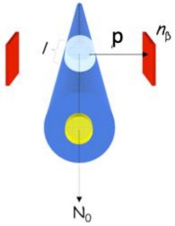
Beam method: 888.0 ± 2.0 s

Neutron lifetime puzzle

9.5 s (4.6σ)

Storage method: 878.4 ± 0.5 s

Beam method: Count the decay



$$-\frac{\mathrm{d}N}{\mathrm{d}t}=\frac{N}{\tau}$$

Storage method : Count the missing

$$\frac{N_1}{N_2}=\mathrm{e}^{-(t_1-t_2)/\tau}$$

- **Measured neutron lifetime values with beam method and storage method show significant discrepancy (more than 4.6σ)**
  - Experimental uncertainties that were not taken into account? (Phys. Rev. D **103**, 074010)
  - New physics?
    - Dark decay? (Mod. Phys. Lett. A **35**, 2030019 (2020))
    - Soft scattering with dark matter? (Phys. Rev. D **103**, 035014)
    - Mirror neutron oscillation? (EPJ C **79:** 484 (2019))

Neutron lifetime in the weak interaction

Ratio of axial to vector coupling (g_A/g_V)
β decay occurs with only g_A and g_V.
Due to the strong interaction, g_A is 27% larger than g_V.

Coupling constant of the weak interaction
(determined from muon decay lifetime)

Radiation correction
Effects of electromagnetic forces involved after collapse

Electron mass

$$\frac{1}{\tau_n} = \frac{G_F^2 m_e^5}{2\pi^3} V_{ud}^2 (1 + 3\lambda^2) f (1 + RC)$$

Neutron lifetime

An element of CKM matrix

Determined by combination of nuclear spin. Some nuclei do not contain λ.

Measurement of $\lambda = g_A/g_V$

Neutron decay in the standard model

$$
\begin{aligned}
d\Gamma \propto \mathcal{N}(E_e)\Big\{ & 1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{\Gamma m_e}{E_e} \\
& + \langle\vec{J}\rangle\cdot\Big[\boxed{A}\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\Big] \\
& + \vec{\sigma}\cdot\Big[N\langle\vec{J}\rangle + G\frac{\vec{p}_e}{E_e} + Q'\hat{p}_e\hat{p}_e\cdot\langle\vec{J}\rangle + R\langle\vec{J}\rangle \\
& \times\frac{\vec{p}_e}{E_e}\Big]\Big\} d\Omega_e d\Omega_\nu dE_e,
\end{aligned}
$$

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} \quad \boxed{A = -2\frac{|\lambda|\cos\phi + |\lambda|^2}{1+3|\lambda|^2}}$$

$$B = -2\frac{|\lambda|\cos\phi - |\lambda|^2}{1+3|\lambda|^2} \quad D = 2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2}$$

$$\tau = \frac{K/\ln 2}{V_{\mathrm{ud}}^2 G_{\mathrm{F}}^2 (1+\lambda^2) f}$$

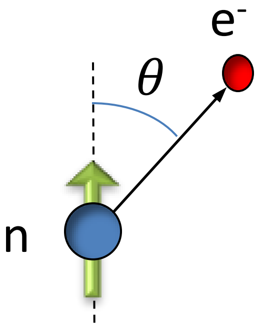
$$\mathcal{N}(E_e) = p_eE_e(E_0-E_e)^2;\ E_e\ (E_\nu),\ \vec{p}_e\ (\vec{p}_\nu)$$

PERKEO III result

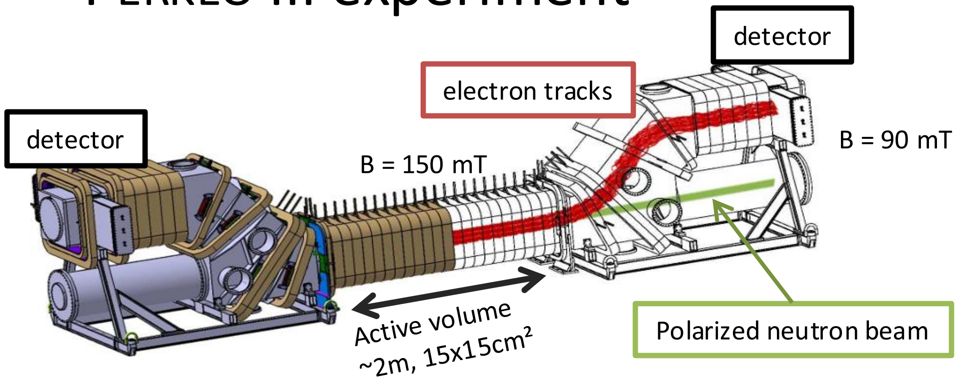
A=−0.11958±0.00021

λ =−1.27641±0.00056

The β-Asymmetry Parameter ***A*** is the most sensitive for λ parameter, which can measured by energy and angular distribution of electrons against neutron spins.



PERKEO III experiment



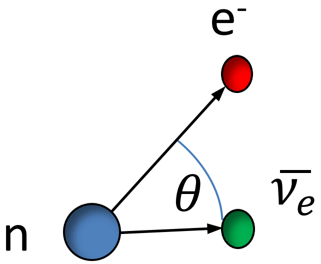
B. Maerkisch et al.(2019) https://doi.org/10.1103/PhysRevLett.122.242501

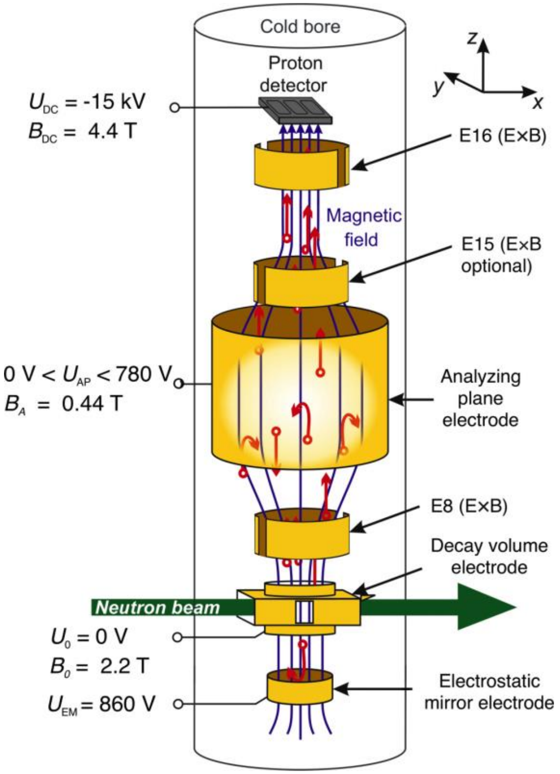
Small “a” measurement

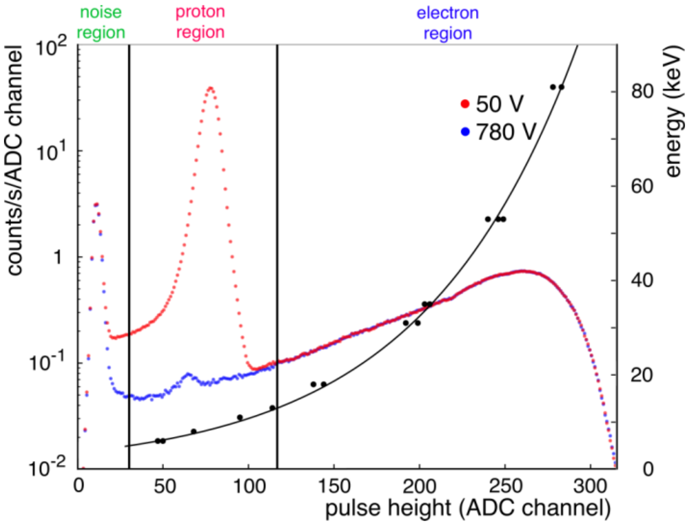
*a*SPECT experiment

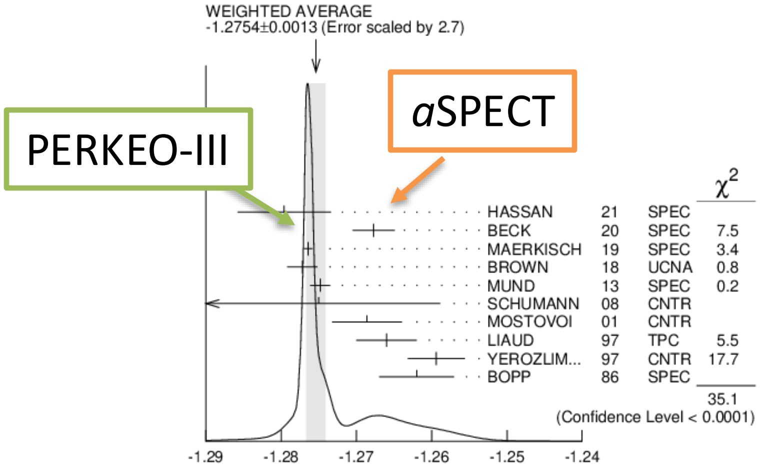
Measurement of the β- ν_e correlation ***a***

$$d\Gamma \propto \mathcal{N}(E_e)\Big\{1 + \boxed{a}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{\Gamma m_e}{E_e} + \langle\vec{J}\rangle\cdot\Big[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\Big]$$









PERKEO-III

*a*SPECT

			χ^2
HASSAN	21	SPEC	
BECK	20	SPEC	7.5
MAERKISCH	19	SPEC	3.4
BROWN	18	UCNA	0.8
MUND	13	SPEC	0.2
SCHUMANN	08	CNTR	
MOSTOVOI	01	CNTR	
LIAUD	97	TPC	5.5
YEROZLIM...	97	CNTR	17.7
BOPP	86	SPEC	
			35.1

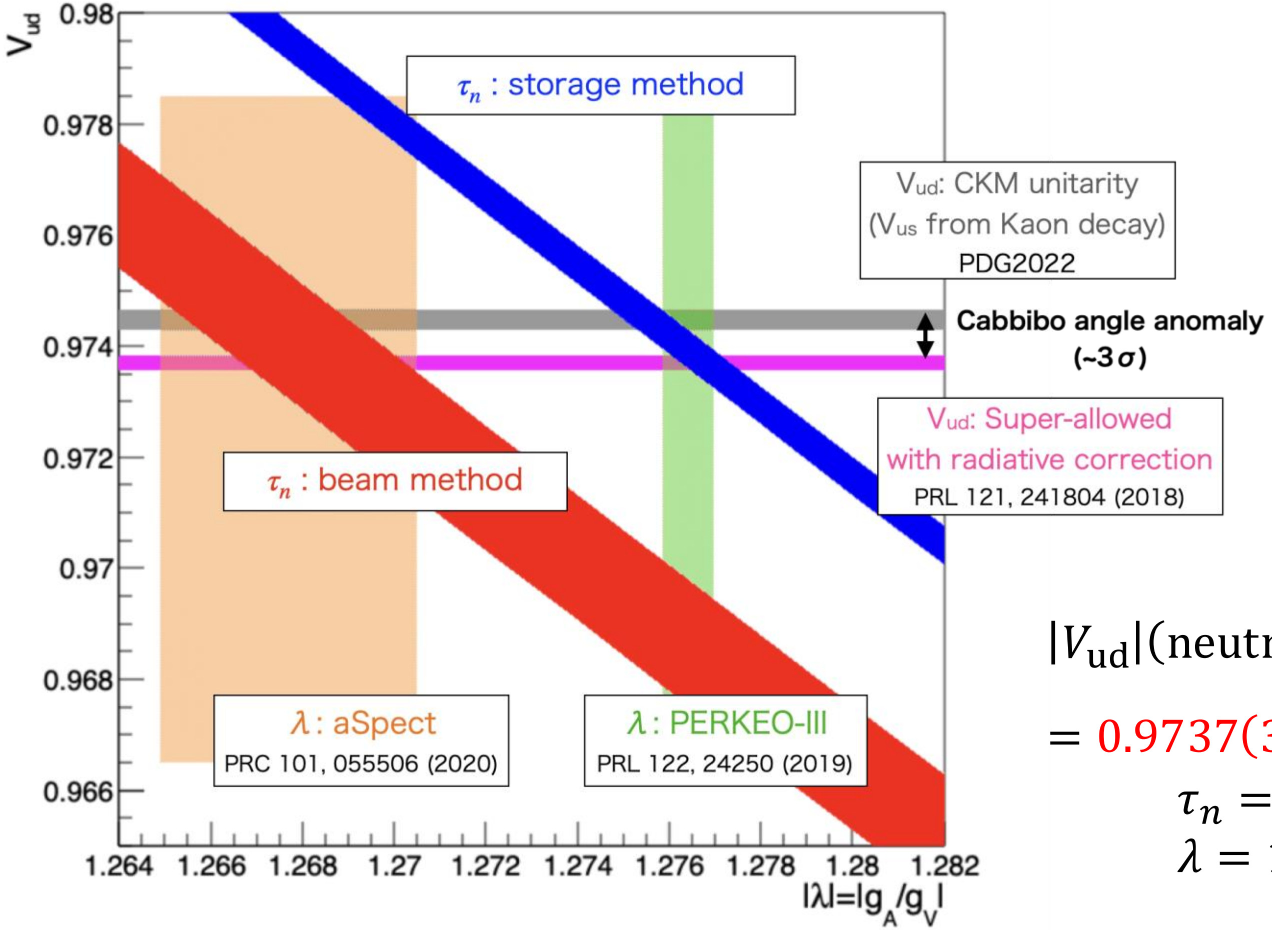
(Confidence Level < 0.0001)

M. Beck et al. (2020) https://doi.org/10.1103/PhysRevC.101.055506

CKM unitarity

If the CKM matrix is 3 generations, it should be a unitary matrix (determinant is 1).

It can be verified Standard Model with very strong restriction (~10 TeV).



$$\sqrt{1-|V_{us}|^2} = 0.9745(2)$$

$$|V_{ud}|\,(0^+\to 0^+) = 0.97373(11)_{\text{exp.}}(9)_{\text{RC}}(27)_{\text{NS}}$$

$$|V_{ud}|(\text{neutron}) = \frac{5024.7\text{s}}{\tau_n(1+3\lambda^2)(1+\Delta_R^V)}$$

$$= 0.9737(3)_{\tau_n}(8)_{\lambda}(1)_{RC}$$

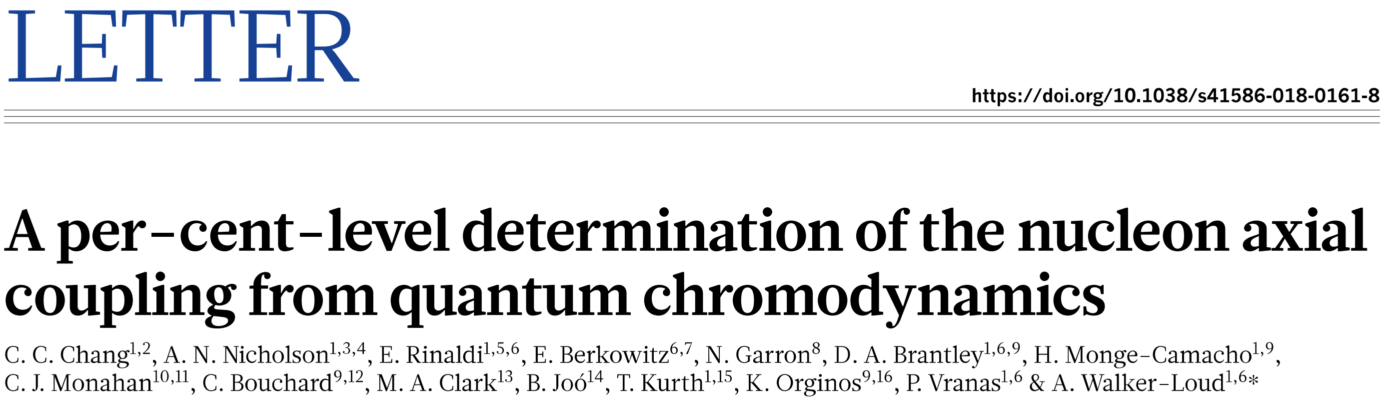
$$\tau_n = 879.4(6)\ s$$

$$\lambda = 1.2756(13)$$

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 0.9985(6)_{|V_{ud}|}(4)_{|V_{us}|}$$

R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022)

Lattice QDC calculation for λ

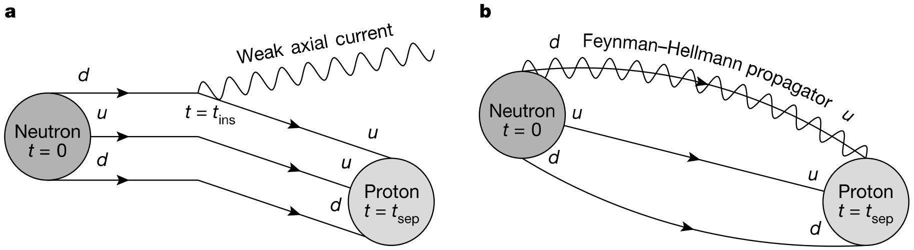


LETTER

https://doi.org/10.1038/s41586-018-0161-8

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

C. C. Chang[1,2], A. N. Nicholson[1,3,4], E. Rinaldi[1,5,6], E. Berkowitz[6,7], N. Garron[8], D. A. Brantley[1,6,9], H. Monge-Camacho[1,9], C. J. Monahan[10,11], C. Bouchard[9,12], M. A. Clark[13], B. Joó[14], T. Kurth[1,15], K. Orginos[9,16], P. Vranas[1,6] & A. Walker-Loud[1,6]*



Resent lattice calculation achieve to calculate g_A in 1% level.

g_A =**−1.271±0.0013**

C. C. Chang et al., *Nature* **558**, 91–94 (2018). https://doi.org/10.1038/s41586-018-0161-8

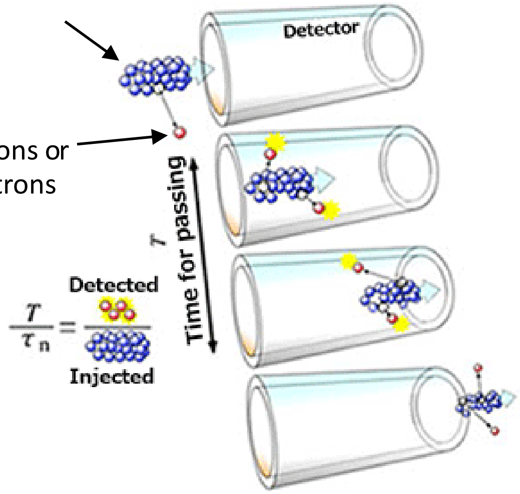
Measurements of Neutron lifetime

Methods to measure neutron lifetime

➢ Beam method

Bunch of neutron beam

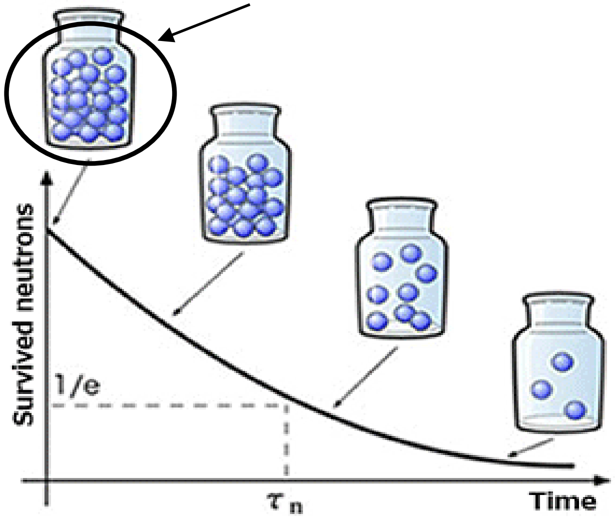
protons or
electrons



- ➢ Counts beta decay protons or electrons from neutron beam and estimate the beta decay event fraction with injected neutron flux

➢ Storage method

Bottled ultra-cold neutrons



- ➢ Confines ultra-cold neutrons into strage and then counts survived neutrons as a function of confinement time

1st precise lifetime experiment by Robson in 1951

Phys. Rev. **83** (1951) 349; at Chalk River reactor in Canada, 3 cm diam. thermal neutron beam with 2×10^9 n/cm^2/s flux

The protons from the radioactive decay of the neutron have been identified by measuring their charge to mass ratio with an electrostatic field and magnetic lens spectrometer. Coincidences have been obtained between these protons and the corresponding beta-particles from the neutron decay using a second magnetic lens spectrometer to measure the energies of the beta-particles. In this manner the beta-spectrum of the neutron has been measured over the region from 300 kev to the end point and has been found to be consistent with the energy distribution expected for an allowed transition. The end point of the spectrum is 782 kev with a probable error of ±13 kev. The half-life of the neutron is 12.8 minutes with a probable error of ±2.5 minutes.

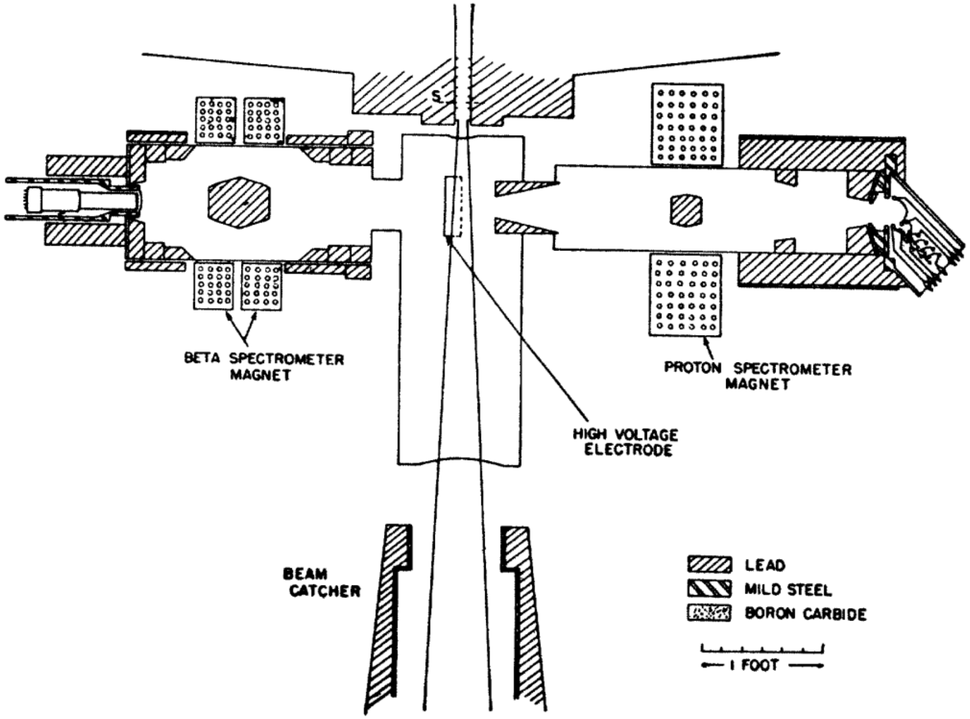
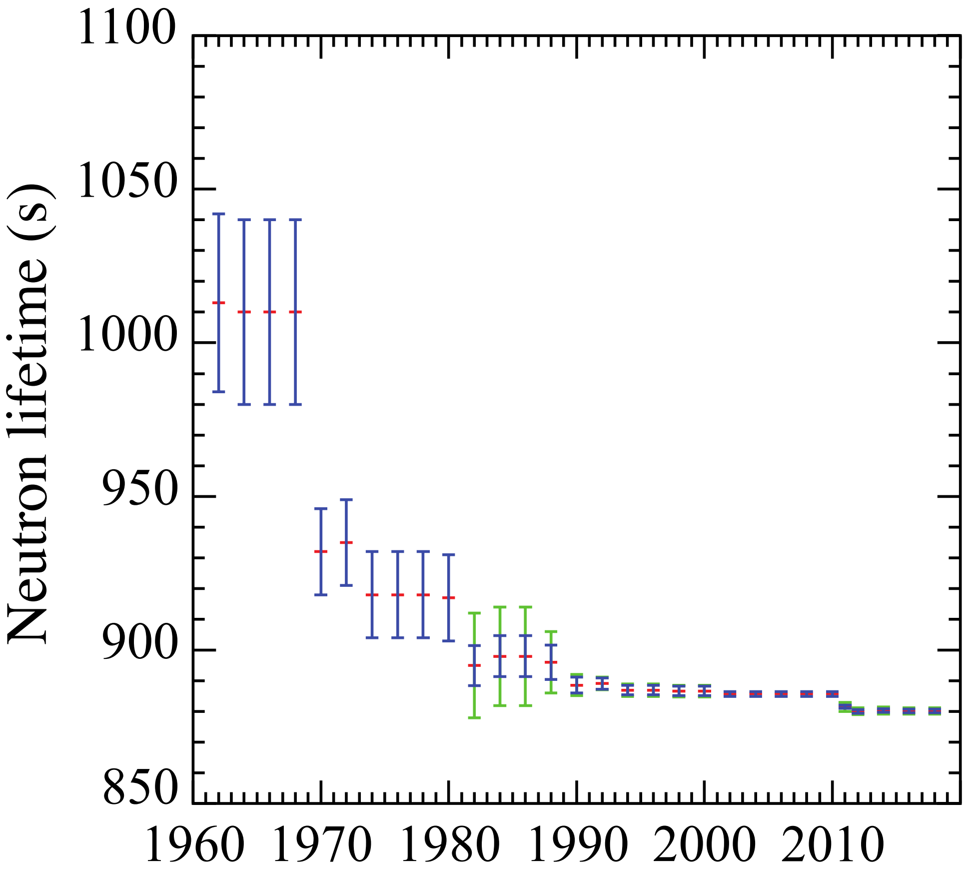


FIG. 1. Plan view of the apparatus mounted outside the main shield of the pile.

