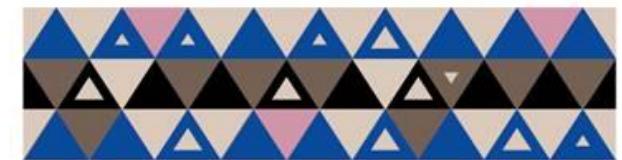


# Fundamental Physics with Slow Neutrons

Shinsuke Kawasaki



8<sup>th</sup> International Symposium on Symmetries in  
Subatomic Physics (SSP2022)  
University of Applied Arts, Vienna, Austria



**SSP2022**

# Fundamental Physics with Slow Neutrons

## nEDM

- Time reversal violation
- Strong CP problem
- UCN storage
- crystal diffraction method

R. Picker

## neutron lifetime

- test of standard model (verification of unitarity of CKM matrix)
- Big bang nucleosynthesis
- neutron lifetime paradox
- UCN storage
- in beam

C.-Y. Liu

## gravity

- test of Newtonian gravity
- search for new force
- quantum state in earth gravity (UCN)
- small angle scattering
- interferometer

H. Abele

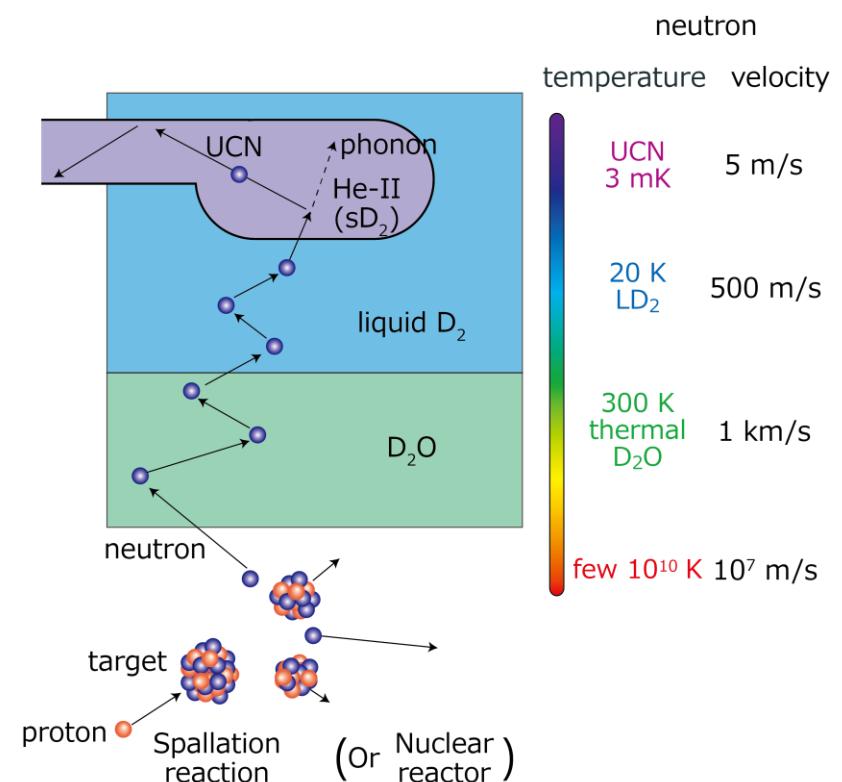
## n-nbar

- baryon number violation
- free flight neutron

# Various Neutrons

Name	Energy	Wavelength	Velocity	Temperature	Application
Fast neutron	>500 keV	~40 fm	~ $10^7$ m/s	~ $6 \times 10^9$ K	Nuclear physics Astro physics
Epi-thermal neutron	10 eV	~0.1 Å	~44,000 m/s	~ $1 \times 10^5$ K	Resonance capture
Thermal neutron	25 meV	~1.8 Å	~2200 m/s	~300 K	Neutron scattering
Cold neutron	2 meV	~6 Å	~600 m/s	~23 K	Neutron scattering for condensed matter (nm)
Very cold neutron VCN	50 μeV	~40 Å	~100 m/s	~0.6 K	Neutron interferometer
Ultra-cold neutron UCN	<300 neV	~500 Å	~8 m/s	~3 mK	Storage experiment