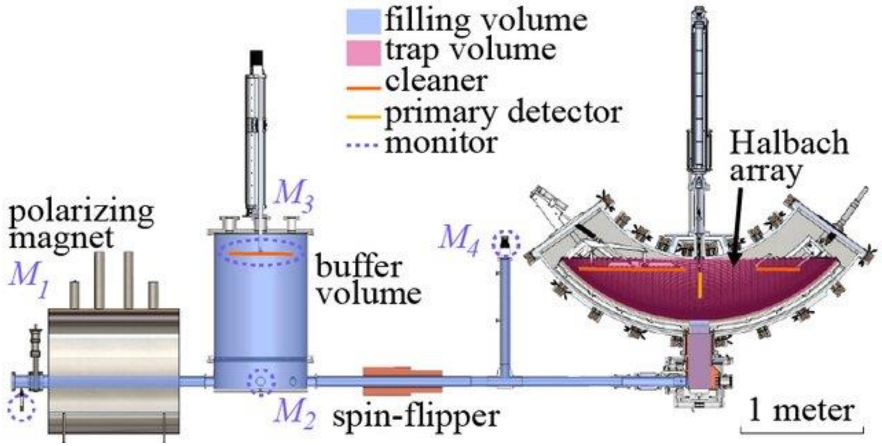
e-p coincidence

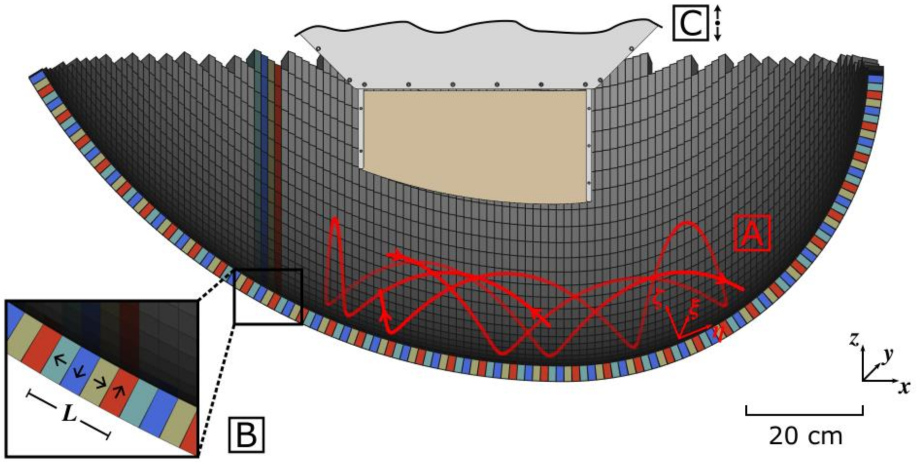
T_n = 1108 (216) s

History of the neutron lifetime



UCNτ experiment





N. Callahan *et al.* Phys. Rev. C **100**, 015501

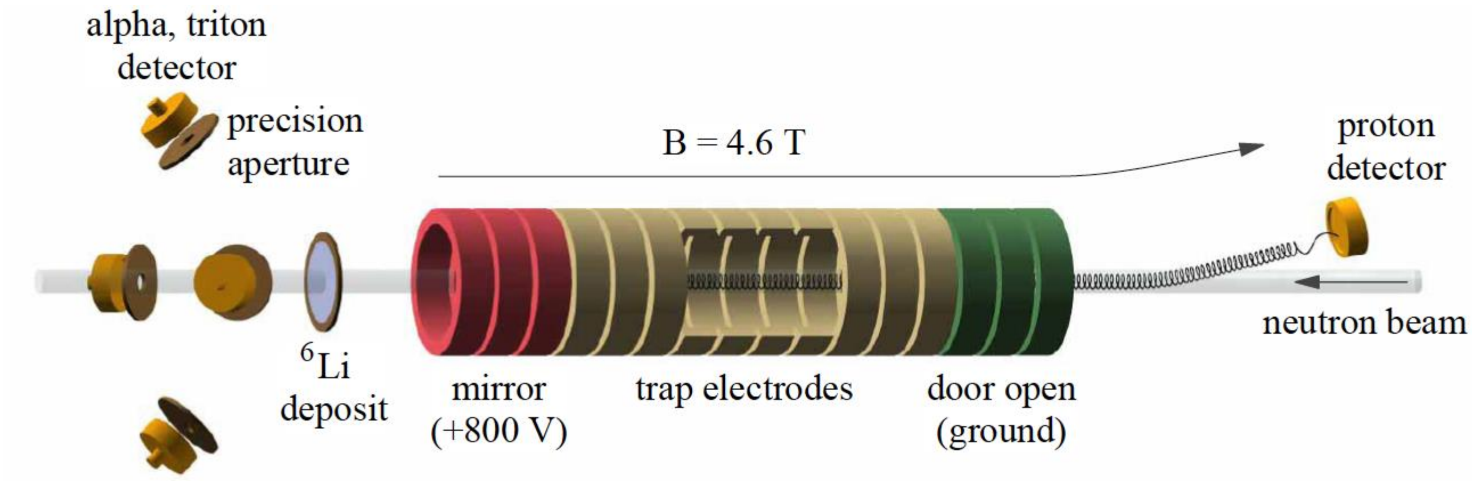
- The most accurate experiment have done in Los Alamos in 2021.

F. M. Gonzalez *et al* (UCN τ Collaboration), Phys. Rev. Lett. 127, 162501 (2021)

$$\tau_n = 877.7 \pm 0.28_{stat}\,{}^{+0.22}_{-1.06}{}_{syst}\ s$$

- Storing UCNs in magnetic bottle, and detecting with scintillation detector.

Beam method
NIST experiment by proton counting



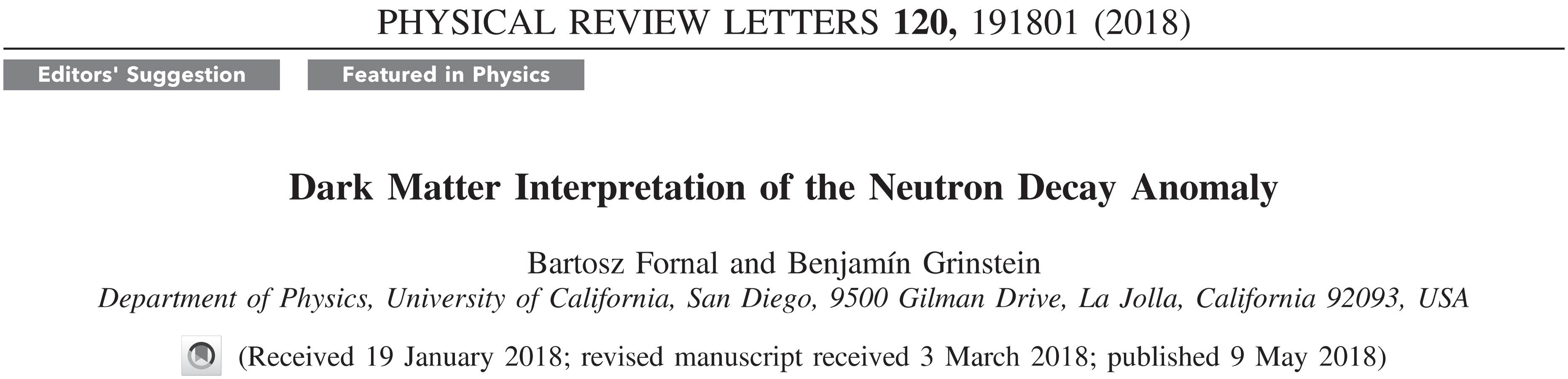
1. Monochromatic beam is transported to the magnetic trap. Neutron flux is monitored by a well calibrated ^{6}Li/SSD detector.
2. Protons from the neutron decays captured in the magnetic trap with electrodes. Stored protons are released and detected by a SSD with thin surface layer.

$$\boldsymbol{\tau_n = 887.7 \pm 1.2\,[stat.] \pm 1.9\,[syst.]\,s\ = 887.7 \pm 2.3\,[combined]\,s}$$

A. T. Yue et al., "Improved determination of the neutron lifetime." Physical review letters 111.22 (2013): 222501.
J. Nico et al., "Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam." Physical Review C 71.5 (2005): 055502.

Neutron lifetime puzzle with new physics

Theoretical considerations for the gap between Beam and Storage methods



PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Editors' Suggestion **Featured in Physics**

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093, USA

(Received 19 January 2018; revised manuscript received 3 March 2018; published 9 May 2018)

The puzzle can be explained if an unobservable decay mode at 1% other than $n \to p + e^- + \bar{\nu}$.

How about neutron decay to dark sector?

1. $n \to \chi\gamma$
2. $n \to \chi\phi$
3. $n \to \chi e^+ e^-$

Neutron → dark matter + photon

Predicts γ-ray emission of 1% of neutron decay

$0.782\ \text{MeV} < E_\gamma < 1.664\ \text{MeV}$ from Q values of neutron and ^{9}Be

NOT Detected

Search for the Neutron Decay $n \rightarrow X+\gamma$, where X is a dark matter particle.

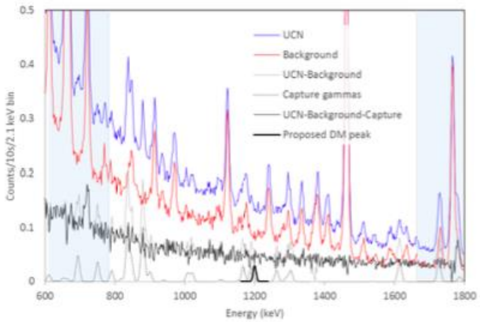
Z. Tang et al, Phys. Rev. Lett. **121**, 022505, https://doi.org/10.1103/PhysRevLett.121.022505

Quantamagazine

NUCLEAR PHYSICS

Neutron Lifetime Puzzle Deepens, but No Dark Matter Seen

https://www.quantamagazine.org/neutron-lifetime-puzzle-deepens-but-no-dark-matter-seen-20180213/



The UCNtau experiment at Los Alamos National Laboratory, which uses the “bottle method” to measure the neutron lifetime.

Beta decay to hydrogen in a new state

- Probability of hydrogen formation

$$n \rightarrow p + e^{-} + \bar{\nu}_e \rightarrow H + \bar{\nu}_e$$

is calculated as $4\text{x}10^{-6}$.

- A theory indicate to 3000 times larger transition to another state of hydrogen.
  - The hydrogen is insensitive for proton counting.
  - 3000 times hydrogen formation expect 1.3%, which is consistent with the value from the experimental difference of 1.15+/-0.27%
- Second Flavor of Hydrogen Atom (SFHA) is deduced by second solution of Dirac equation.

$$R_{0,-1}(r) \propto \frac{1}{r^{q}}, \qquad q = 1 \pm \sqrt{(1-\alpha^{2})}$$

  - $1 + \sqrt{(1-\alpha^{2})}$ is the normal one, $1 - \sqrt{(1-\alpha^{2})}$ is the new one.

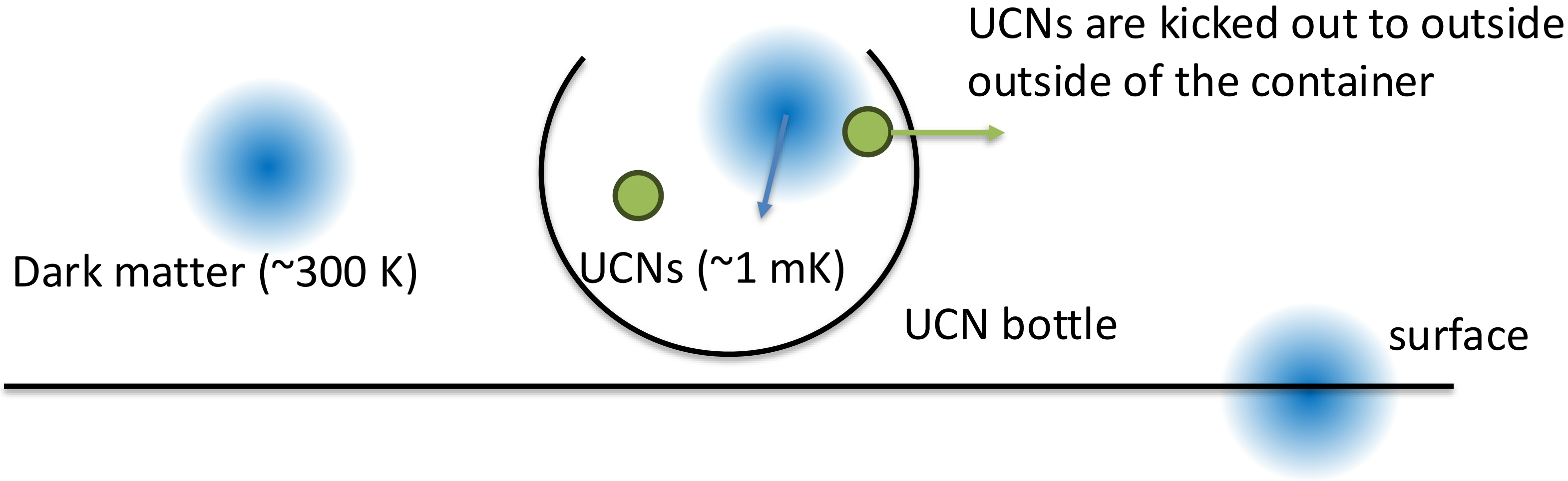
- The SFHA is dark, which is only coupled with 21 cm line.

Couldn't atomic physics find the state? 🤔

E. Oks, New Astronomy, 2024, 113 102275 https://doi.org/10.1016/j.newast.2024.102275

Dark matter kicking out UCNs

- Some dark matters are captured in the gravity of the Earth.
- They are thermalized (300 K or 25 meV), and can interact with UCNs.
- Even small momentum transfer (*q* = *9* eV/c for 50 neV), UCNs are kicked out from the container.



UCNs are kicked out to outside
outside of the container

Dark matter (~300 K)

UCNs (~1 mK)

UCN bottle

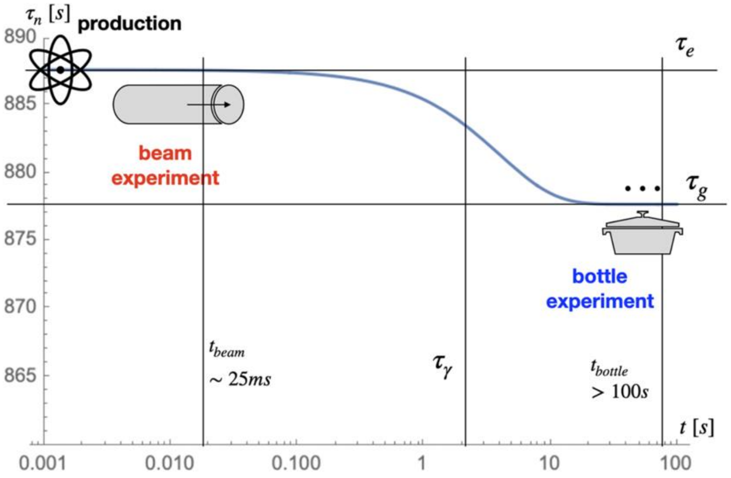
surface

Is there any other experimental limits for this? 🤔

S. Rajendran and H. Ramani, Phys. Rev. D 103, 035014(2021), https://doi.org/10.1103/PhysRevD.103.035014

Exited state in a neutron

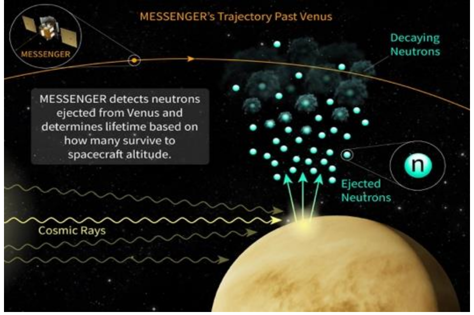
- Neutrons are in an excited state when generated and transition to the ground state on a timescale of of seconds.
- The neutrons in the exited state have longer lifetime of 888 s than the ground state of 880 s.



Does such an exotic state couldn’t yet found in other experiments? 🤔

B. Koch and F. Hummel, Phys. Rev. D 110, , 073004 (2024), https://doi.org/10.1103/PhysRevD.110.073004

Space measurements

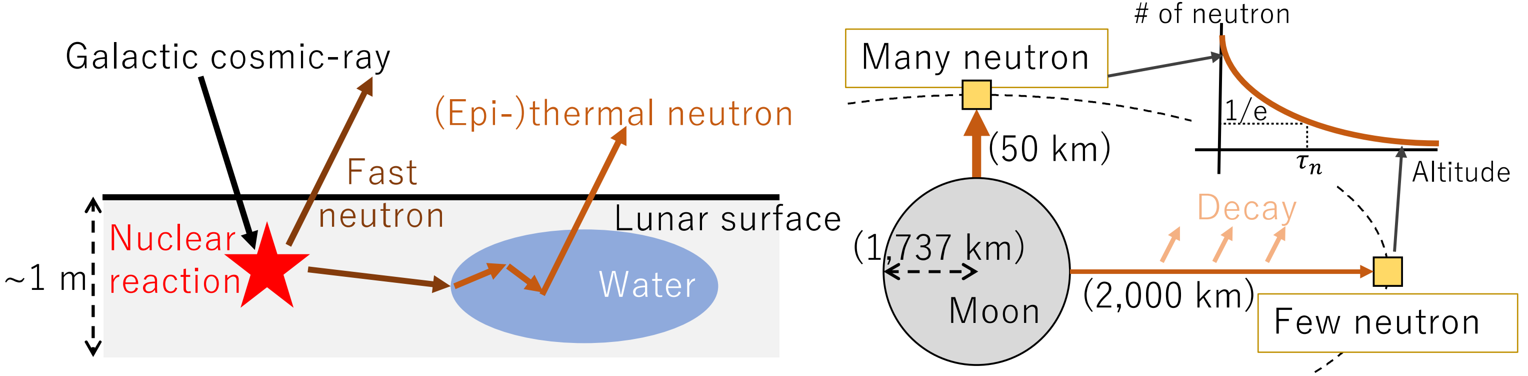


Credit: Johns Hopkins Applied Physics Laboratory, USA

- Neutron lifetime obtained by a Lunar Exploration Satellite
- Measurement of distance dependence of the thermal neutron from the moon surface

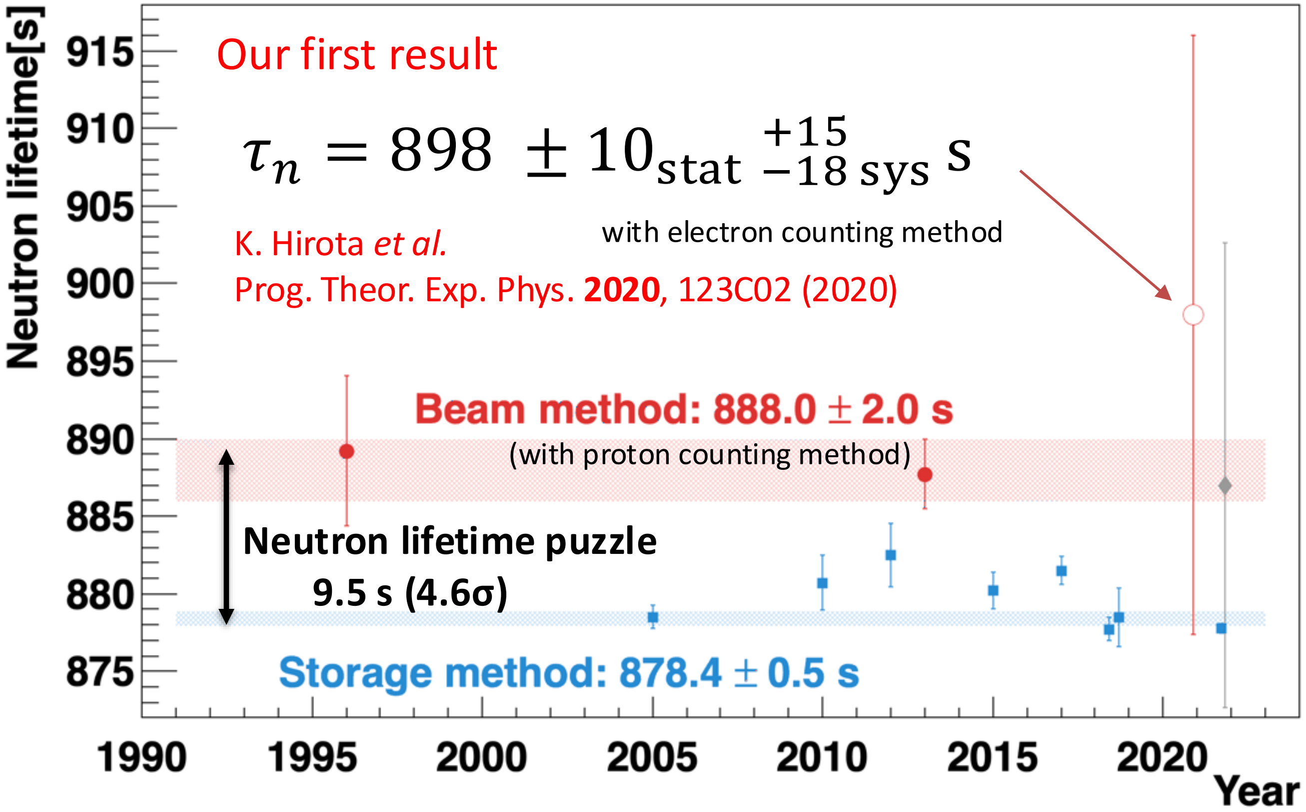
$$\tau_n = 887 \pm 14\ {}^{+7}_{-3}\ s$$

Lunar Prospector, Jack T. Wilson, et al., PRC **104**, 045501 (2021)



- It is classified “storage experiment” with thermal neutrons.
  - Dark matter will not affect on this measurement.
- Plan for a new satellite
  - MoMoTarO, N. Tsuji et al., PoS(ICRC2023)296

Neutron lifetime puzzle



Our first result

$$\tau_n = 898 \pm 10_{\mathrm{stat}}\ {}^{+15}_{-18}{}_{\mathrm{sys}}\ \mathrm{s}$$

with electron counting method

K. Hirota *et al.*
Prog. Theor. Exp. Phys. **2020**, 123C02 (2020)

Beam method: 888.0 ± 2.0 s
(with proton counting method)

Neutron lifetime puzzle
9.5 s (4.6σ)

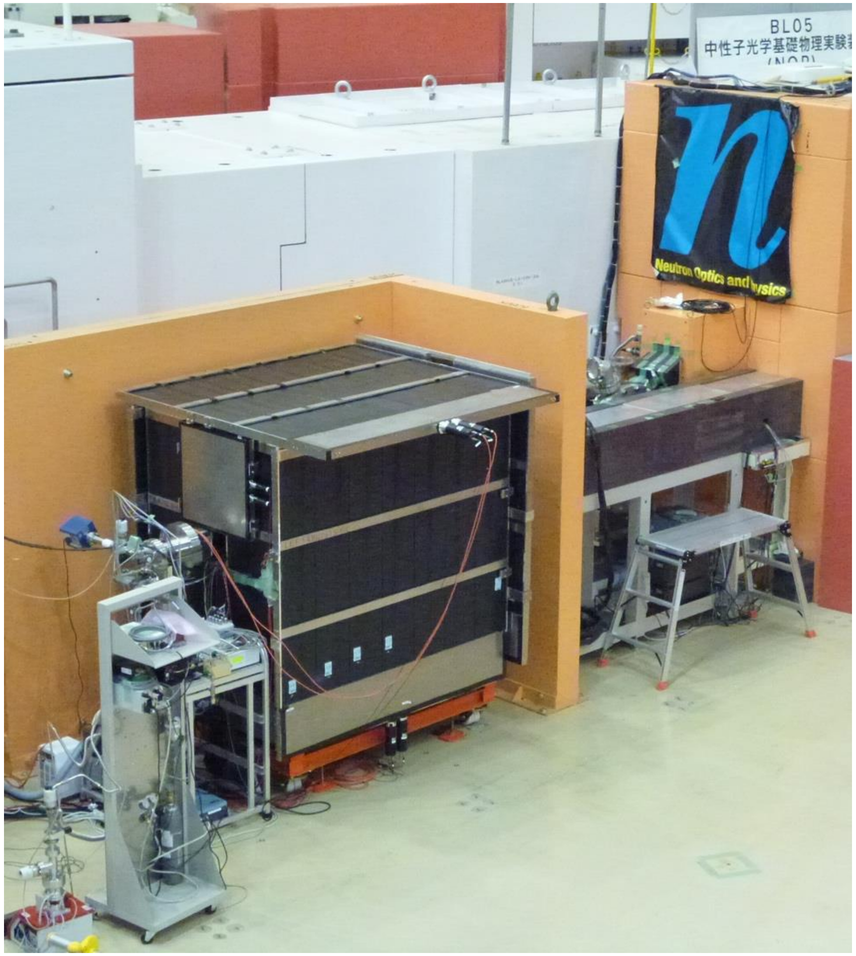
Storage method: 878.4 ± 0.5 s

Space-based method:
$887\ \pm 14_{\mathrm{stat}}\ {}^{+7}_{-3}{}_{\mathrm{sys}}\ \mathrm{s}$
(PRC **104**, 045501 (2021))

- Measured neutron lifetime values with beam method and storage method show significant discrepancy (more than 4.6σ).
- New type of measurement is ongoing at J-PARC.
  - Counting not proton but electron from the beta decay.
  - Deferent observable and different systematics.