## Neutron Cooling



nature of matter wave plays a significant role in slow neutrons

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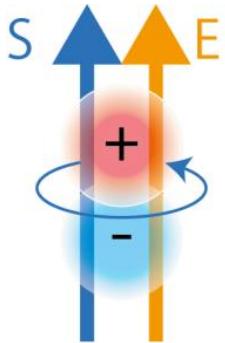
- baryon number violation
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# neutron EDM

- Current upper limit @PSI 2020

- $d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26} \text{e} \cdot \text{cm}$   
 $\rightarrow |d_n| < 1.8 \times 10^{-26} \text{e} \cdot \text{cm} (90\% \text{C.L.})$

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



- Test of Time reversal symmetry
  - Same as CP symmetry assuming CPT conservation

- Strong-CP problem

- $d_n = -(1.5 \pm 0.7) \times 10^{-16} \bar{\theta} \text{ e} \cdot \text{cm}$

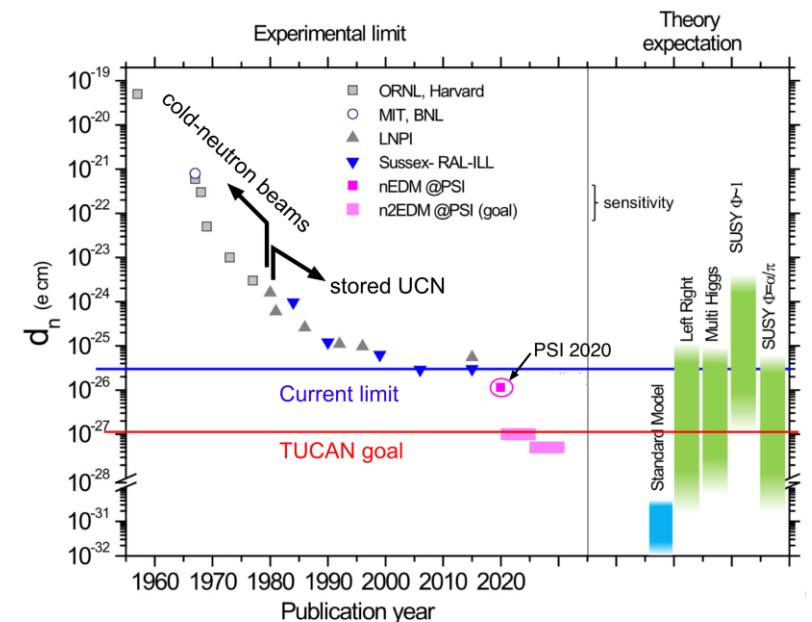
Jordy de Vries et al., Phys. Rev. D 104, 055039 (2021)

$$\rightarrow \bar{\theta} \lesssim 10^{-10}$$

- SUSY mass scale

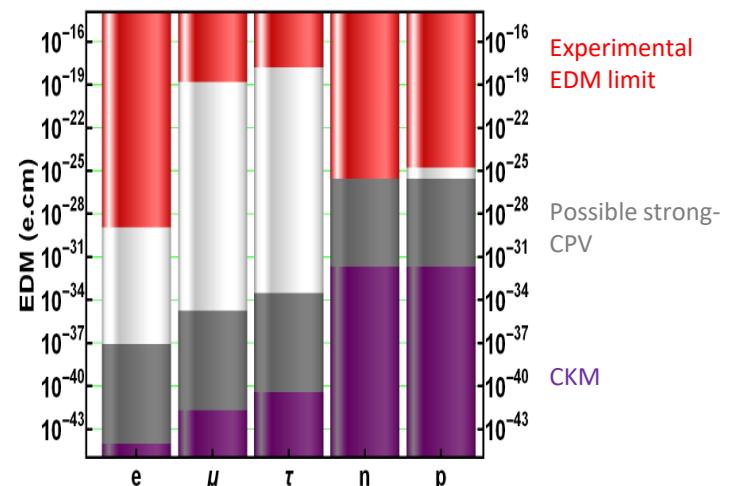
- $d_n \sim \left(\frac{300 \text{ GeV}}{M}\right)^2 \frac{\sin\phi}{\tan\beta} \times 10^{-24} \text{e} \cdot \text{cm} \Rightarrow \sim 2 \text{ TeV} (\text{PSI limit})$   
 $\Rightarrow \sim 10 \text{ TeV} (|d_n| \sim 1 \times 10^{-27} \text{e} \cdot \text{cm})$

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



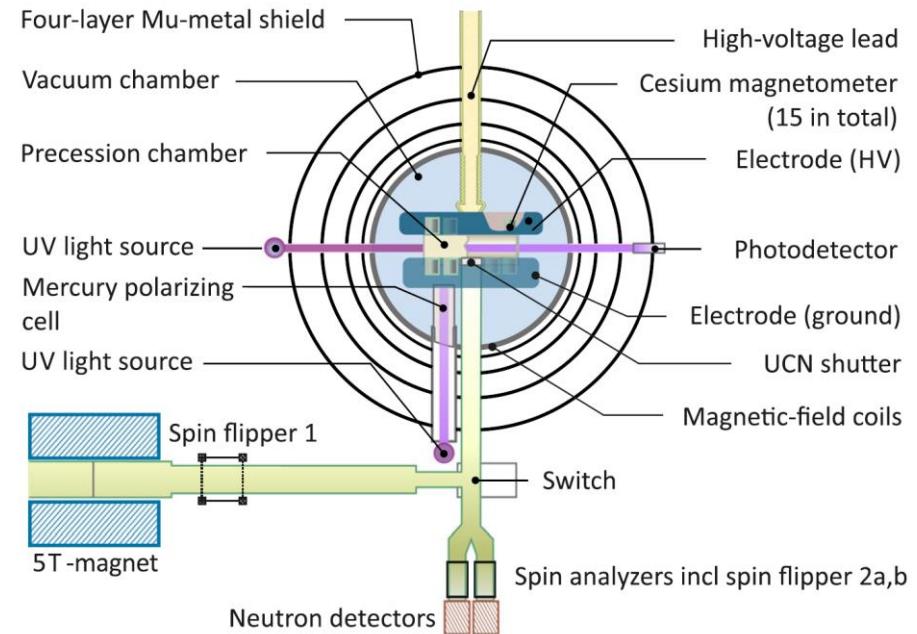
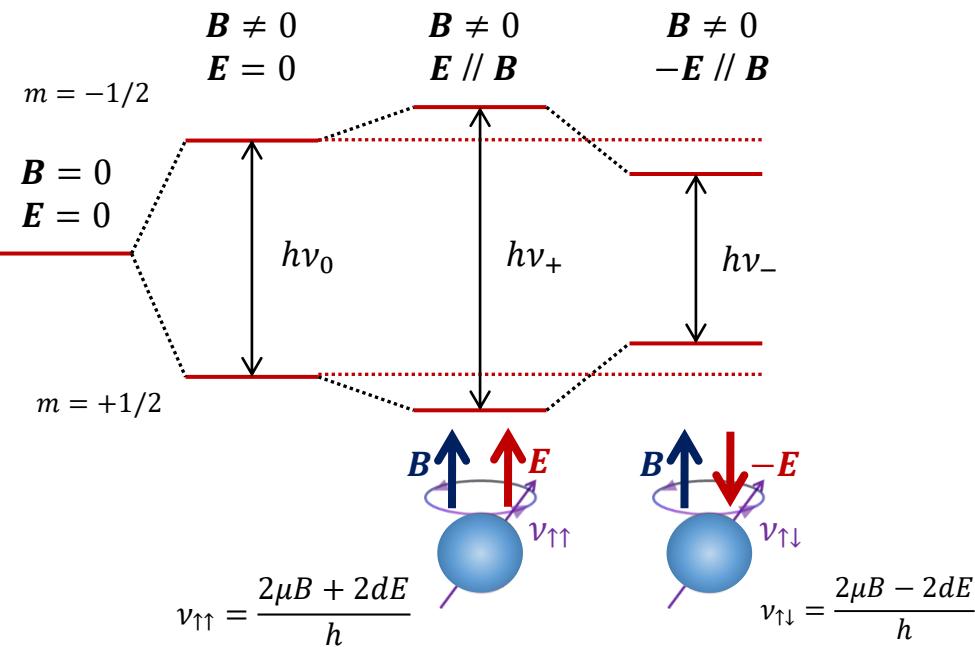
Slide courtesy: B. Lauss, nEDM workshop 2017, based on NIMA 440, 471 (2000), Phys. Rev. D 92, 092003 (2015)  
AIP Conf. Proc. 1753, 060002 (2016)