Experiment at J-PARC

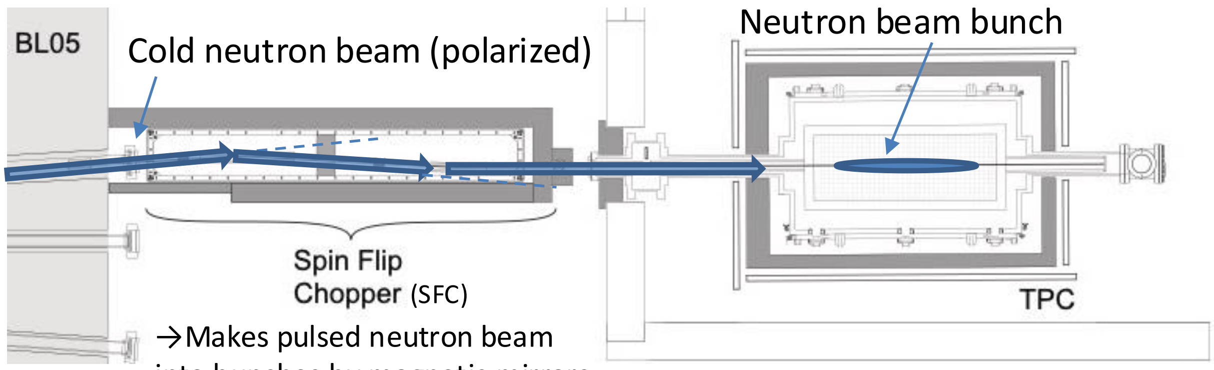
Neutron Lifetime experiment using pulsed neutron at J-PARC



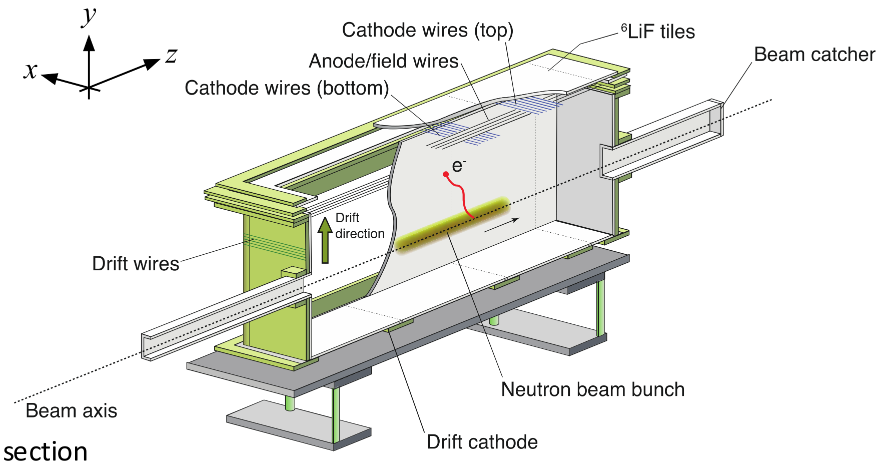
K. Mishima[1], Y. Fuwa[2], T. Hasegawa[1], T. Hoshino[4],
R. Hosokawa[4], G. Ichikawa[3], S. Ieki[5], T. Ino[3],
Y. Iwashita[6], M. Kitaguchi[1], S. Makise[4],
S. Matsuzaki[4], T. Mogi[7], K. Morikawa[1],
N. Nagakura[7], H. Okabe[1], H. Otono[4],
Y. Seki[5], D. Sekiba[8], T. Shima[9], H. E. Shimizu[10],
H. M. Shimizu[1], N. Sumi[3], H. Sumino[6], M. Tanida[4],
T. Tomita[4], H. Uehara[4], T. Yamada[6], S. Yamashita[11],
K. Yano[4], T. Yoshioka[4]

Nagoya Univ.[1], JAEA[2], KEK[3], Kyushu Univ.[4], Tohoku Univ.[5], Kyoto Univ.[6], The Univ. of Tokyo[7], Univ. of Tsukuba[8], Osaka Univ.[9], Sokendai[10], Iwate Pref. Univ.[11]

Lifetime measurement at J-PARC/BL05 by electron detection



→Makes pulsed neutron beam into bunches by magnetic mirrors and spin flippers



- Detector: Time Projection Chamber (TPC)
  - Gas: ^{4}He, CO$_2$, ^{3}He (~85%, ~15%, 0.5 - 2 ppm, respectively)
    Total pressure: 100 kPa or 50 kPa
  - Signals are detected with a Multi Wire Proportional Chamber (MWPC)

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\frac{(S_{\mathrm{He}}/\varepsilon_{\mathrm{He}})}{(S_\beta/\varepsilon_\beta)}$$

ρ : ^{3}He dencity
σ_0 : ^{3}He neutron absorption cross section
v_0 : Velocity of neutron
S_{He} : Number of ^{3}He neutron absorption event
S_β : Number of neutron β decay
$\varepsilon_{\mathrm{He}}, \varepsilon_\beta$: Efficiency

- We aim to provide the most precise experimental neutron lifetime value for beam method as an important piece to solve the neutron lifetime puzzle
  - **<u>Goal: measurement with ~1 s accuracy</u>**

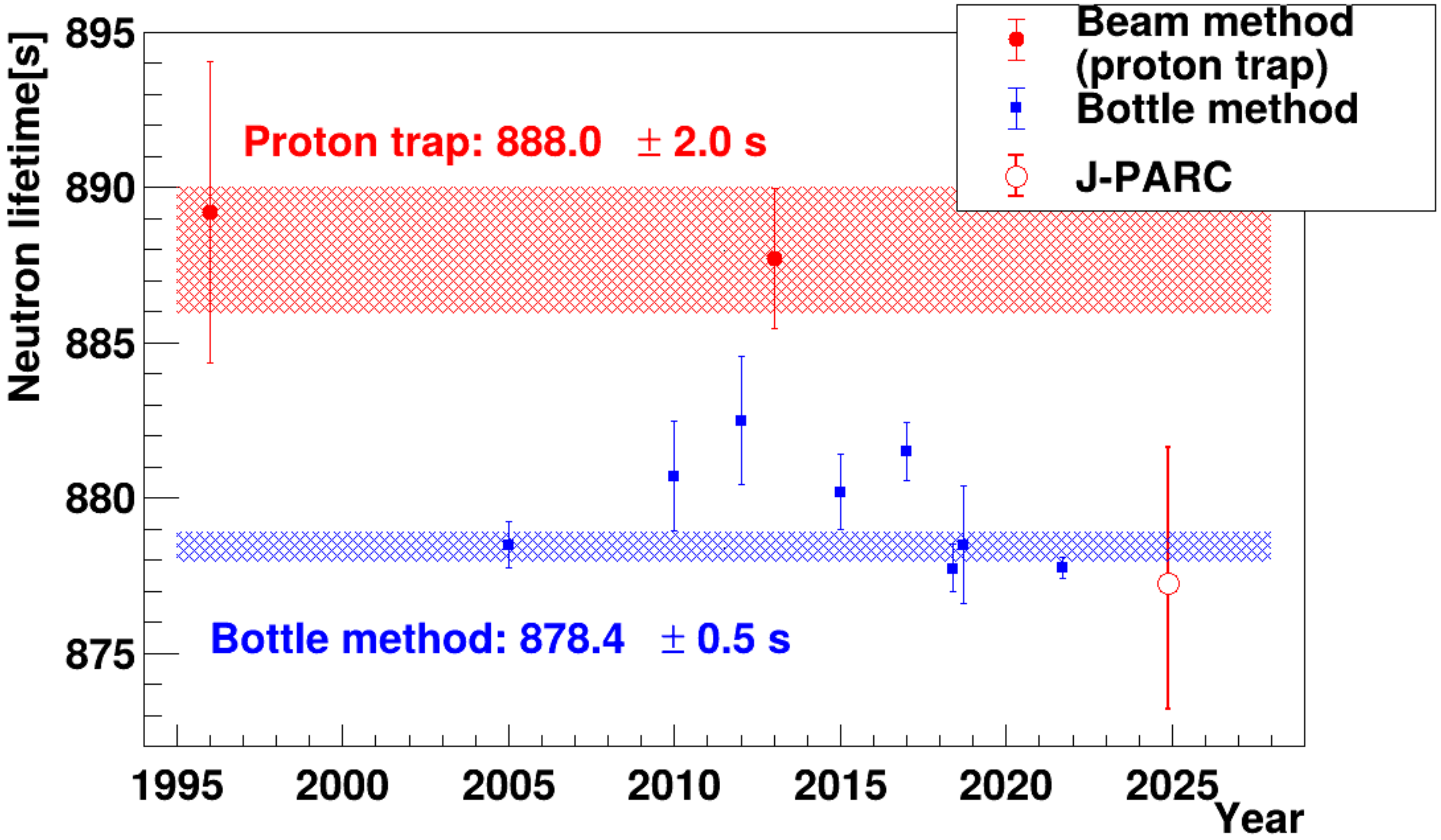
注: 数値はまだ変わるかも

A new result from J-PARC

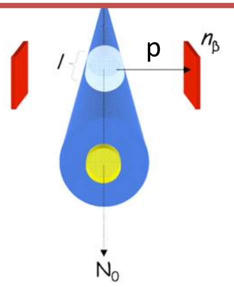
The improved results using data from 2014 to 2023 are as follows:

$$\tau_n = 877.2 \pm 1.7(stat.)^{+4.0}_{-3.6}\,(sys.) = 877.2^{+4.4}_{-4.0}\ \mathrm{s}$$

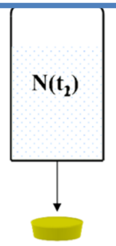
[Y. Fuwa et al., arXiv:2412.19519v1]



Beam method
(proton trap)
Count the dead

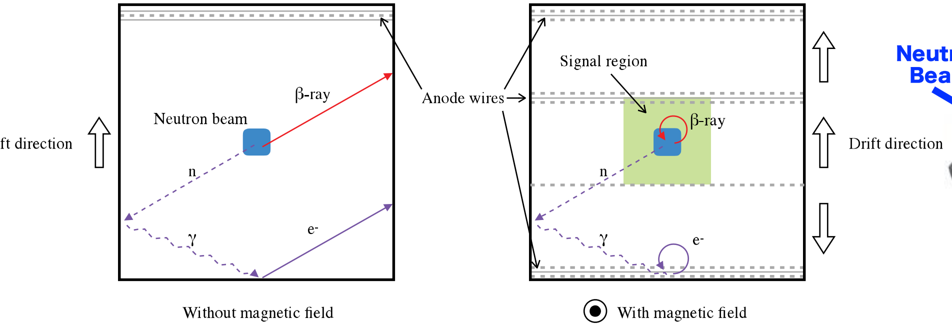


Bottle method
Count the living



This value gives a 2.3σ tension with the average value obtained from the proton trap.

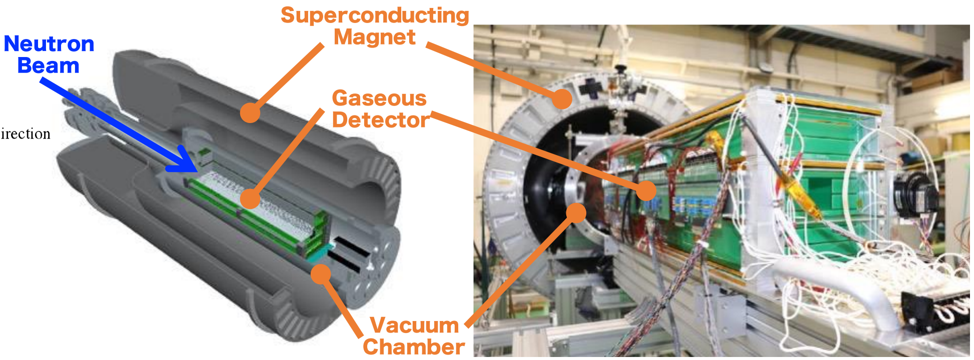
Background suppression with solenoidal magnetic field

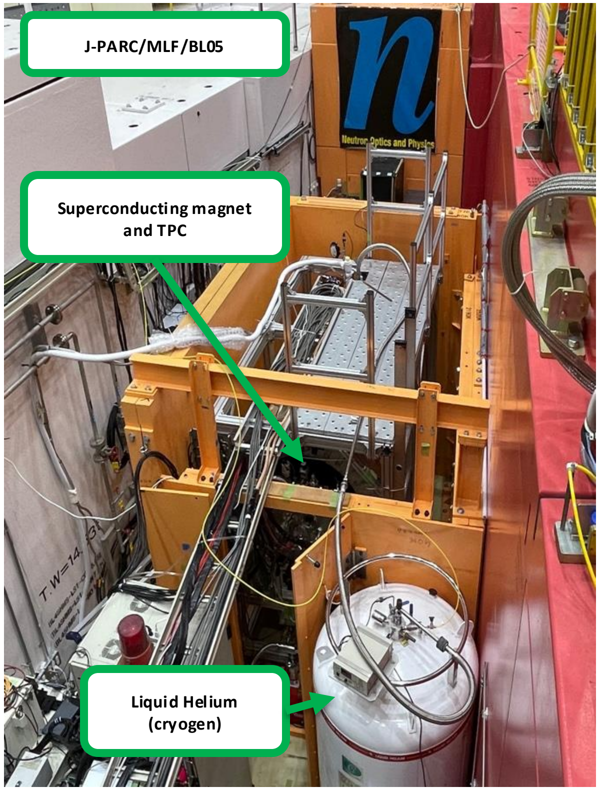


Without magnetic field

With magnetic field

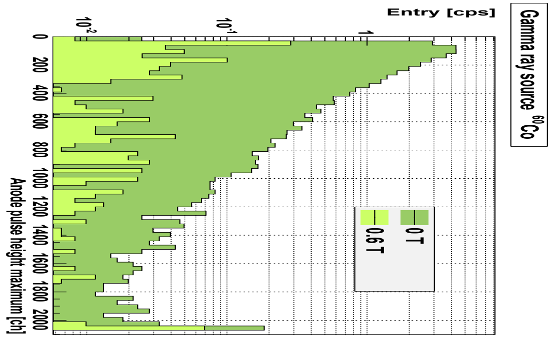
N. Sumi *et al.*, *Nucl. Inst. Meth. Phys. Res A* 1045 (2023) 167586.





To achieve 1 s, we are preparing for background suppression by using multi-layered TPC in a solenoid magnetic field.

Gamma ray suppression with magnetic field



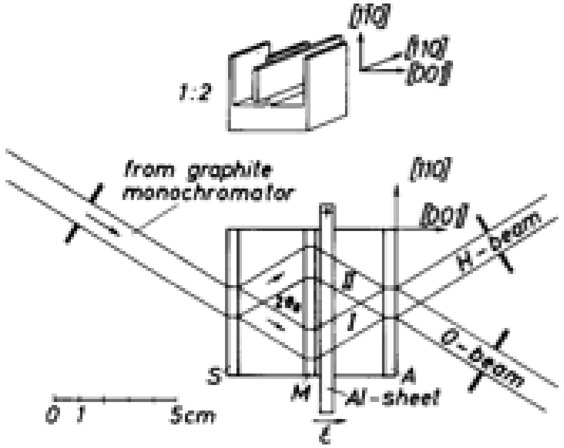
The first data was obtained on this apparatus in Feb. 2024. 3 hours of physics run, corresponds to ~80 s.

The next run will come in next Dec.

中性子の量子性を利用した実験
(中性子干渉)
あと重力とか

中性子干渉計による
スピノル回転の証明

- 中性子は量子力学黎明期から歴史的に重要な測定に使用されてきた。
- 特に1974年に開発された中性子干渉によるものが大きい。
  - Bragg散乱により1つの中性子が2経路に分波した後、再度合流する。その際の急いうさを検出する。
  - シリコン結晶から切り出して作る。
- 磁場を印加し中性子を回転させたとき、中性子は2πで逆位相になり、4πでもとに戻る、というフェルミオンの性質を実験的に証明した。



H. Rauch, W. Treimer, U. Bonse, Phys. Lett. 47A, 369(1974)

Rauch, H., Zeilinger, A., Badurek, G., Wilfing, A., Bauspiess, W., & Bonse, U. (1975)
“Verification of coherent spinor rotation of fermions”
Physics Letters A, *54*(6), 425-427
https://doi.org/10.1016/0375-9601(75)90798-7.

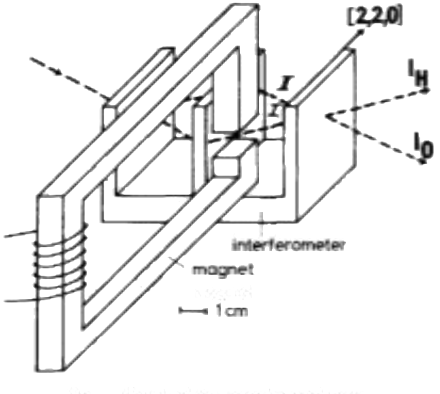


Fig. 1. Sketch of the experimental setup.

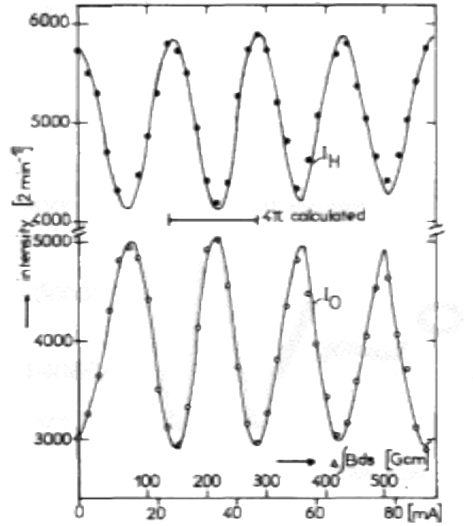
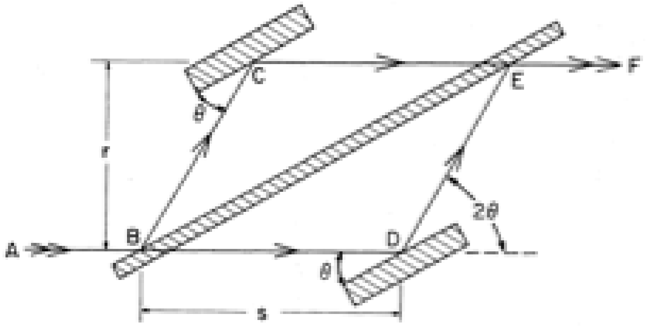


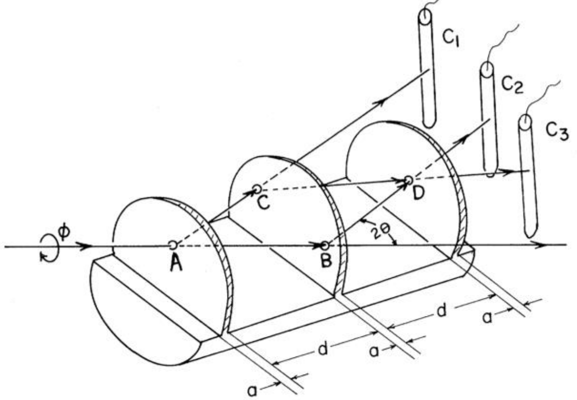
Fig. 2. Observed intensity oscillations of the 0- and H-beam as a function of the difference of the magnetic field action on beam I and II ($\Delta\int B ds = \int B_z ds$ (path I) $- \int B_z ds$ (path II).