Current EDM limits for Strong CP



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

# nEDM measurements using UCN



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

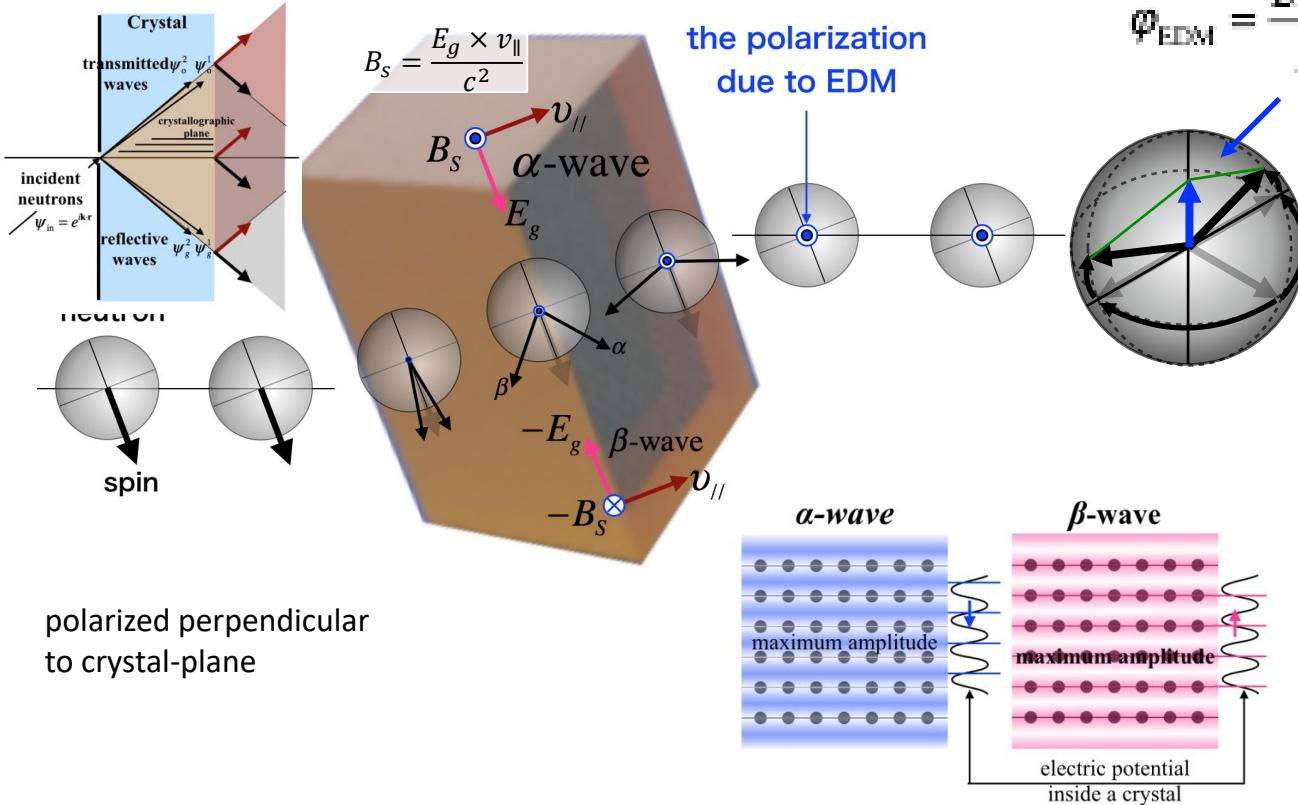
$$\Delta\nu = \nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow} = \frac{4dE}{h}$$

Stored UCNs precess under the electro-magnetic field. In order to measure nEDM, take the difference of Lamour frequency of neutron under electric field reversal.

Current upper limit:  $\rightarrow |d_n| < 1.8 \times 10^{-26} \text{ e} \cdot \text{cm}$  (90% C.L) @ PSI, 2020

Next generation experiments goal:  $10^{-27}$  ecm

# Crystal nEDM at J-PARC



$$\varphi_{\text{EDM}} = \frac{2Ed_{\perp}L}{\hbar v_{||}}$$

Statistical sensitivity

$$\sigma_d = \frac{\hbar}{2\alpha Et_c \sqrt{N}}$$

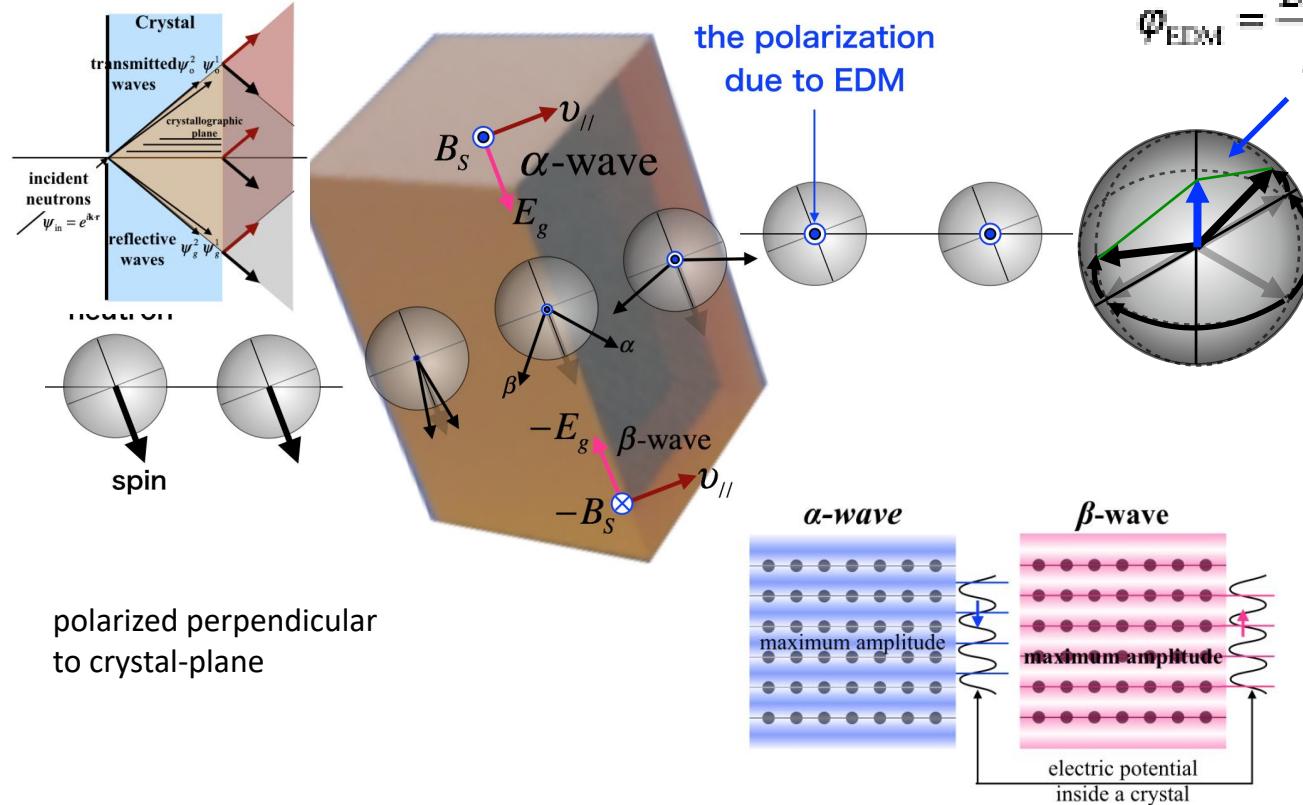
	Free flight method	Crystal diffraction method	UCN method
interaction time $\tau$ [s]	$\sim 10^{-1}$	$\sim 10^{-3}$	$\sim 10^2$
electric field E [V/cm]	$\sim 10^4$	$\sim 10^8$	$\sim 10^4$
neutron counts n [n/s]	$\sim 10^8$	$\sim 10^4$	$\sim 10^2$
sensitivity $\sigma(d_n)$	$\sim 10^{-25}/\sqrt{\text{Day}}$	$\sim 10^{-25}/\sqrt{\text{Day}}$	$\sim 10^{-25}/\sqrt{\text{Day}}$