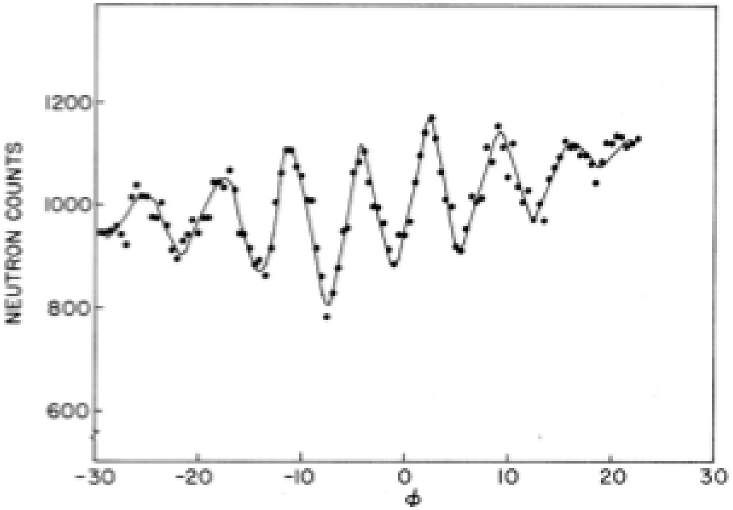
波動関数への重力の影響 (COW実験)

- 2つに別れた波動関数は重力とどの用に相互作用するのか？
- 中性子干渉計を回転させることで重力ポテンシャルの影響を測定した。
  - 3人の著者の名前の頭文字からCOW実験と呼ばれている。
  - 波動関数が上と下に分かれる時は位相差がつく。
- 結果、普通にgに対する位相差がついた。
  - ちょっとズレたが、Si結晶の厚みとたわみで説明できそう、というのが後世の理解。



A. W. Overhauser and R. Colella
“Experimental Test of Gravitationally Induced Quantum Interference”
Phys. Rev. Lett. 33, 1237 (1974)
https://doi.org/10.1103/PhysRevLett.33.1237





R. Colella and A. W. Overhauser S. A. Werner, “Observation of Gravitationally Induced Quantum Interference”
Phys. Rev. Lett. 33, 1237 (1974) https://doi.org/10.1103/PhysRevLett.33.1237

不確定性原理
ハイゼンベルグと小澤の不等式

- 量子力学では、例えば位置 (q)と運動量 (p)は同時に測定できない(不確定性原理)。
- ハイゼンベルグによって提唱された不等式

$$\epsilon_q \eta_p \geq \frac{\hbar}{2}$$

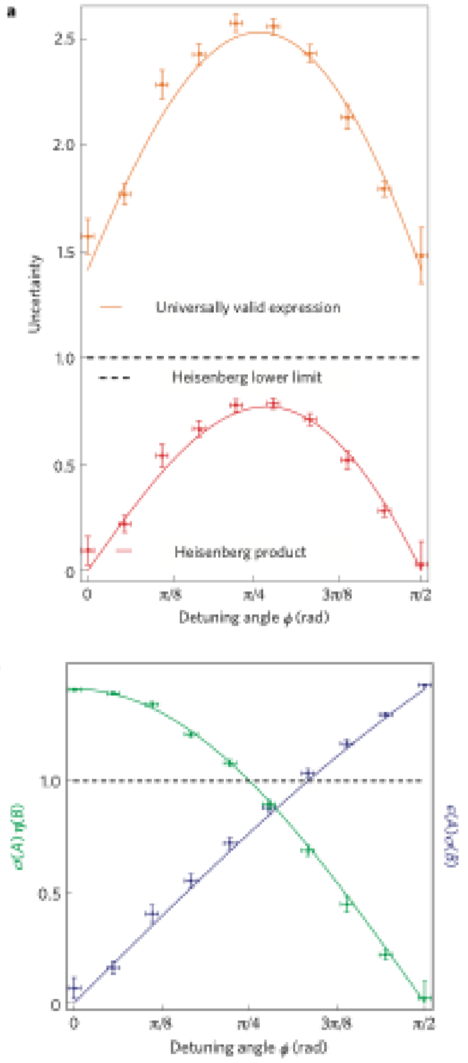
ϵ_q: 測定誤差　　η_p: 観測による擾乱

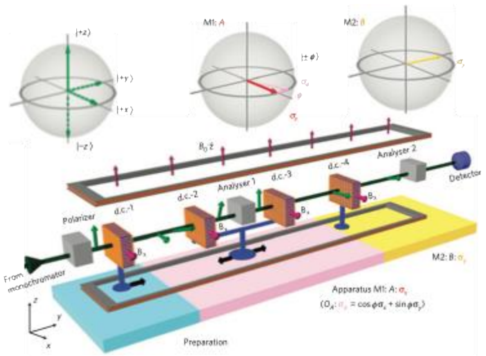
- しかし、きちんと計算すると別の形になるはず(小澤の不等式)。
  - ハイゼンベルグ表記は量子ゆらぎと擾乱を混同しているので正しくない。

$$\epsilon_q \eta_p + \sigma_q \eta_p + \sigma_p \epsilon_q \geq \frac{\hbar}{2}$$

M. Ozawa, Phys. Rev. A 67, 042105 (2003) https://doi.org/10.1103/PhysRevA.67.042105

- 中性子スピンを向きを精密に制御、測定しその誤差、擾乱を観測。
- 結果、ハイゼンベルグ限界を破った。





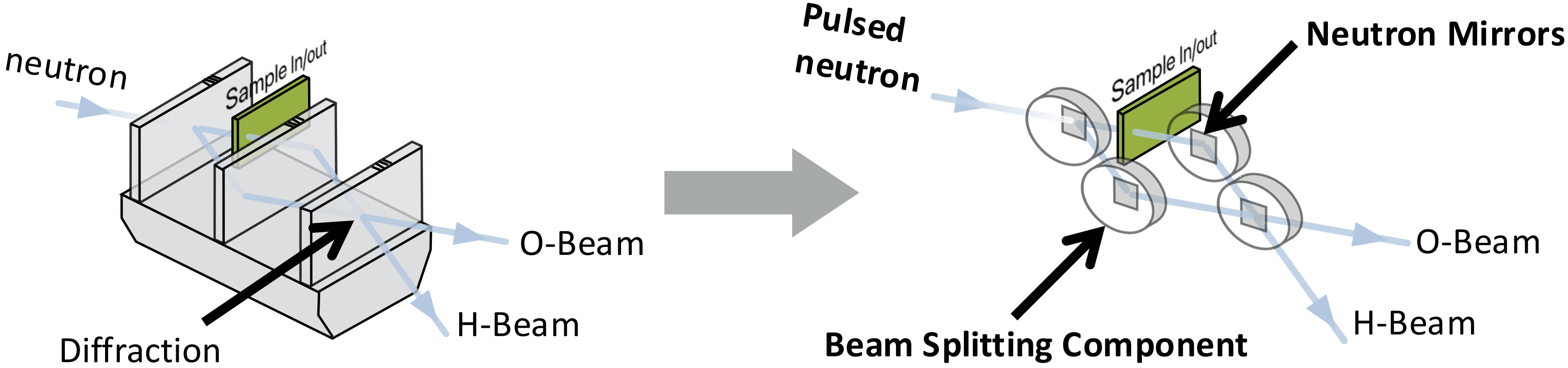
J. Erhart et al., *Nature Phys* **8**, 185–189 (2012). https://doi.org/10.1038/nphys2194

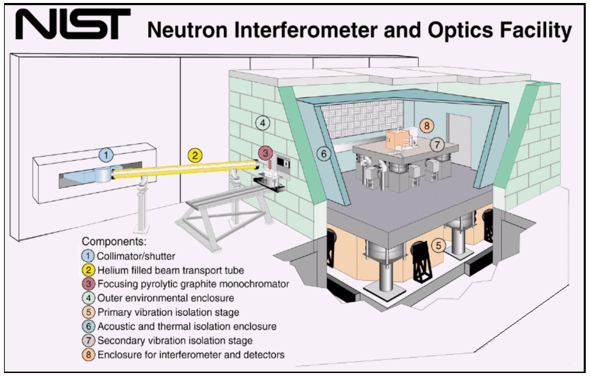
Concept of New-Type Neutron Interferometer

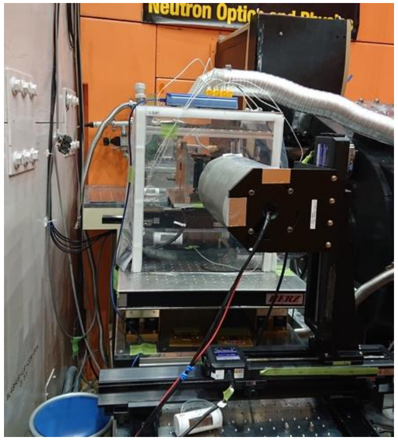
The neutron wave should be handled in the precision of ~few nm

To achieve high sensitivity interferometers, we need:

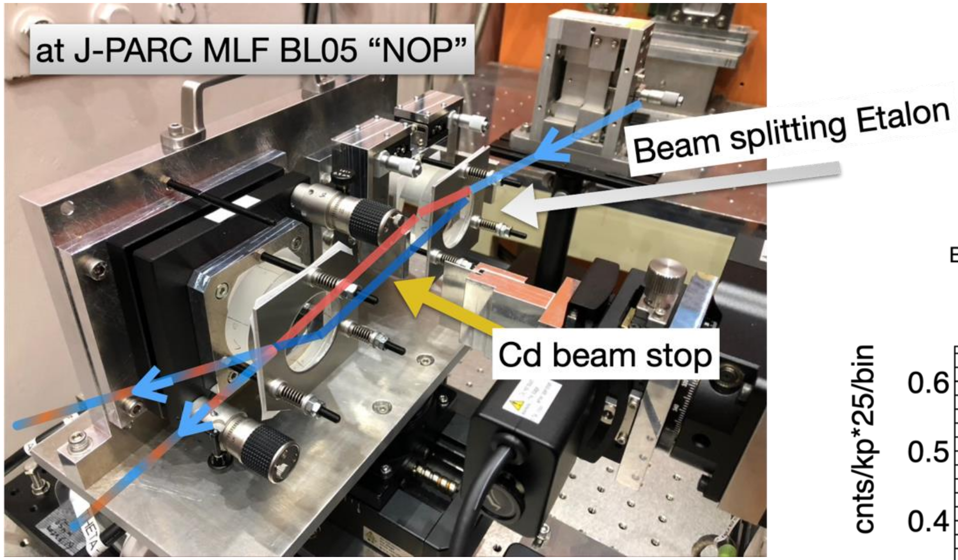
- **Neutron Multilayer Mirrors** to use arbitrary wavelength
- **Beam Splitting Component** to enable large interaction length
- **Alignment Technique** of each mirror to satisfy a coherence length
- **Pulsed Neutron Source** to observe the wavelength dependence of fringe

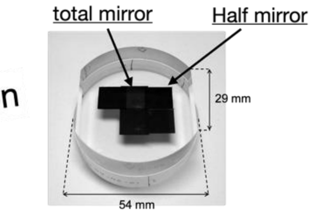






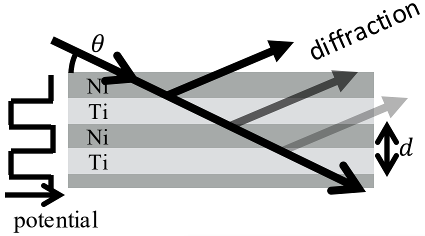
Multi-layer type neutron interferometer

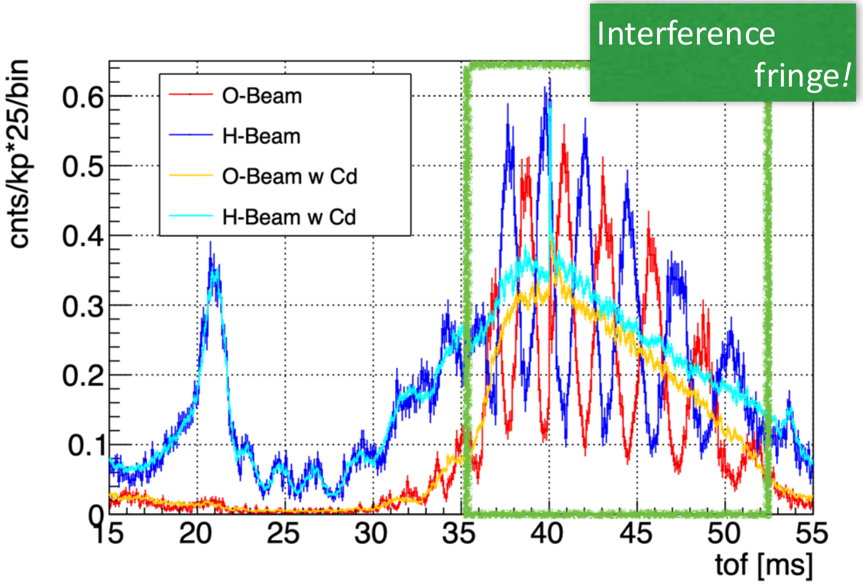




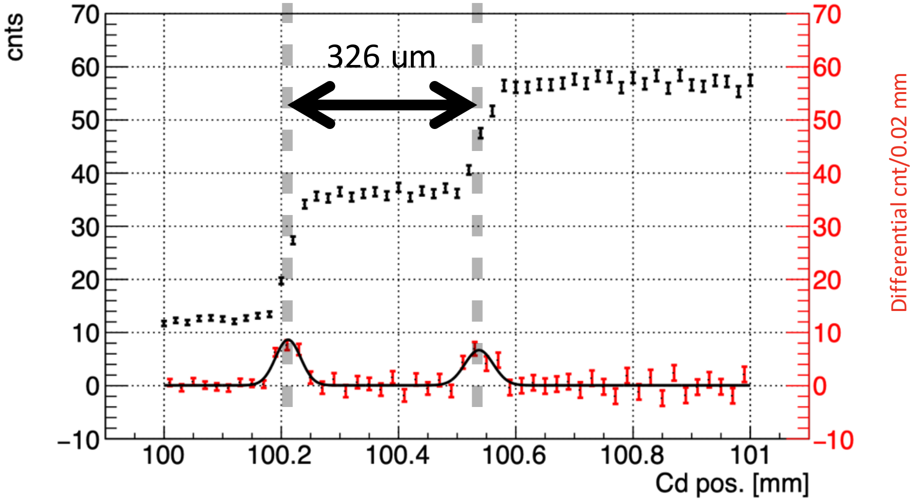
Beam Splitting Etalon (BSE)

Bragg Law: $\lambda = 2d\sin\theta$





Beam scan with Cd beam stop

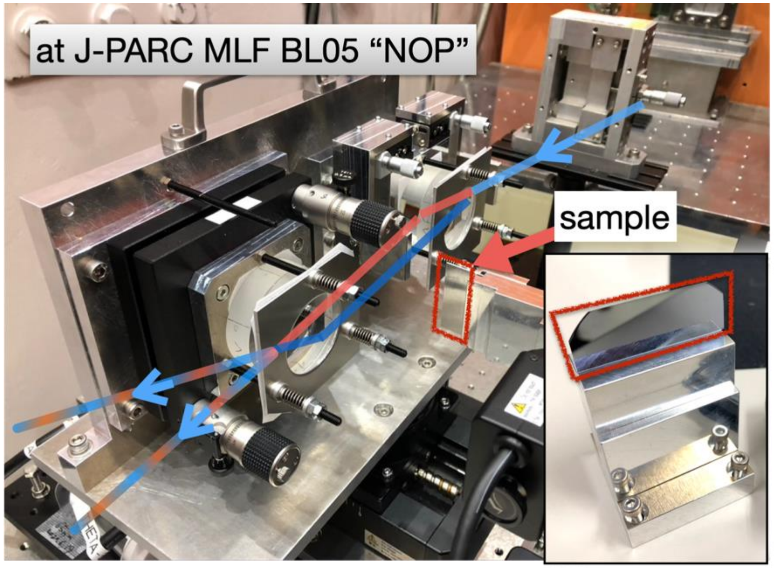


- Two beam paths are completely separated
- Oscillation observed in TOF (visibility of 60%)
- Single path doesn't make oscillation

We successfully demonstrated the neutron interferometer

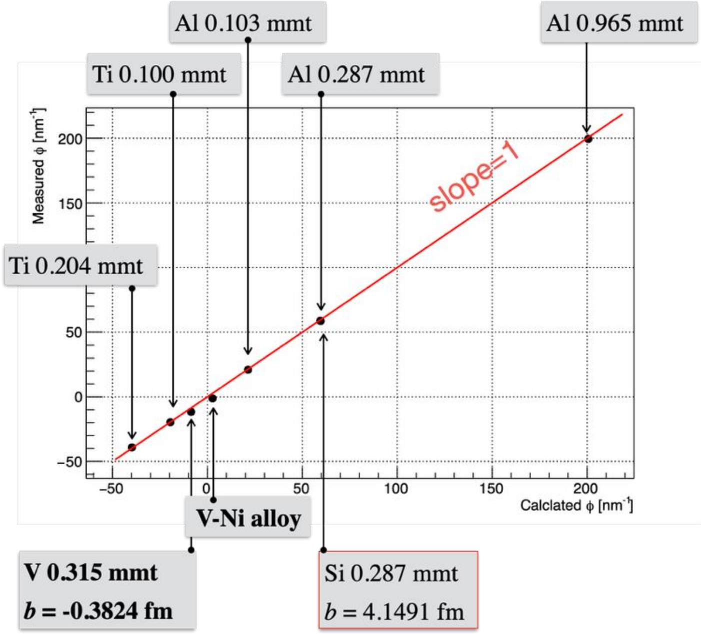
T. Fujiie *et al.*, *Phys. Rev. Lett.* 132, 023402 (2024).

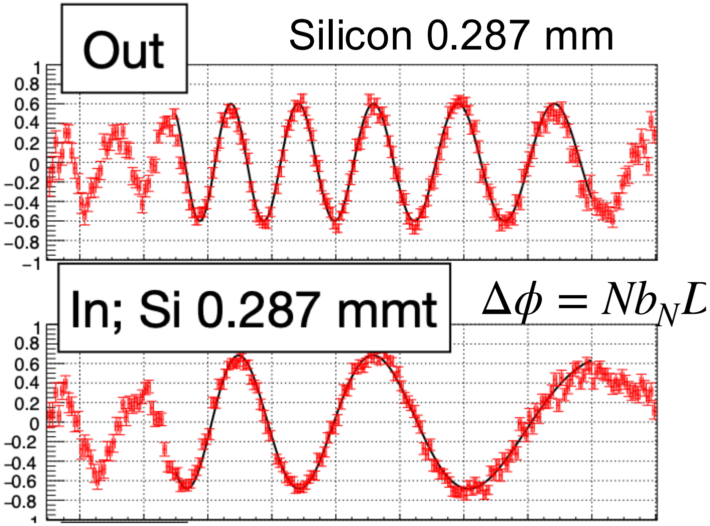
Measurement of coherent scattering length



Inserting material in one path shifts the phase by its scattering length.

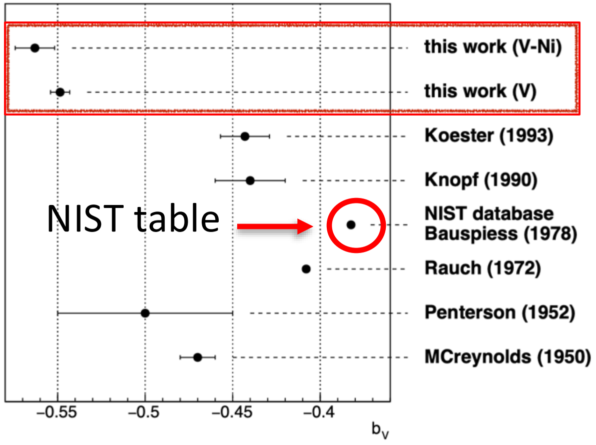
Scattering length measured and reference





$$\Delta\phi = N b_N L$$

Coherent scattering length of V



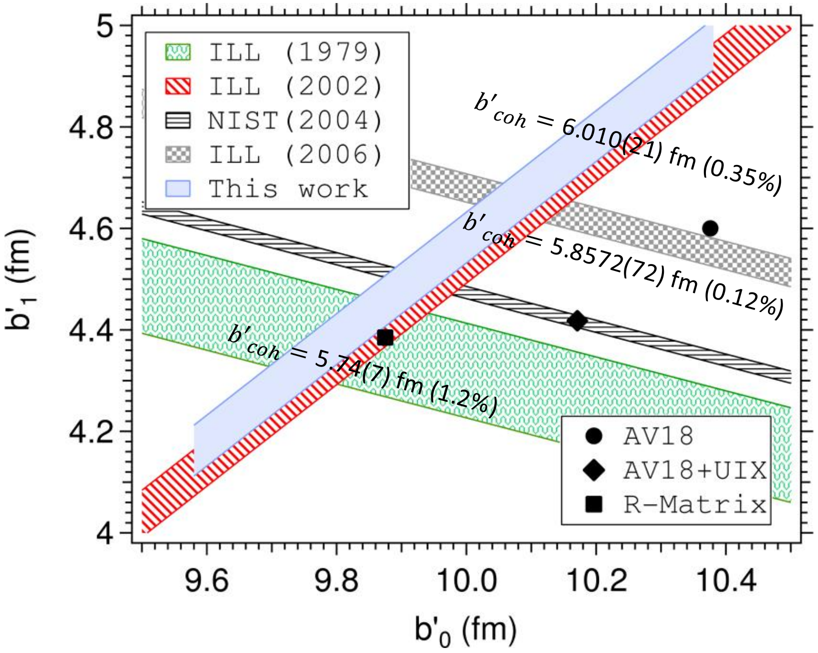
Scattering length of V was 45% different from the NIST recommended value.

Further investigation is required.

T. Fujiie *et al.*, *Phys. Rev. Lett.* 132, 023402 (2024).

少数多体系計算のための ^{3}He中性子散乱長測定

M. G. Huber *et al. Phys. Rev. C* 90, 06400470 (2014)



Real part Spin triplet Spin singlet

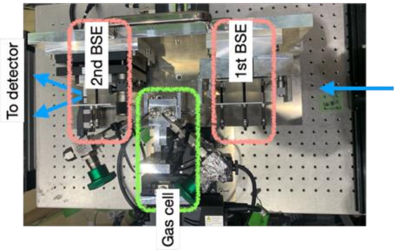
$$b'_{coh} = \frac{I+1}{2I+1} b'_1 + \frac{I}{2I+1} b'_0$$

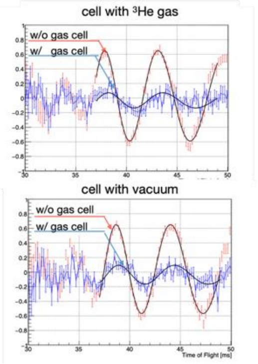
Absolute phase difference

$$b'_{inc} = \frac{\sqrt{I(I+1)}}{2I+1} (b'_1 - b'_0)$$

Spin-dependent phase difference

- ^{3}Heや^{4}Heくらいなら多体系の原子核計算から散乱長の計算が可能。
  - モデルごとに数%の差がある。
- 精度良い実験はモデルの選別ができるが、系統誤差以上に実験結果がばらついているのが現状
  - 高圧ガスセルで1ヶ月くらいの実験が必要
  - 結果20年アップデートされず。
- J-PARCで実験準備中。





名古屋大 南部

COW実験@J-PARC

- 干渉計で得られる干渉縞の位相差 Δϕ は相互作用差 ΔE の関数で書ける。
- 異なる高さの2経路を通過した中性子は、異なる地球重力のポテンシャルを受けるので、干渉計を角度αだけ回転させることで、中性子に及ぼされる地球重力のポテンシャルを測定できる。

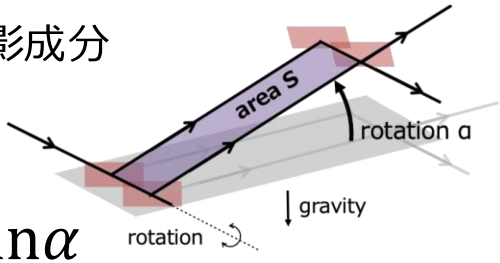
位相差

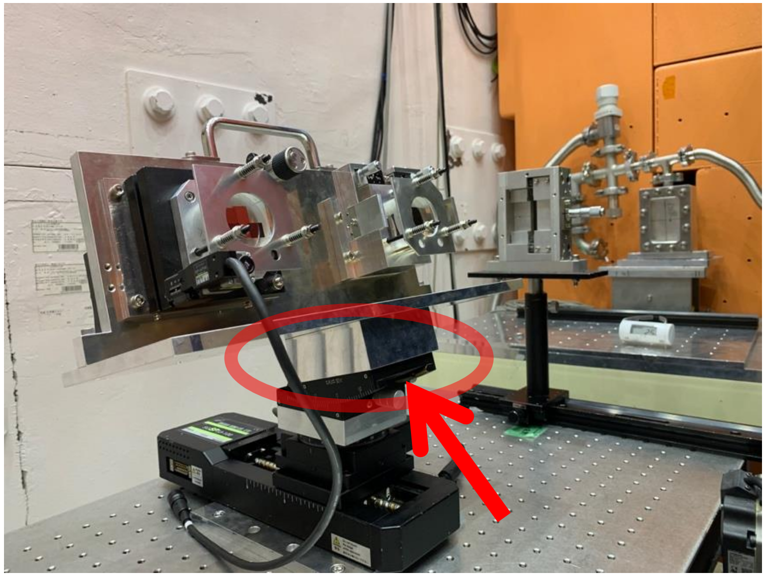
$$\Delta\phi = 2\pi \frac{m\lambda L}{h^2} \Delta E$$