slide from S. Ito

The merit of the crystal diffraction method is to use high electric field of  $\sim 10^8$  kV/cm inside crystal. The superposition of transmitted and reflected waves with the same wavenumber can be described by two standing waves:  $\alpha$  waves with maxima between crystal lattices and  $\beta$  waves with maxima on the crystal lattice. In the case of non-centrosymmetric crystals, the  $\alpha$  and  $\beta$  waves experience opposite electric fields

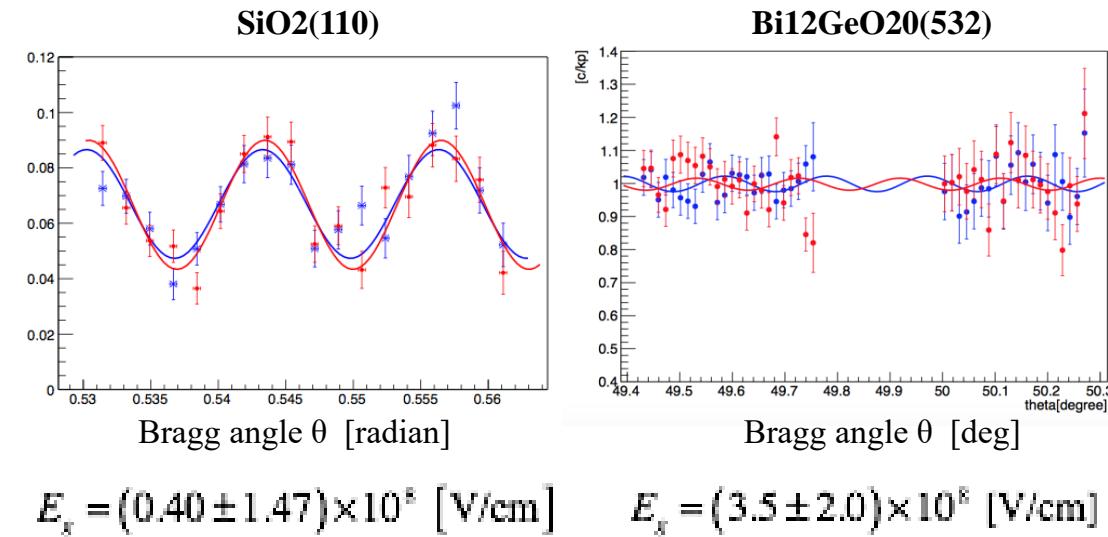
nEDM search by crystal diffraction is also important as an experimental method for different systematic errors

# Crystal nEDM at J-PARC



$$\varphi_{\text{EDM}} = \frac{2Ed_{\perp}L}{\hbar v_{//}}$$

measurement of internal electric field by Pendellösung fringe



The merit of the crystal diffraction method is to use high electric field of  $\sim 10^8$  kV/cm inside crystal. The superposition of transmitted and reflected waves with the same wavenumber can be described by two standing waves:  $\alpha$  waves with maxima between crystal lattices and  $\beta$  waves with maxima on the crystal lattice. In the case of non-centrosymmetric crystals, the  $\alpha$  and  $\beta$  waves experience opposite electric fields