S: 2経路が囲む面積の射影成分

地球重力の場合

$$\Delta\phi = 2\pi\lambda \frac{m^2}{h^2} gS\sin\alpha$$





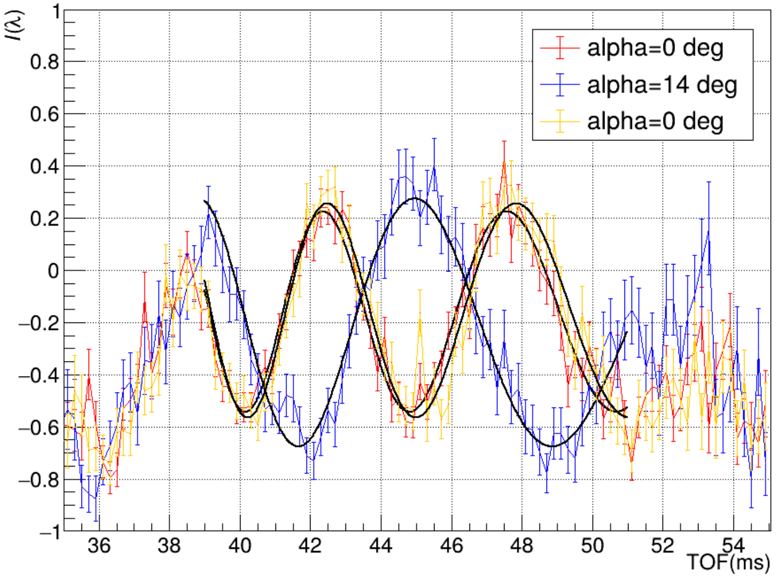
導入したゴニオステージ

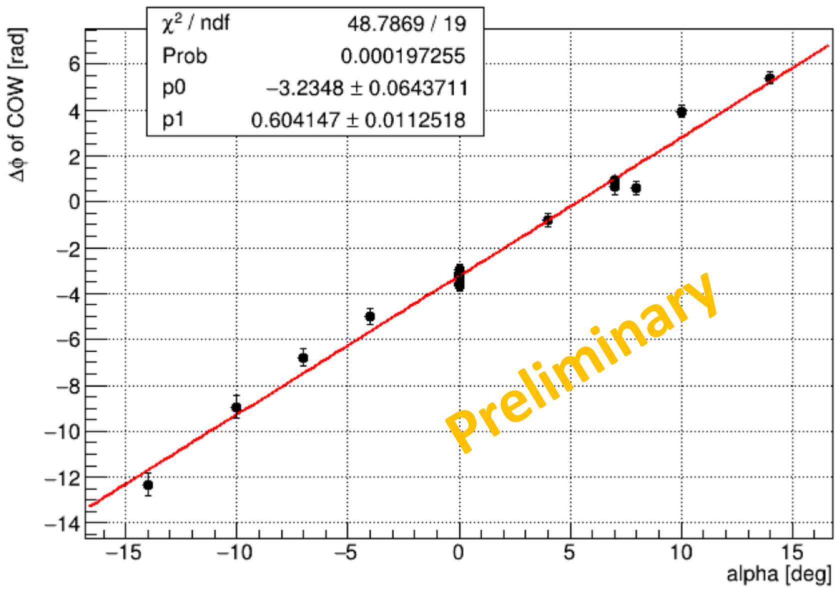
藤家、原田、中村、（立教大）、南部（名大）

干渉計回転の結果

- 干渉計ごとゴニオステージで回転させた（最大角度14 deg）ところ、位相がシフトした。
- ゴニオをもとの位置に戻すと、位相差も戻る。

- 回転角度α毎の位相差を導出、回転角と位相の関係が得られた。
  - ➢ 傾きの評価がCOW実験に相当

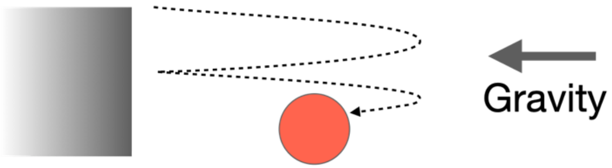


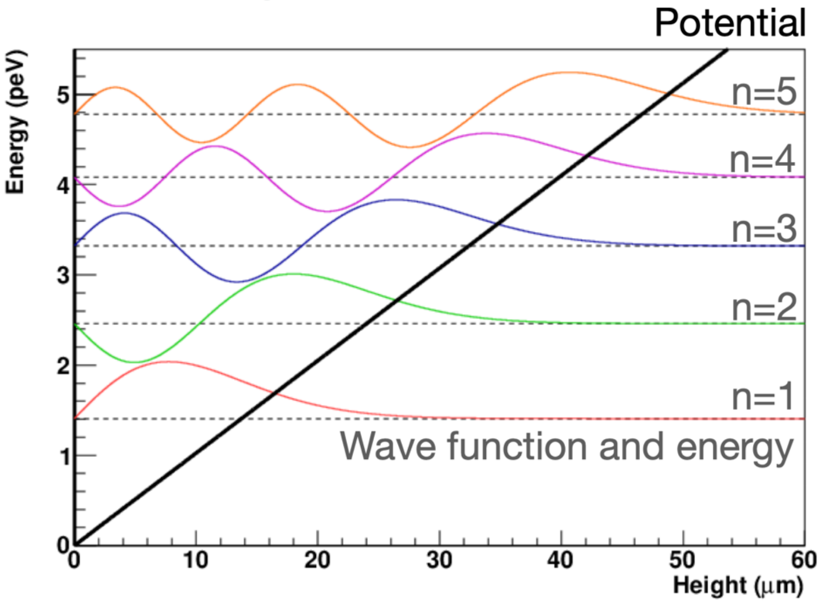


立教大藤家氏提供

重力場における中性子量子化の測定

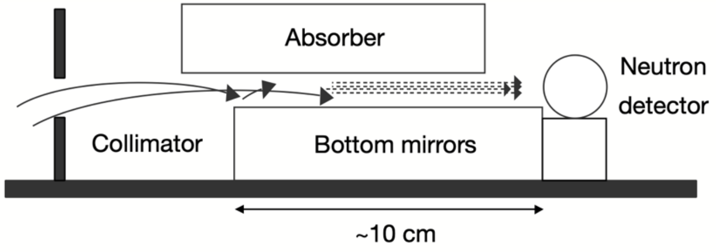
Is Gravity Quantum?
Gravitational bound states of neutrons



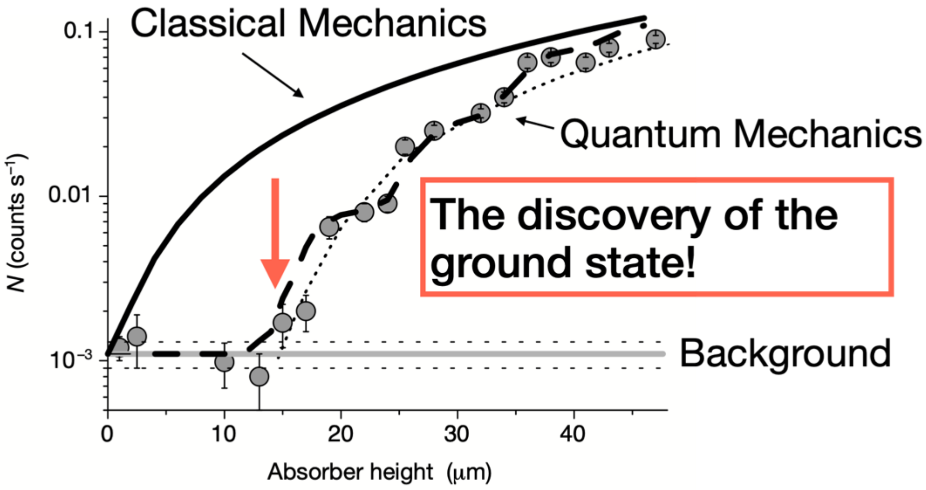


Extremely slow (~ 7 m/s) neutrons (Ultra Cold Neutrons) are bound by Earth's gravity and a surface potential. The typical size and energies are ~**10 μm** and ~**1 peV**.

Absorber/Scatterer = **State selector**



Eigenstates higher than the ceiling are removed.



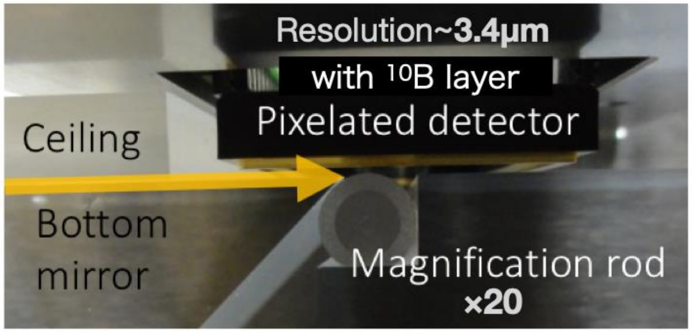
The discovery of the ground state!

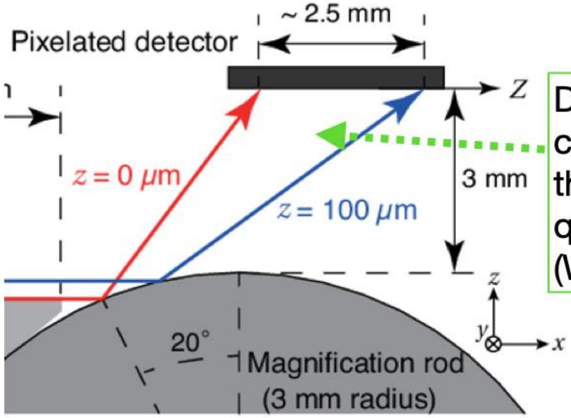
V. V. Nesvizhevsky, et al., Nature 415 (2002) 297-299.

Spatial Magnification of Quantum States (Tokyo)

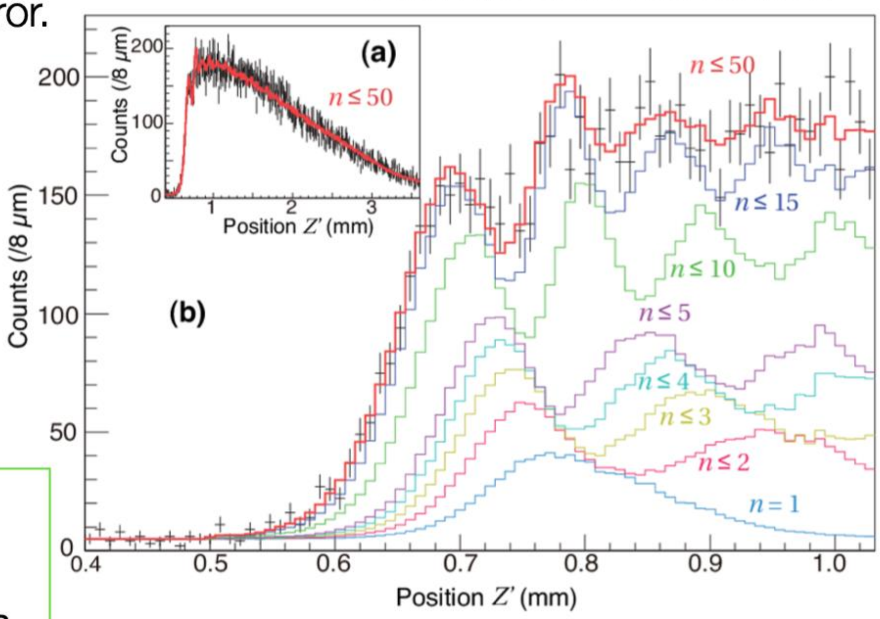
GI, et al., Phys. Rev. Lett. 112 071101 (2014).

Magnifying the neutron image by a convex mirror.





Dispersion is calculated by using the phase space of quantum mechanics. (Wigner function)



Resolution is equivalent to **0.7 μm**, but the systematic error disturbs the search for short-range gravity.

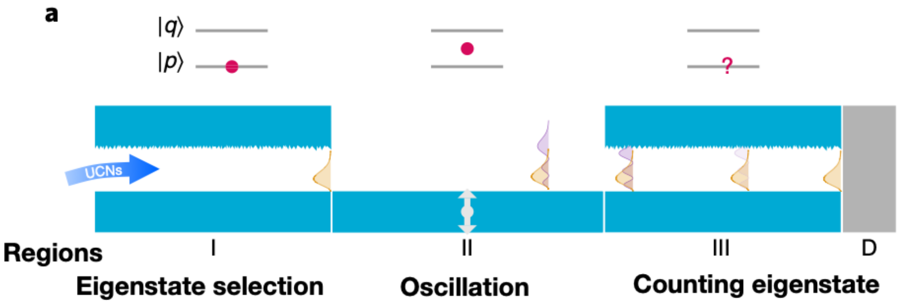
→ Our group has developed a detector with sub-micron resolution without magnification.

Slide from 市川豪(KEK)

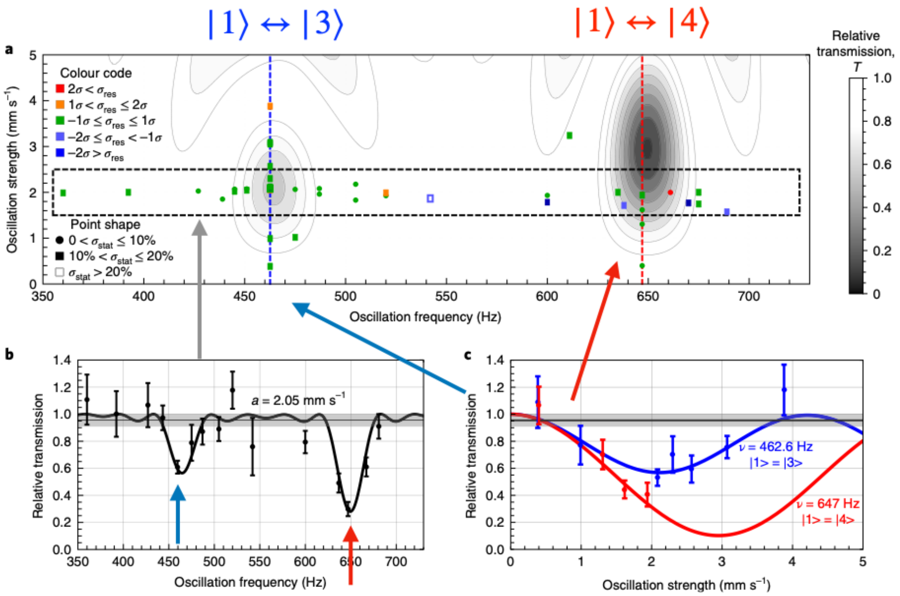
qBOUNCE Experiment

T. Jenke, et al., Nature Phys. 7 468-472 (2011).
T. Jenke, et al., Phys. Rev. Lett. 112, 151105 (2014).
G. Cronenberg, et al., Nature Phys. 14 1022-1026 (2018).

Inducing **Rabi oscillations** by the vibrating bottom mirror.



Regions
Eigenstate selection **Oscillation** **Counting eigenstate**



UCNs oscillate between eigenstates at resonant frequency.
Raised neutrons are removed by the ceiling.

Energy measurement with ~3×10^{-4} accuracy

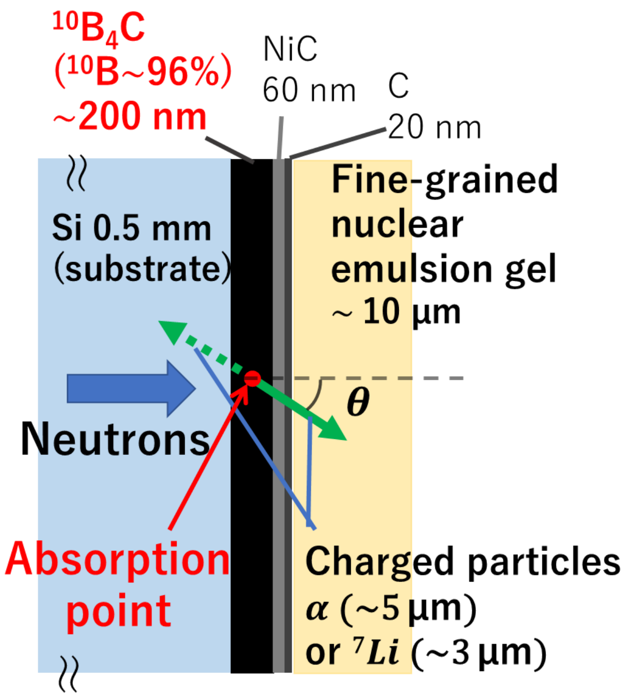
$$\Delta E^{\rm theor}_{3\to1} = 1.915\,{\rm peV} \qquad \Delta E^{\rm theor}_{4\to1} = 2.676\,{\rm peV}$$

$$\Delta E^{\rm exp}_{3\to1} = 1.922 \pm 0.005\,{\rm peV} \qquad \Delta E^{\rm exp}_{4\to1} = 2.687 \pm 0.007\,{\rm peV}$$

Slide from 市川豪(KEK)

High spatial resolution emulsion for ultracold neutrons

Structure of the detector (cross section)



Sputtered at KURRI

Estimated Resolution < 100 nm ($\theta \leq 0.9$ rad)

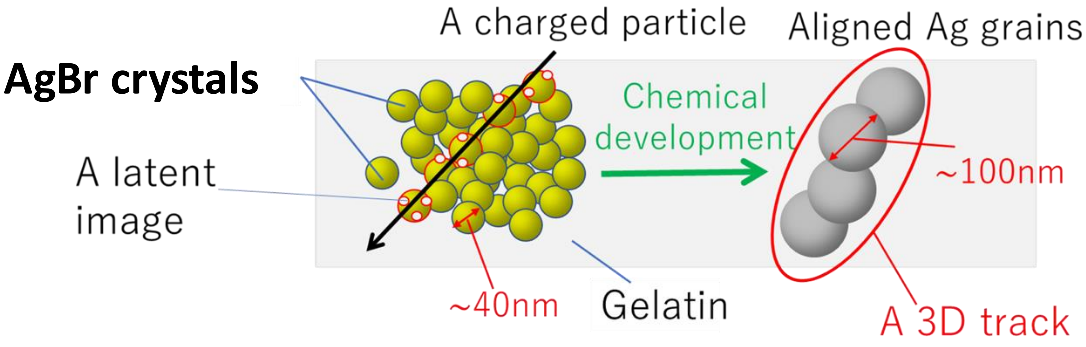
→1~2 order higher than existing detectors

Absorption efficiency ~41%

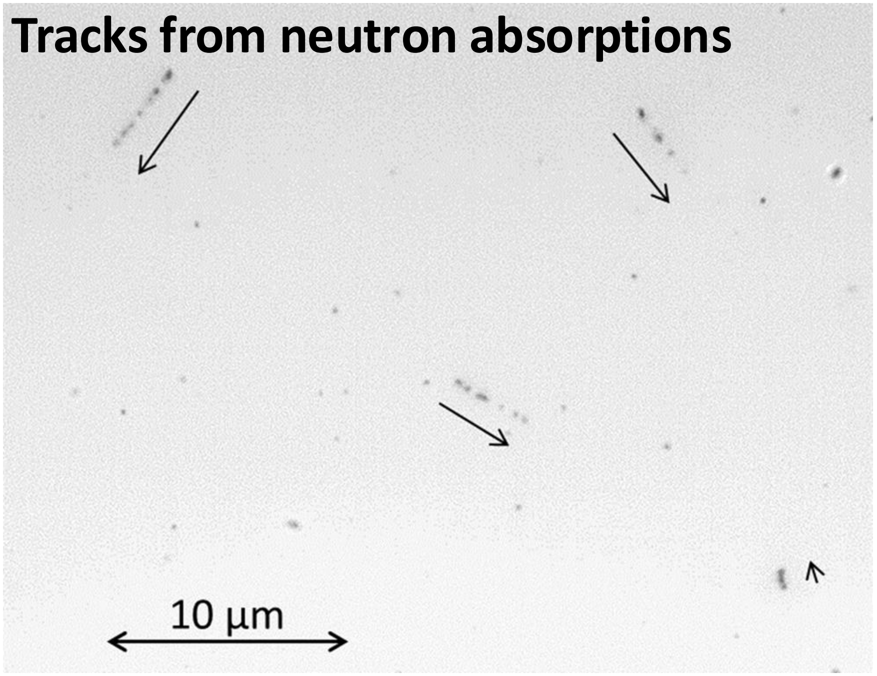
(velocity of neutrons ~10 m/s)

Naganawa et al., Eur. Phys. J. C (2018) 78,959

Principle of track formation

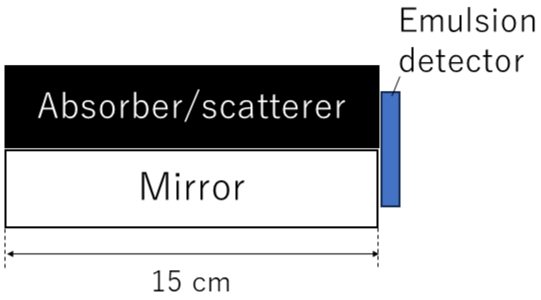


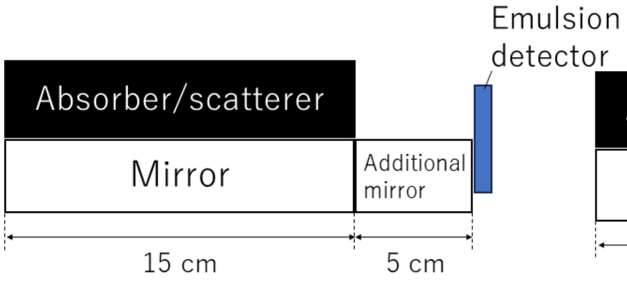
- **Fine-grained nuclear emulsion gel (Nagoya Univ.)**
- **Especially high resolution**
- **Strong against γ –ray background**

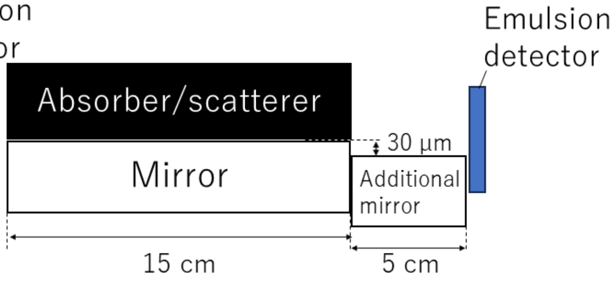


Measurements of the quantum bound states in the earth gravity

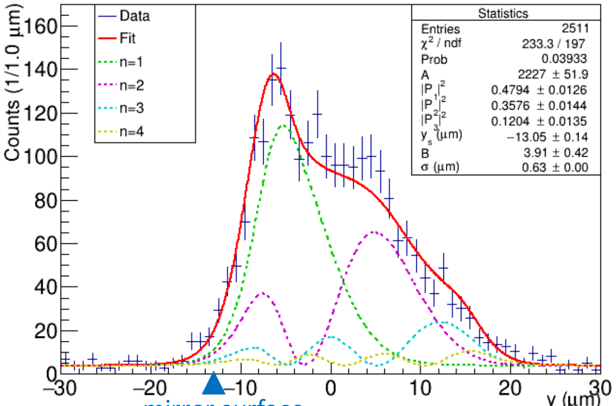
Measurements with the emulsion detector has been done at the reactor of ILL.
Three different conditions were measured.





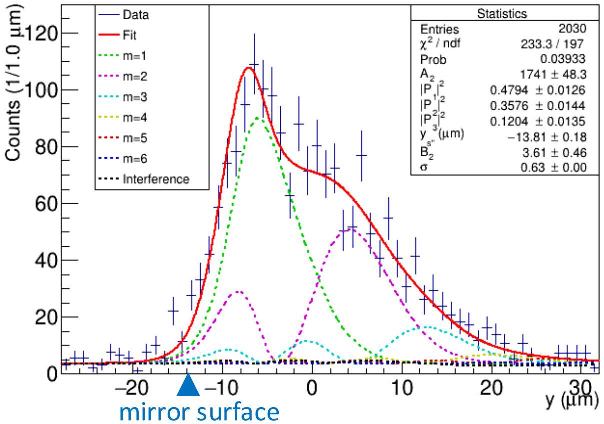


Setup1



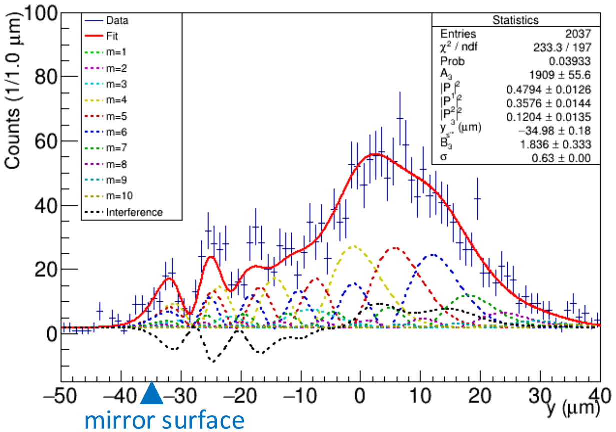
mirror surface

Setup2



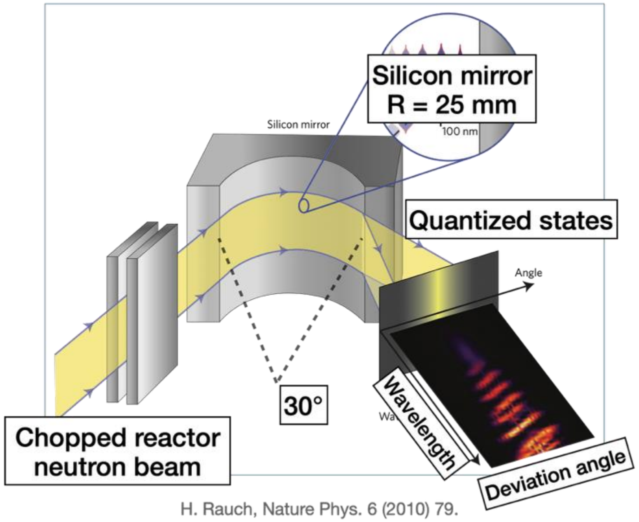
mirror surface

Setup3

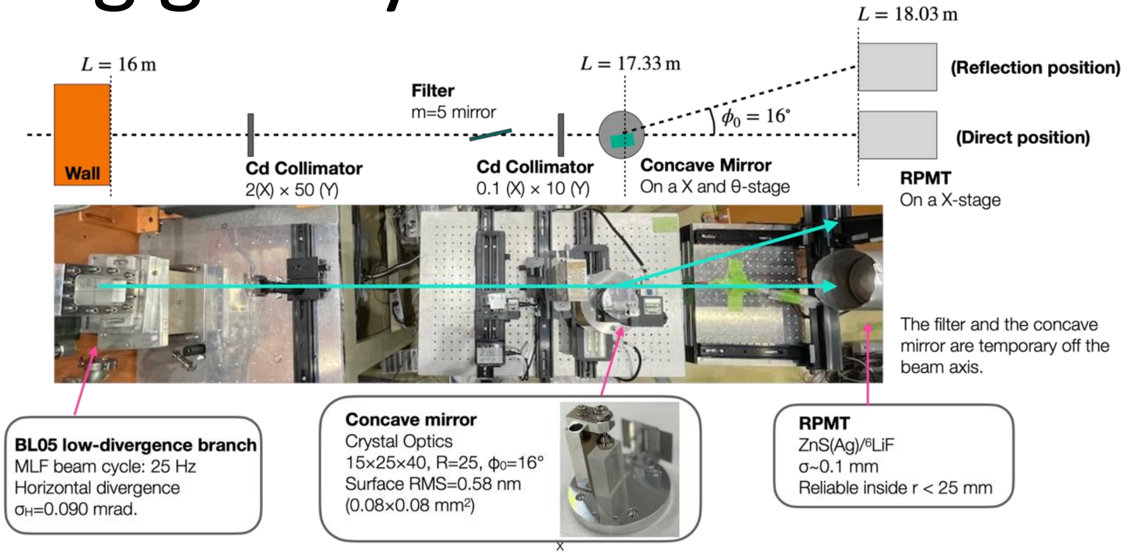


mirror surface

Neutron Whispering gallery



H. Rauch, Nature Phys. 6 (2010) 79.



The filter and the concave mirror are temporary off the beam axis.

BL05 low-divergence branch
MLF beam cycle: 25 Hz
Horizontal divergence
σ_H=0.090 mrad.

Concave mirror
Crystal Optics
15×25×40, R=25, ϕ_0=16°
Surface RMS=0.58 nm
(0.08×0.08 mm²)

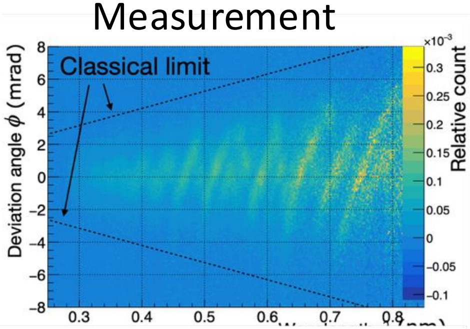
RPMT
ZnS(Ag)/^{6}LiF
σ~0.1 mm
Reliable inside r < 25 mm

Neutrons bouncing on a concave mirror form bound states near the surface due to centrifugal force, called “Neutron whispering gallery”.
[V. V. Nesvizhevsky et al., Nat. Phys. 6, 114-117 (2010)].

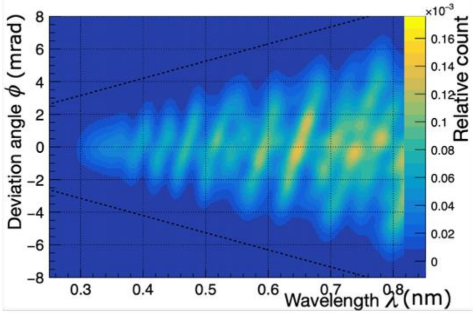
For mirror curvature of *R*=25 mm and neutron of v=1000 m/s corresponds to $a = 4 \times 10^6\ g$ and typical height of the quantum state of 40 nm.

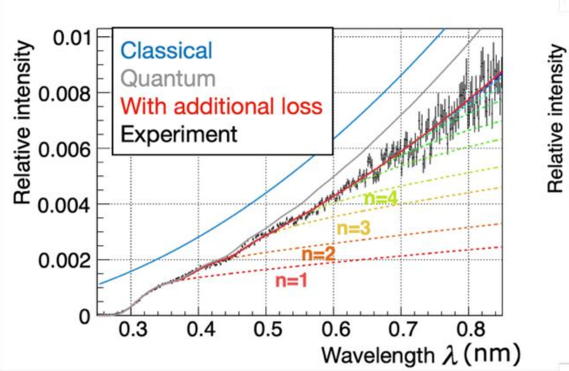
The experiment at J-PARC well agreed with the calculation from the Schrödinger equation.

Measurement

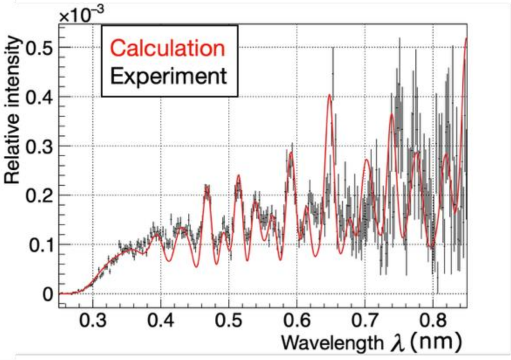


Calculation





Wavelength distributions.



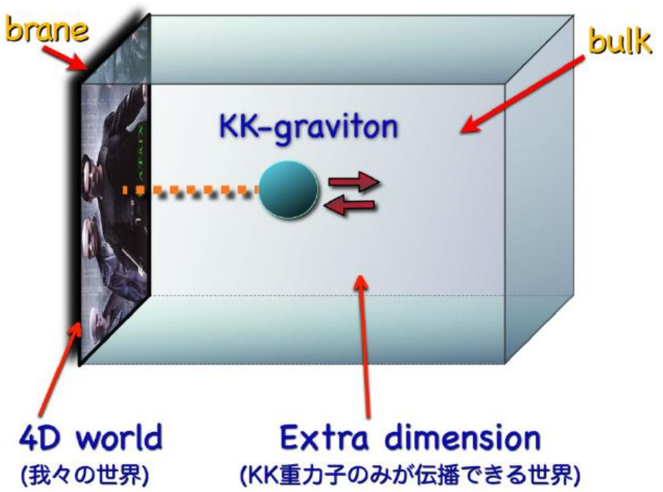
Wavelength distributions of $\phi \leq 0.1$ mrad.

短距離重力探索

Why is gravity so weak?

Currently discovered interactions are

• Strong	~ 1
• Electromagnetic	~ 10^{-2}
• Weak	~ 10^{-5}
• Gravity	~ 10^{-40}



Large extra dimension model
*This figure is for illustrative purposes.
LOI-BL05 (2005)

Comparing other 3 interactions, the gravity is too small. It is called "Hierarchy problem".

To solve the problem, Large Extra Dimension model was proposed.
The model expects that

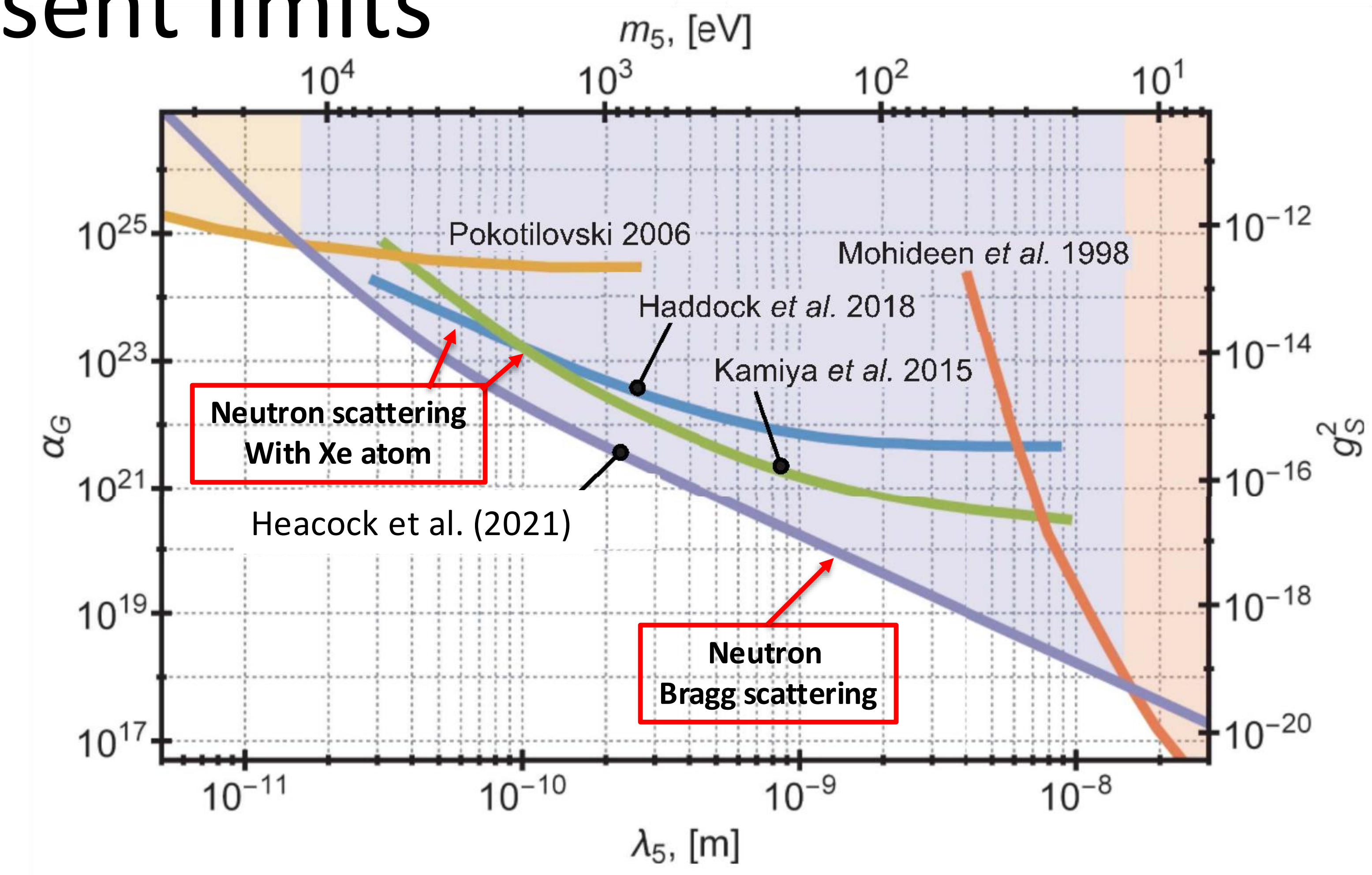
- The gravity is week because the gravitational force is escaping to the other dimensions.
- In that case, gravity will be strong in short range.

$$\boxed{V(r) = -G_N \frac{mM}{r}\left(1 + \alpha e^{-r/\lambda}\right)}$$

Nima Arkani-Hamed, Savas Dimopoulos and Gia Dvali
Physics Letters B 429.3 (1998): 263-272.

Present limits

B. Heacock *et al.*, Science, 373, 6560, 1239-1243 (2021).



Neutron scattering With Xe atom

Heacock et al. (2021)

Neutron Bragg scattering

The limits is determined by experiments using neutrons.

Why neutron?

Background of Casimir force due to polarization of atoms

Polarizability of atom : ~10^{-30} m^3

Polarizability of neutron :~10^{-48} m^3

Experimental Principle

Short range Yukawa-force expects small angle scattering.

$$a_G F_G(\theta) = 2\alpha G M m_n \frac{1}{\underline{\frac{1}{m_n c^2}\left(\frac{\hbar c}{\lambda}\right)^2} + \underline{8E_n \sin^2\frac{\theta}{2}}}$$

↑

Scattering amplitude
of short range gravity

↑

Terms added by
short range gravity
λ : Range of
short range gravity

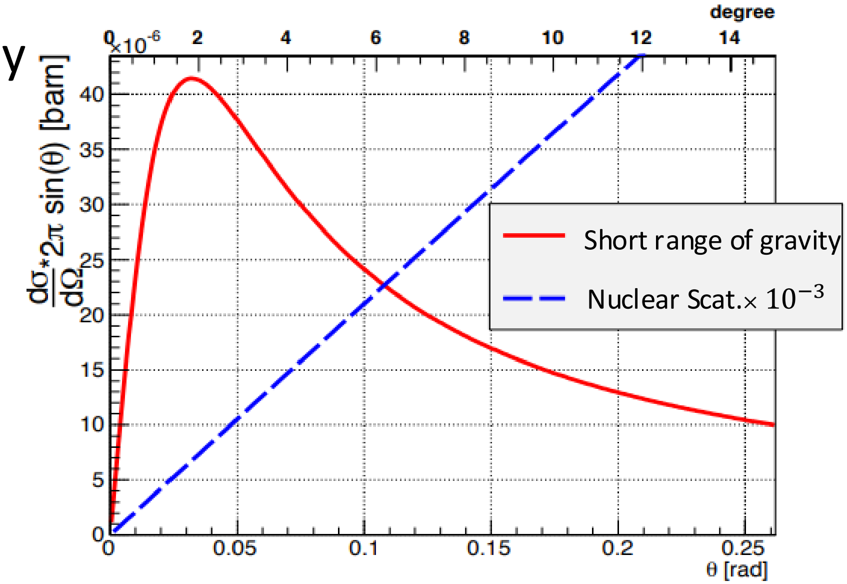
↑

Angle dependence of
forward scattering
E_n: Neutron energy
θ : Scattering angle

Differential cross section of short range gravity is evaluated with Born approximation

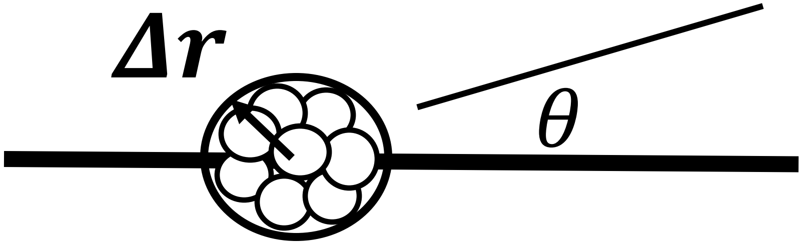
$$\frac{d\sigma}{d\Omega} = (b_N)^2 + 2\left(b_N \cdot a_G F_G(\theta)\right) + \left(a_G F_G(\theta)\right)^2$$

- Nuclear scattering → Isotropic
- Short range gravity → strong angular dependence in the forward direction



Scattering of Nano-particles

Many atoms are scattered together



Scatter radius

$$\Delta r = \frac{1}{q} \propto \frac{\Lambda}{\theta}$$

Momentum transfer

- Λ : Neutron wave length $(0.1 < \Lambda\,[\mathrm{nm}] < 1.0)$
- θ : Scattering angle

Optimal size of the target for λ ~ 100 nm ⇒ **Nano-Particle**

$$a_G F_G(\theta) = 2\alpha G M m_n \frac{1}{\frac{1}{m_n c^2}\left(\frac{\hbar c}{\lambda}\right)^2 + 8E_n \sin^2\frac{\theta}{2}}$$

The total mass of atoms contained in a nanoparticle

The heavier target mass, the better sensitivity

We are using nano particles of vanadium, which has smallest coherent scattering length

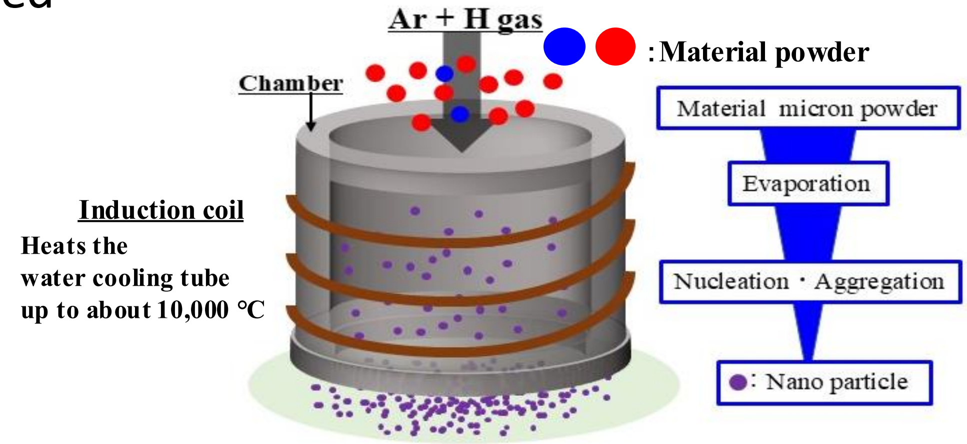
Fabrication of vanadium nano particle

- Vanadium nano particles are fabricated by RF thermal plasma method.
- Averaged radius is ~20 nm.
- Calculated the scattering length of the nanoparticle from elemental analysis is

$$b_{coh} = 0.719 \pm 0.23 \text{ fm}$$

cf. $b_{coh}(\text{V}) = -0.555 \pm 0.03 \text{ fm}$

RF thermal plasma method



Ar + H gas

🔵🔴 : Material powder

Chamber

Induction coil

Heats the water cooling tube up to about 10,000 ℃

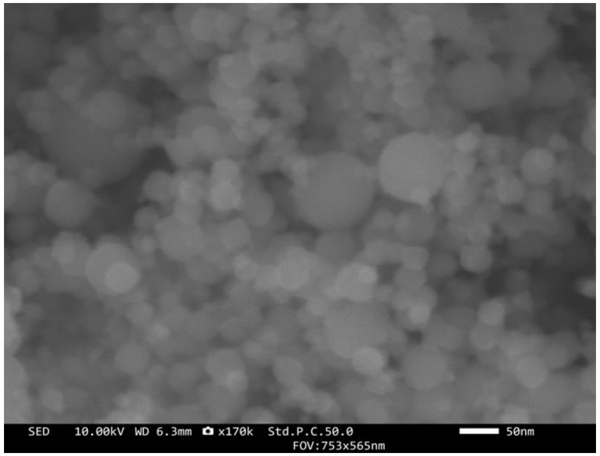
Material micron powder

Evaporation

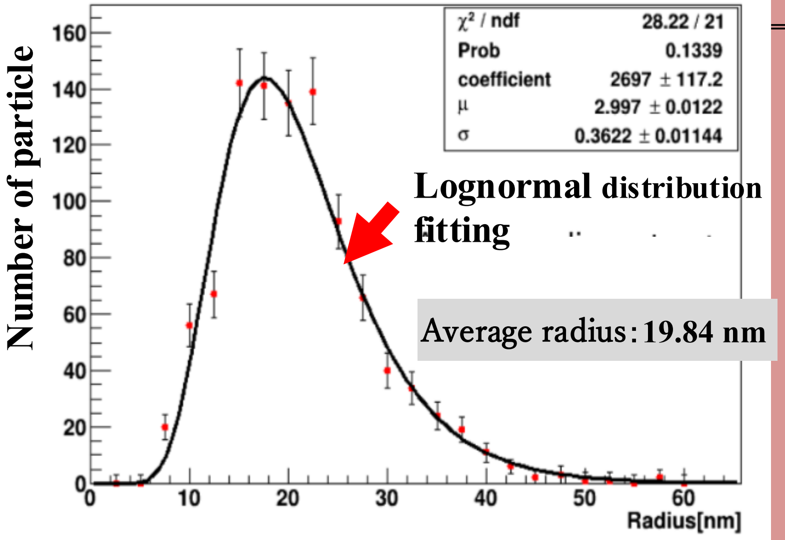
Nucleation・Aggregation

●: Nano particle

SEM image of V nanoparticle



Particle size distribution



χ^2 / ndf	28.22 / 21
Prob	0.1339
coefficient	2697 ± 117.2
μ	2.997 ± 0.0122
σ	0.3622 ± 0.01144

Lognormal distribution fitting

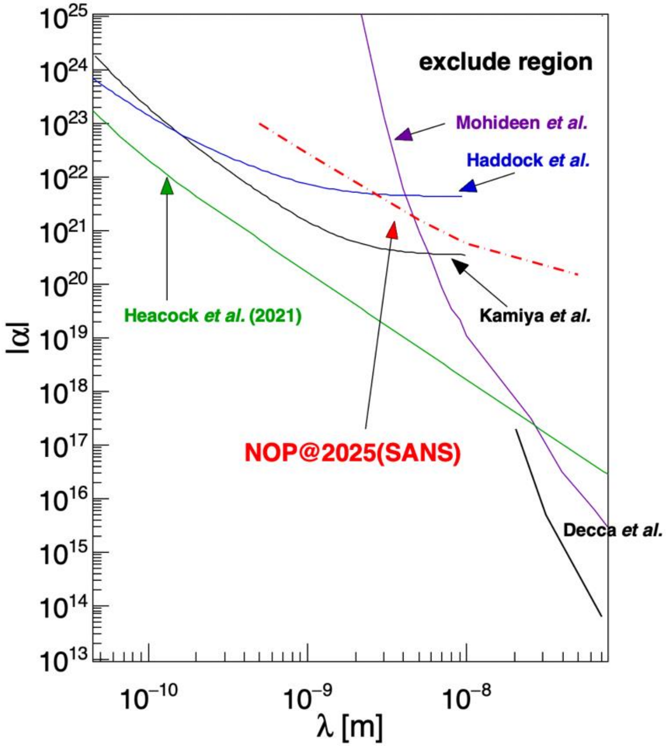
Average radius: **19.84 nm**

Elemental analysis

Element	b_{coh} [fm]	Mass%
C	6.6484	0.68
O	5.805	6.15
B	5.30	0.02
Mg	5.375	0.003
Al	3.449	0.009
Si	4.15071	0.04
Ca	4.70	0.004
Ti	-3.370	0.001
V	-0.555	92.71
Cr	3.635	0.03
Mn	-3.750	0.002
Fe	9.45	0.08
Zn	5.680	0.01

Excluded region of λ - α parameters at 95 % C.L.

Experimental limit



- **Compared to noble gas target**

it has high sensitivity in the λ_B region of several tens of nm.

However,,
mainly due to the systematic error of 9.3% in the effective density,
the upper limit is worse by about two orders of magnitude than the current world best limit

- **New experiment using nanoparticles**

This can be resolved by performing SAXS measurements with a SANS cell.
(Spring-8： photon energy = 40 KeV)

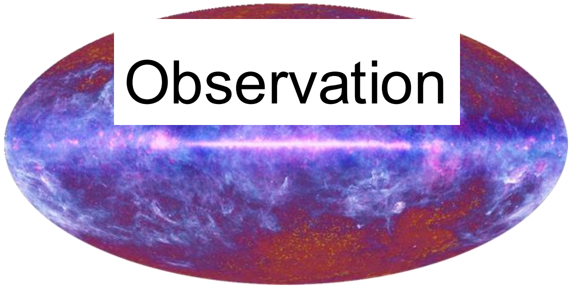
大阪大学廣本氏提供(博士論文から)

中性子を用いた
時間反転対称性の破れ探索

Why is there far more matter than antimatter?

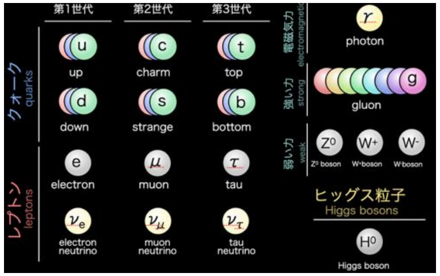
Sakharov conditions

- Baryon number violation
- Departure from thermal equilibrium
- **C- and CP-violation**


Observation

$n_{\mathrm{b}}/n_{\gamma} = (0.61 \pm 0.02) \times \mathbf{10^{-9}}$

Standard Model



$n_{\mathrm{b}}/n_{\gamma} = \mathbf{10^{-18}}$

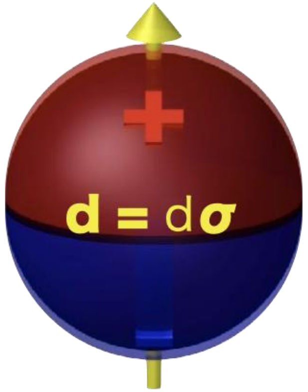
More CP-violation

(from unknown source) is required !

Since CP-violation = T-violation,
Permanent EDM search has High detection capability.

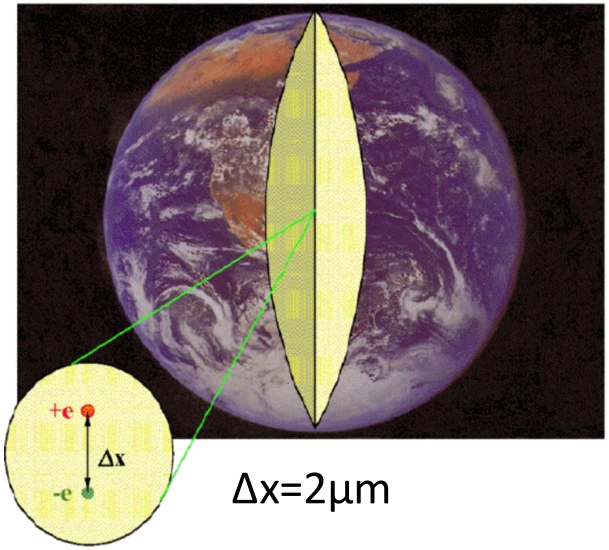
超冷中性子を用いた中性子電気双極子モーメント探索実験

中性子電気双極子モーメント
neutron EDM



- 静止した中性子に電気双極子モーメント(nEDM)があると、中性子がスピン軸に電荷分布を持つ。
  - この存在は時間反転対称性を破る。
- 中性子は(u,d,d)の3つのクォークから成る複合粒子。中性子の大きさ程度(~1 fm)くらいの電荷分布があってもいいようにも思うが、まだ見つかっていない。
  - 現在の上限は $1.8 \times 10^{-26} \mathrm{e} \cdot \mathrm{cm}$
  - これは中性子を地球サイズと思うとΔx=2μmに相当。
  - なにか不自然に思える。

“Strong CP Problem”



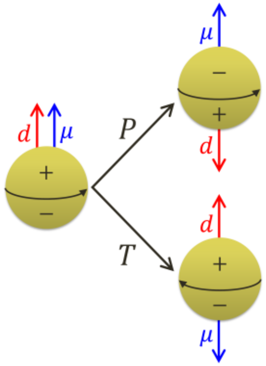
Δx=2μm

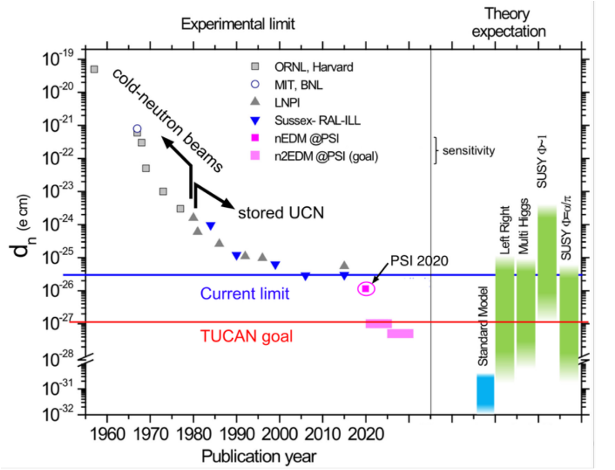
Search of the neutron EDM

- Current upper limit @PSI 2020
  - $d_n = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26} \mathrm{e} \cdot \mathrm{cm}$

    $\rightarrow |d_n| < 1.8 \times 10^{-26} \mathrm{e} \cdot \mathrm{cm} (90\% \mathrm{C.L})$

    C. Abel et al, Phys. Rev. Lett. 124, 081803 (2020)





Slide courtesy: B. Lauss, nEDM workshop 2017, based on NIMA 440, 471 (2000), Phys. Rev. D 92, 092003 (2015) AIP Conf. Proc. 1753, 060002 (2016)

- Test of Time reversal symmetry
  - Same as CP symmetry assuming CPT conservation
- Strong-CP problem
  - $d_n = -(1.5 \pm 0.7) \times 10^{-16} \bar{\theta}\ \mathrm{e} \cdot \mathrm{cm}$

    Jordy de Vries et al., Phys. Rev. D **104,** 055039 (2021)

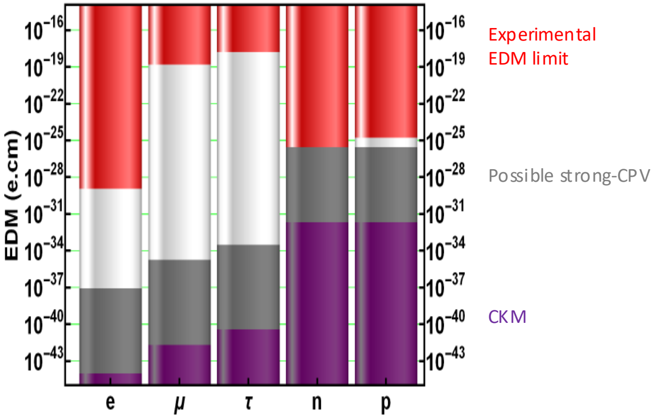
    -> $\theta \lesssim 10^{-10}$
- Constraint to theories
  - SUSY mass scale

$$d_n \sim \left(\frac{300\ \mathrm{GeV}}{M}\right)^2 \frac{\sin\phi}{\tan\beta} \times 10^{-24} e \cdot cm \Rightarrow \sim 2\ \mathrm{TeV}\ \text{(PSI limit)}$$

$$\Rightarrow \sim 10\ \mathrm{TeV}\ (|d_n| \sim 1 \times 10^{-27} \mathrm{e} \cdot \mathrm{cm})$$

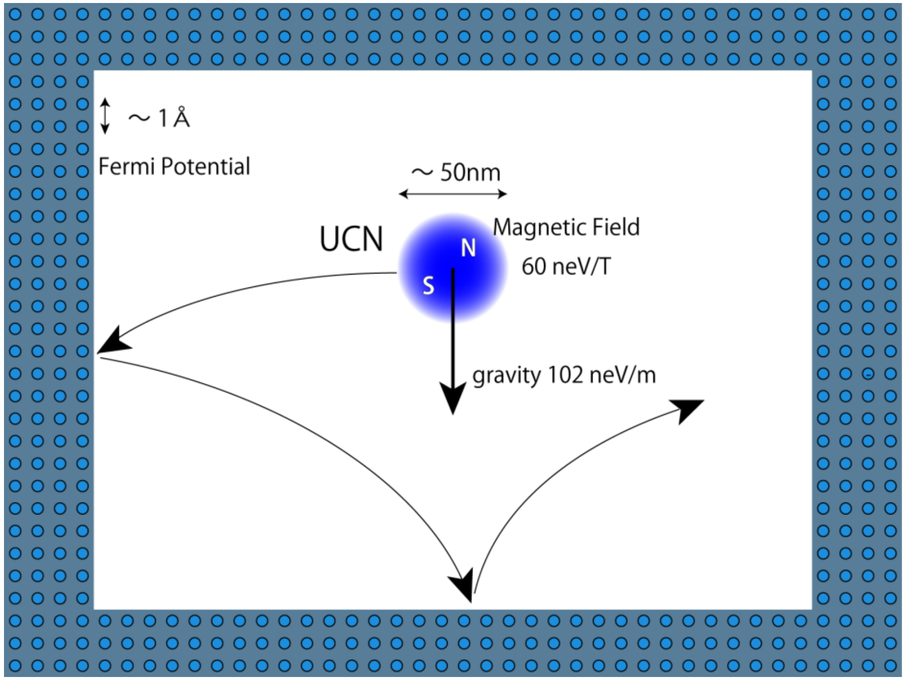
S. A. Abel and O. Lebedev, JHEP01(2006)133

Current EDM limits for Strong CP



K. Kirch and P. Schmidt-Wellenburg, EPJ Web of Conferences **234** (2020) 01007

Ultra Cold Neutron (UCN)



UCN can be confined ～ 100 sec

by material/gravity/magnetic potential

Ultra Cold Neutron

Energy ～ 100 neV

Velocity ～ 5 m/s

Wave length ～ 50 nm

Interaction

Gravity	100 neV/m
Magnetic field	60 neV/T

Weak interaction

β-decay n → p + e

Strong interaction

Fermi potential 252 neV (Ni)

atom distance : ~ Å

UCN feels average nuclear potential

Unique property

UCN can be measured for ～ 100 sec in trap

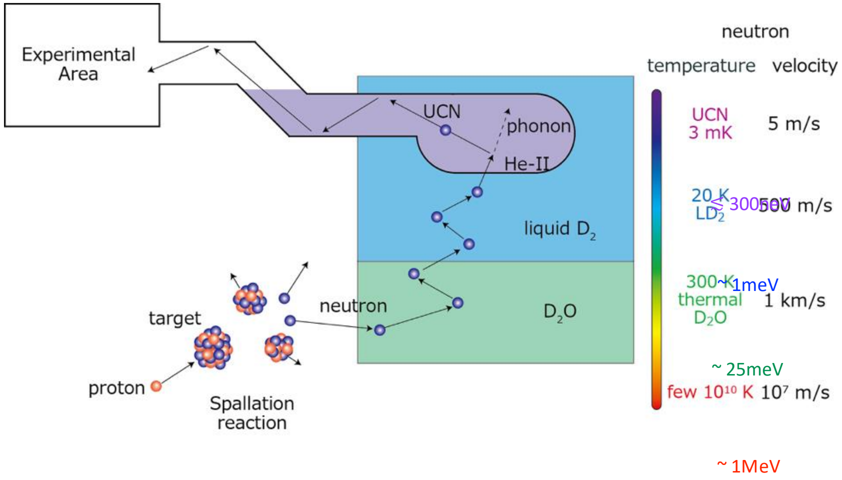
→ Use various experiments

nEDM, n lifetime, gravity ….

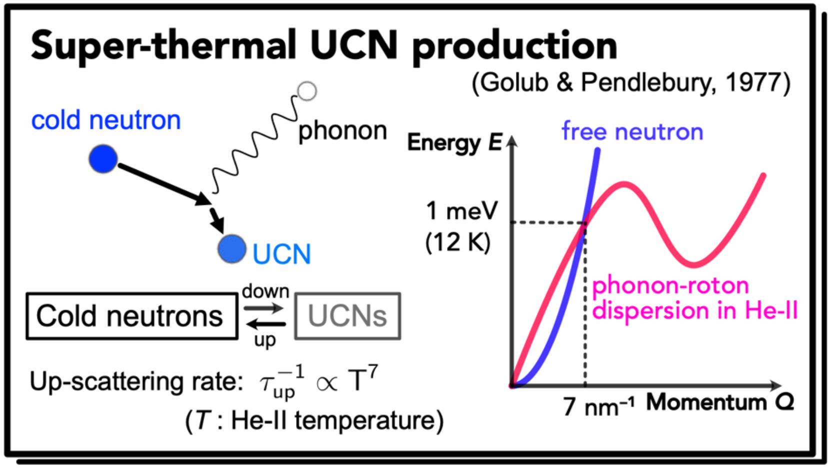
UCN production scheme in TUCAN Source (TRIUMF Ultra-Cold Advanced Neutron)

- Combination of
  - Spallation neutron source
  - Neutron moderator
  - Super-thermal UCN production with superfluid He (He-II)

Y. Masuda et al, PRL 108 (2012) 134801



- Spallation Neutron Source
  - Fast neutron produced by accelerator driven proton beam impingement on W target
  - 20kW proton beam line (BL1U at TRIUMF Meson hall)
- RT D_2O and 20K liquid deuterium (LD_2) moderator

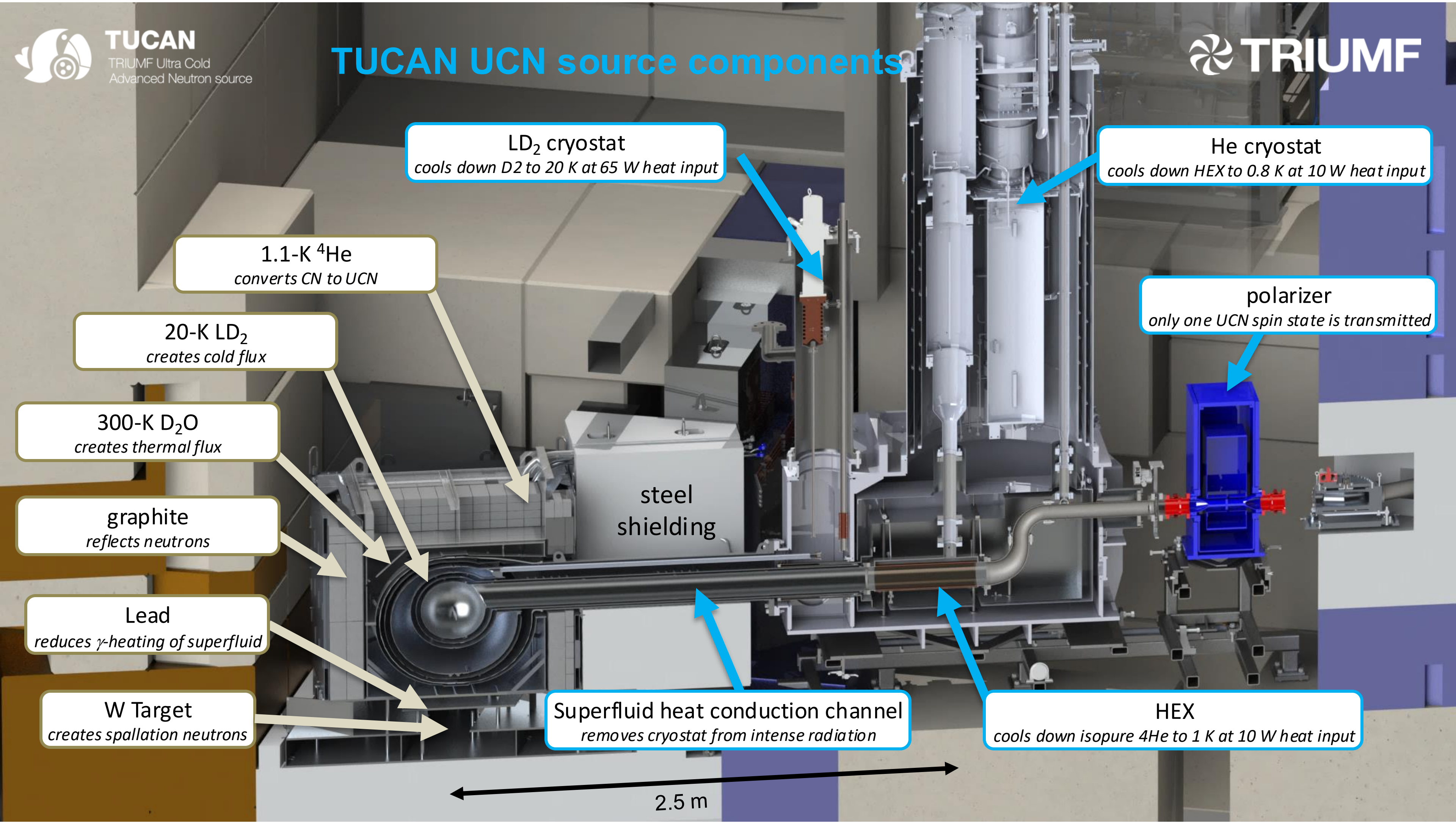


Up-scattering rate: $\tau_{\mathrm{up}}^{-1} \propto T^7$

(T : He-II temperature)

- Crucial aspects:
  - Keep the He-II temperature at ~1K to suppress up-scattering by phonons under a heat load of beam irradiation

TUCAN 実験



TUCAN UCN source components

LD_2 cryostat
cools down D2 to 20 K at 65 W heat input

He cryostat
cools down HEX to 0.8 K at 10 W heat input

1.1-K ^4He
converts CN to UCN

20-K LD_2
creates cold flux

polarizer
only one UCN spin state is transmitted

300-K D_2O
creates thermal flux

steel shielding

graphite
reflects neutrons

Lead
reduces γ-heating of superfluid

W Target
creates spallation neutrons

Superfluid heat conduction channel
removes cryostat from intense radiation

HEX
cools down isopure 4He to 1 K at 10 W heat input

TUCAN 実験

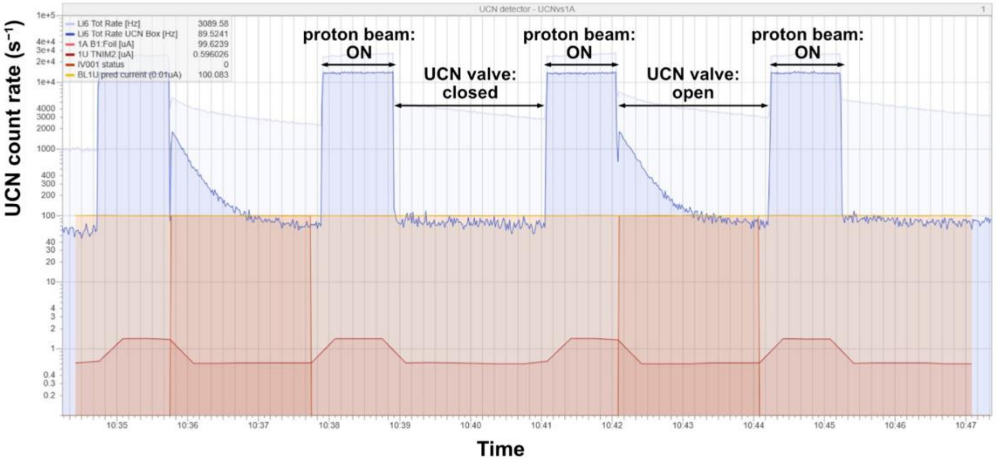
- 2025年6月の実験で無事UCNを検出！
  - いろいろ苦労はありましたが
  - 計数はおおよそ計算通り。
  - 冷却も大丈夫そう。
  - 論文をもうすぐ投稿
- 液体重水素モデレーターを準備中
  - UCN数はここから61倍に増える計算。
  - 10月からのビームタイムで重水素の効果を確認予定。
- TRIUMFは2026年はビームが出ないのでnEDM実験の準備を進める計画。

トピックス

TUCAN国際共同実験にて超冷中性子の生成に成功しました

2025年7月7日

KEK素核研ミューオン・中性子グループが参加するTUCAN国際共同実験が、カナダの国立素粒子原子核物理研究所(TRIUMF)にて、KEKで開発したヘリウム冷凍機を使って超冷中性子（UCN: Ultra-Cold Neutron）の生成に成功しました。



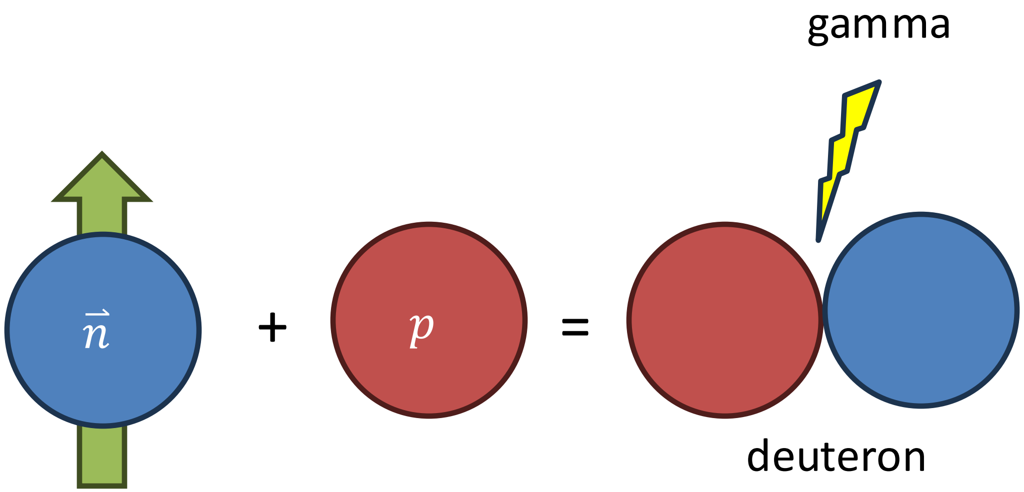
KEK IPNS ニューストピックス (2025年7月7日)https://www2.kek.jp/ipns/ja/news/7515/

複合核共鳴を利用した
時間反転対称性の破れ探索

原子核反応でのパリティの破れ

- ベータ崩壊など、弱い相互作用の中でパリティ(P)は破れている。
- 実は強い相互作用の中でもPの破れが観測されている。
- 例えば偏極中性子を陽子標的に当てて出てくるガンマ線は$(-3.0 \pm 1.4) \times 10^{-8}$だけ偏っている。

D. Blyth et al., Phys. Rev. Lett. 121, 242002(2018), https://doi.org/10.1103/PhysRevLett.121.242002



NPDGamma experiment@SNS, US

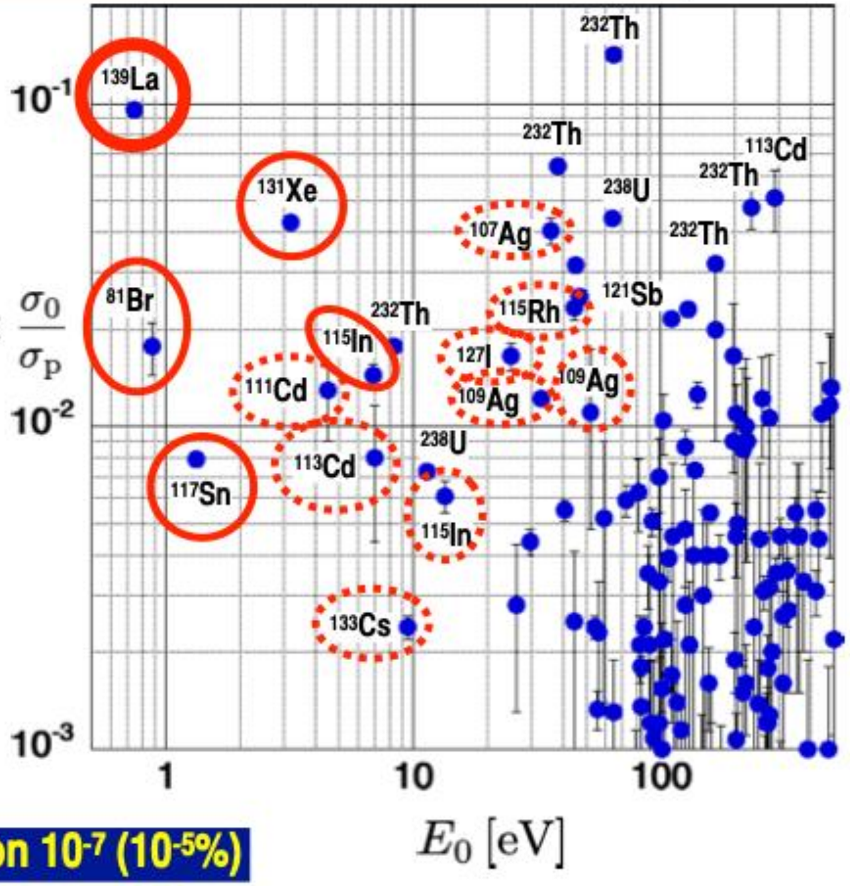
原子核内でのパリティの破れ

Enhancement of P-violation in Compound Resonances

Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

$$A_{\mathrm{L}} = \frac{\Delta\sigma}{\sigma_0} \times \frac{\sigma_0}{\sigma_{\mathrm{P}}}$$

10^{-7} for NN



NN-interaction 10^{-7} (10^{-5}%)

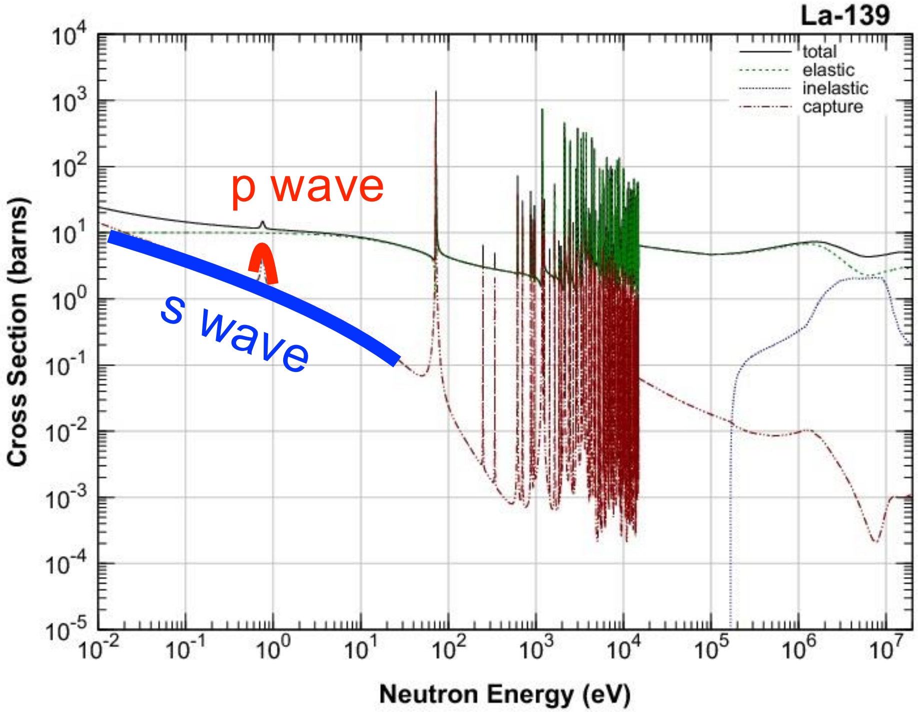
Enhancement of symmetry violation

Neutron capture around p-wave resonance

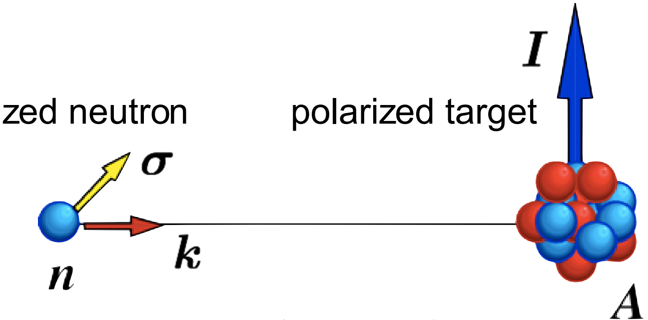
polarized neutron

		Longitudinal asymmetry A_L
^{139}La	$E_n = 0.734$ eV	0.097±0.003

P-violation is enhanced in
the interference between s-wave and p-wave
of compound nuclei.



T-violation is also enhanced !?



polarized neutron

polarized target

$$\boldsymbol{\sigma} \cdot (\boldsymbol{k} \times \boldsymbol{I})$$

$$\Delta\sigma_{\mathrm{T}} = \kappa(J)\frac{W_{\mathrm{T}}}{W}\Delta\sigma_{\mathrm{P}}$$

Discovery potential

compare with EDM searches

$$|\Delta\sigma_{\mathrm{T}}| < 1.0 \times 10^{-4}\mathrm{barn}$$

$\kappa \sim 1$ with ^{139}La

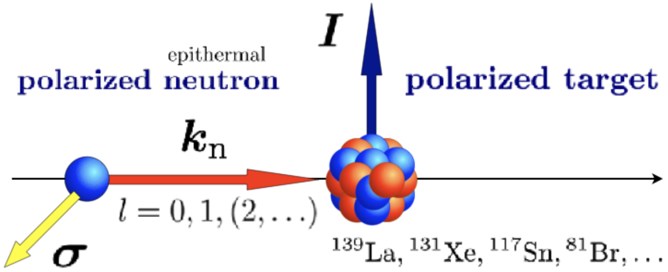
T-violation search using compound nuclei

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

P-odd and T-odd interactions can be largely enhanced in neutron induced compound nuclei

New T-violation search experiment based on optical behavior of neutron can be performed without final state interaction. The fundamental study and development of polarized target and neutron polarization device are ongoing.

T-odd cross section: $\boldsymbol{\sigma} \cdot (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{I}})$

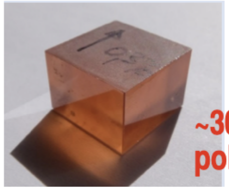


1. Optical Test final-state interaction free

2. Enhancement 10^6 times enhancement

3. New Type of New Physics Search chromo-EDM

Development



~30% ^{139}La polarization

Polarized target : $LaAlO_3$

K. Ishizaki *et al*. NIM A1020, 165845 (2021)

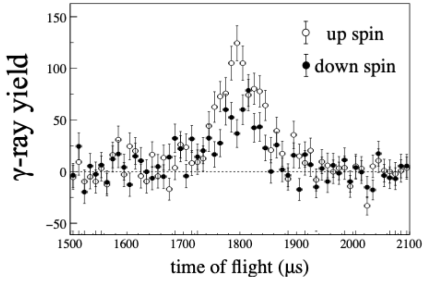
~40% neutron polarization

^{3}He neutron polarizer

T. Okudaira *et. al.* , NIM A 977, 164301 (2020)

Enhancement mechanism

Neutron spin dependent asymmetry

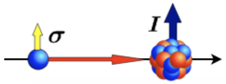


T. Yamamoto *et al*. Phys. Rev. C. 101, 064624 (2020)

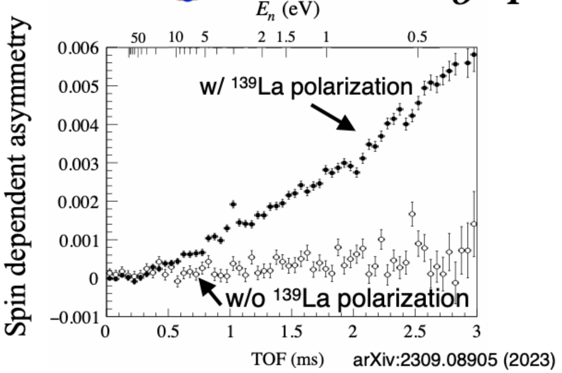
Enhancement factor was determined using (n,γ) reaction

→T-violation enhancement in ^{139}La+n : 10^6 times!

Experiment with polarized target + neutron



T-even spin dependent cross section: $\boldsymbol{\sigma} \cdot \boldsymbol{I}$



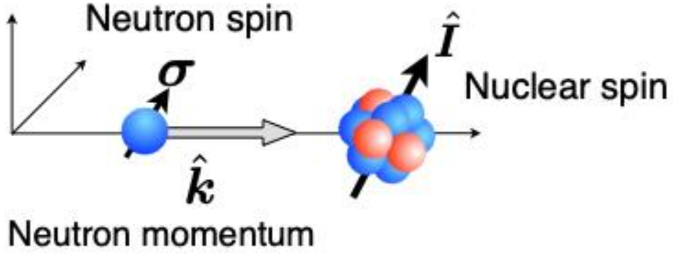
arXiv:2309.08905 (2023)

Spin dependent cross section of ^{139}La+n was successfully observed !

T-violation search using compound nuclei

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

Phase 1 experiment : T-violation search with parallel spins



- Low T-violation sensitivity
- Easy neutron spin transport
- Existing beamline

KEK IPNS Program Advisory Committee Stage1 approval

→planned on 2025

Polarized La target using 4T super conducting magnet

$LaAlO_3$ Crystal and dilution refrigerator is now preparing

Large ^{3}He cell for 80% neutron polarization

110W Laser system is now constructing

中性子-反中性子振動
N-Nbar oscillation

バリオン生成と中性子反中性子振動

いくつかの統一模型は

中性子反中性子振動を予言する

$n \rightleftarrows \bar{n}$ $\Delta B = 2$

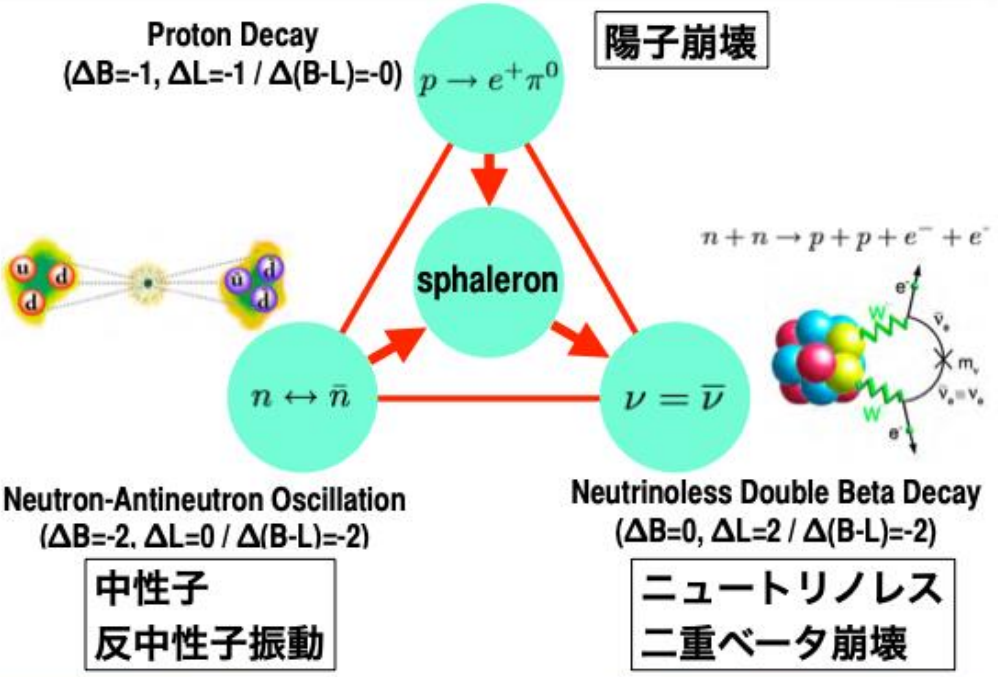
ex. $SU(2)_L \times SU(2)_R \times SU(4)_c$

post-sphaleron baryogenesis

$$\tau_{n\bar{n}} \le 5 \times 10^{10}\ \mathrm{s}$$

K.S.Babu et al., Phys. Rev. D 87, 115019 (2013)

見つかったら → 新物理



Proton Decay
(ΔB=-1, ΔL=-1 / Δ(B-L)=-0)

$p \to e^+\pi^0$

陽子崩壊

sphaleron

$n \leftrightarrow \bar{n}$

$\nu = \bar{\nu}$

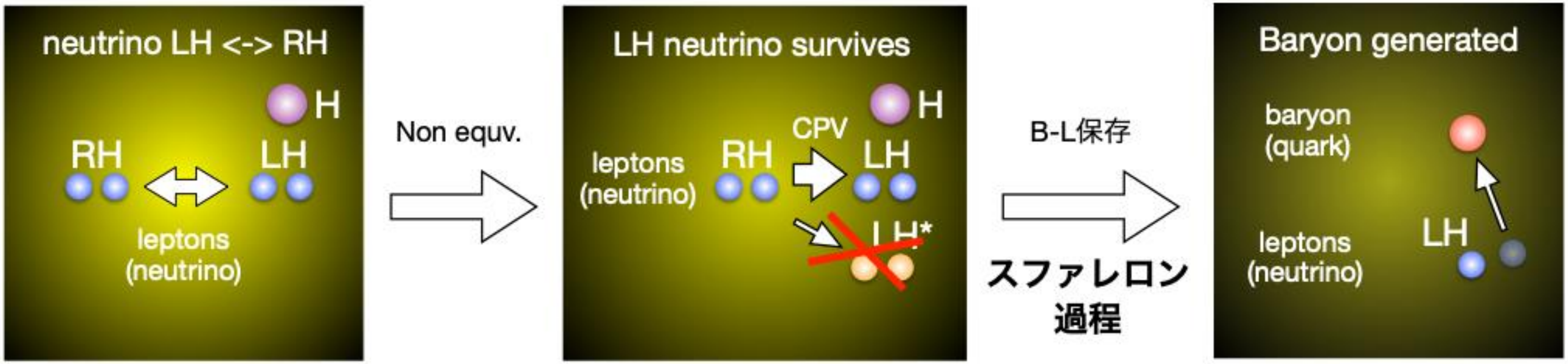
$n + n \to p + p + e^- + e^-$

Neutron-Antineutron Oscillation
(ΔB=-2, ΔL=0 / Δ(B-L)=-2)

中性子
反中性子振動

Neutrinoless Double Beta Decay
(ΔB=0, ΔL=2 / Δ(B-L)=-2)

ニュートリノレス
二重ベータ崩壊



neutrino LH <-> RH

H

RH

LH

leptons
(neutrino)

Non equv.

LH neutrino survives

H

CPV

leptons
(neutrino)

RH

LH

LH*

B-L保存

スファレロン
過程

Baryon generated

baryon
(quark)

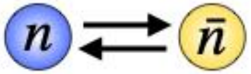
leptons
(neutrino)

LH

バリオン生成と中性子反中性子振動

いくつかの統一模型は

中性子反中性子振動を予言する



$\Delta B = 2$

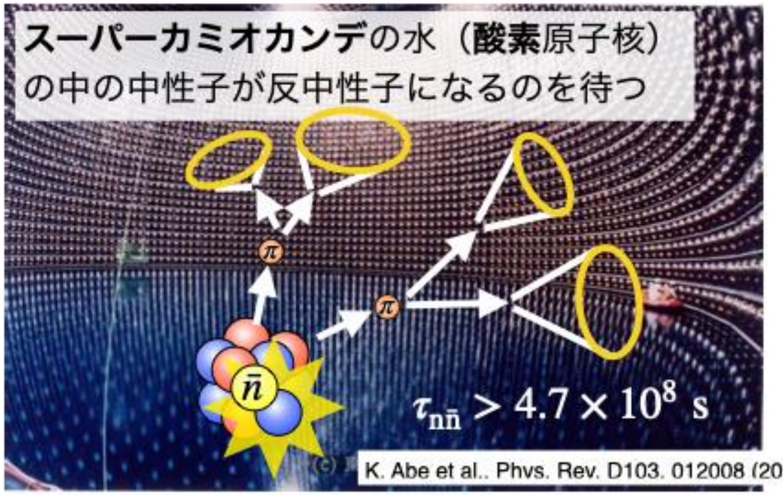
ex. $SU(2)_L \times SU(2)_R \times SU(4)_c$

post-sphaleron baryogenesis

$\tau_{n\bar{n}} \leq 5 \times 10^{10}$ s

K.S.Babu et al., Phys. Rev. D 87, 115019 (2013)

見つかったら → 新物理



スーパーカミオカンデの水（**酸素**原子核）の中の中性子が反中性子になるのを待つ

$\tau_{\mathrm{n\bar{n}}} > 4.7 \times 10^8$ s

K. Abe et al., Phys. Rev. D103, 012008 (2021)

$$\psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \qquad \mathscr{M} = \begin{pmatrix} m_n - i\lambda/2 & \delta m \\ \delta m & m_n - i\lambda/2 \end{pmatrix}$$

$$|n_\pm\rangle = \frac{1}{\sqrt{2}}(|n\rangle \pm |\bar{n}\rangle) \qquad m_\pm = (m_n \pm \delta m) - i\lambda/2$$

$$P(n(t) = \bar{n}) = |\langle \bar{n} | n(t) \rangle|^2 = [\sin^2(t/\tau_{n\bar{n}})]\mathrm{e}^{-\lambda \mathrm{t}} \simeq (\mathrm{t}/\tau_{\mathrm{n\bar{n}}})^2$$

$$\tau_{n\bar{n}} = 1/|\delta m|$$

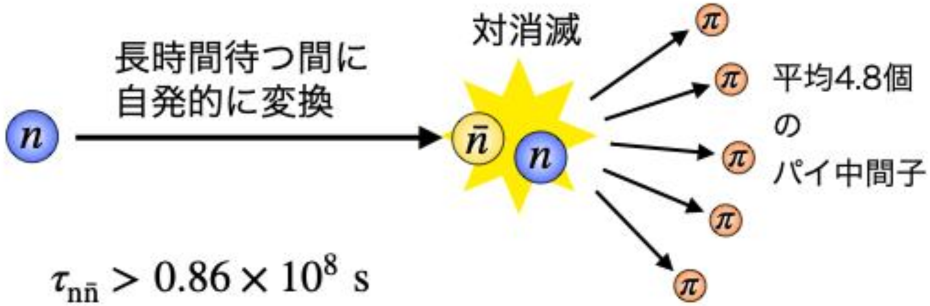
Sensitivity (Figure of Merit)

$\propto NT^2$

Number of neutrons

(Average square of) free flight time

ILL原子炉からの大量の**中性子ビーム**を長距離飛行させて反中性子を探す

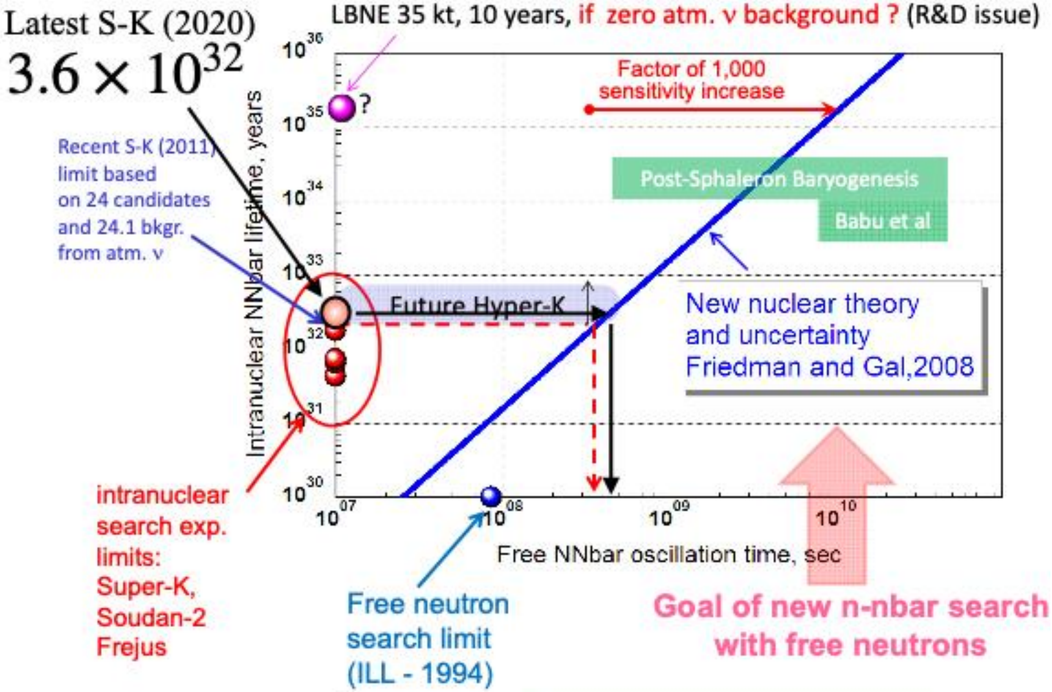


$\tau_{\mathrm{n\bar{n}}} > 0.86 \times 10^8$ s

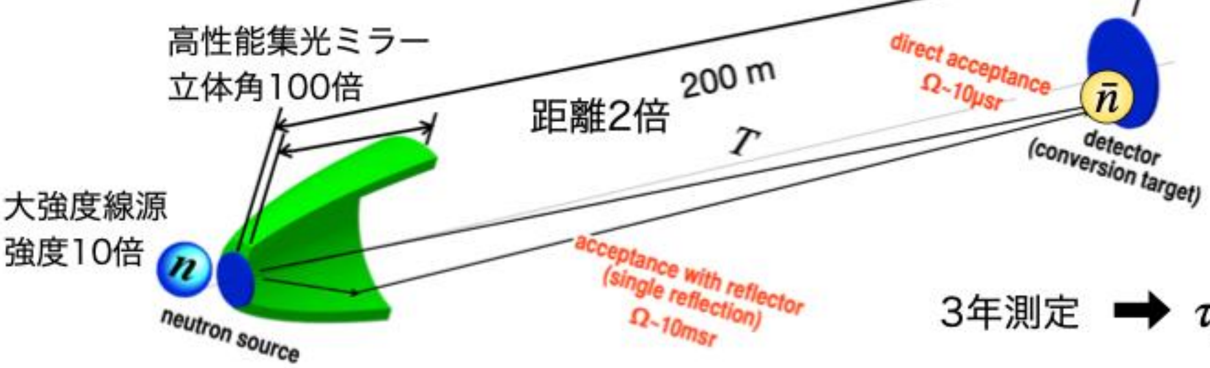
M. Baldo-Ceolin et al., Z. Phys. C 63, 409 (1994).

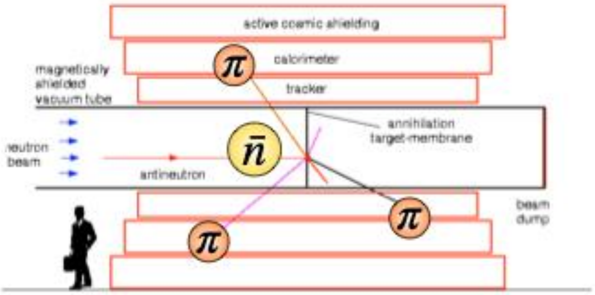
バリオン生成と中性子反中性子振動

ハイパーカミオカンデ 進行中



NNBar@ESS 進行中？

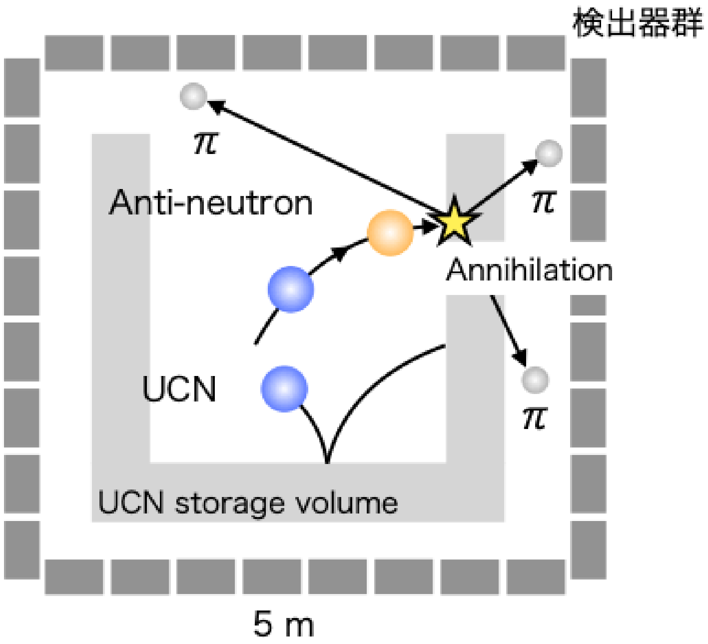




3年測定 ➡ $\tau_{n\bar{n}} > 3 \times 10^{9}$ s

超冷中性子蓄積を用いた中性子反中性子振動探索

蓄積超冷中性子を用いた探索 at **新研究炉**



$$i\frac{\partial}{\partial t}\begin{pmatrix}\Psi_n(t)\\ \Psi_{\bar{n}}(t)\end{pmatrix}=\begin{pmatrix}E_n-\boldsymbol{\mu}_n\cdot\boldsymbol{B}-i\Gamma_\beta/2 & \varepsilon\\ \varepsilon & E_n+\boldsymbol{\mu}_n\cdot\boldsymbol{B}-i\Gamma_\beta/2\end{pmatrix}\begin{pmatrix}\Psi_n(0)\\ \Psi_{\bar{n}}(0)\end{pmatrix}$$

$$|\Psi_{\bar{n}}(t)|=\frac{4\varepsilon^2}{\omega^2+4\varepsilon^2}\ \exp\left(-\Gamma_\beta\ t\right)\ \sin^2\left(\frac{1}{2}\sqrt{\omega^2+4\varepsilon^2}\ t\right)$$

$$P_{n\bar{n}}(t)=|\Psi_{\bar{n}}(t)|^2\simeq\left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

Γ_β 中性子寿命

$\varepsilon=\dfrac{1}{\tau_{n\bar{n}}}$ 振動の行列要素

$\omega=2|\boldsymbol{\mu}_n\cdot\boldsymbol{B}|$

磁場中のエネルギー差

➡ 蓄積して長時間測定

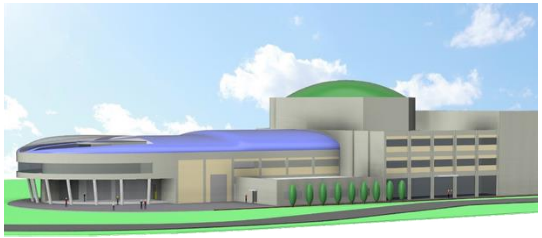
原子核の束縛による抑制を受けない

大量の中性子で数を稼げないか？

➡ **大強度超冷中性子源**

新型研究炉

敦賀もんじゅ跡地



まとめ

- 中性子は電荷を持たない核子であり、そのユニークな特性から様々な基礎物理実験に用いられてきた。
  - 特にその波動性を用いた実験により、量子力学の根幹を支える実験を行ってきた。
  - 最近はUCNでの実験がさかんに行われている。

- 新しい実験がいくつか立ち上がっていますので、興味を持っていただければ。