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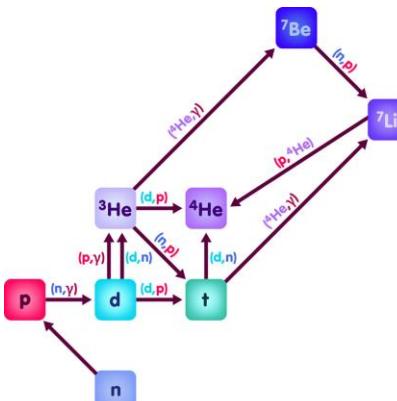
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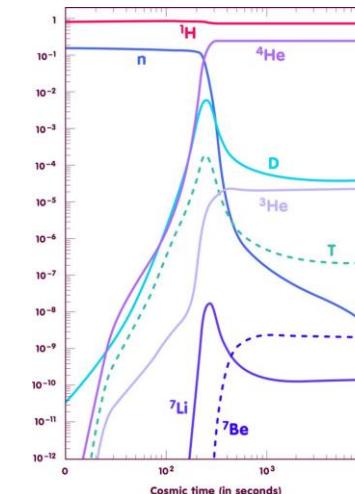
- baryon number violation
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# Neutron Lifetime

- Test of Standard Model
  - $V_{ud}$  of the CKM matrix can be calculated with
    - **Neutron lifetime:**  $\tau_n$
    - Axis/vector coupling constant:  $\lambda \equiv G_A/G_V$
  - $|V_{uc}|^2 = \frac{(4905.17 \pm 1.7) \text{ sec}}{\tau_n(1+3\lambda^2)}$
- An input parameter of the Big Bang Nucleosynthesis
  - Abundance of the light elements in early universe can be calculated with
    - Baryon to photon ratio
    - Nuclear cross section
    - **Neutron lifetime**

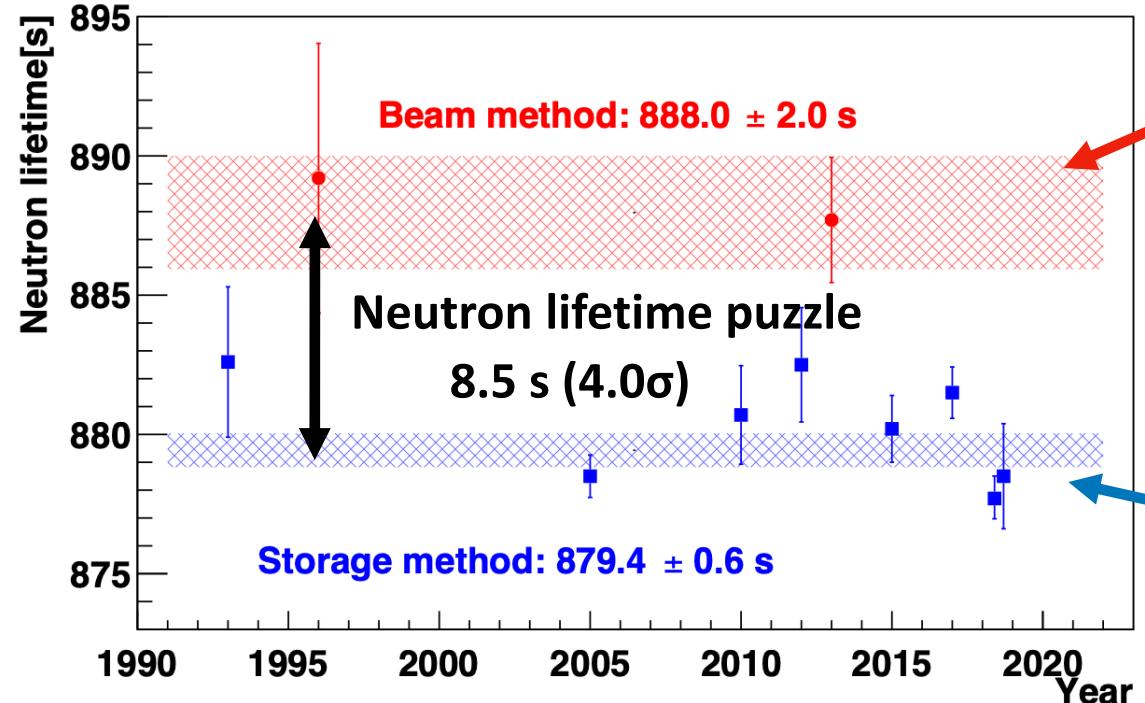


[https://www.einstein-online.info/en/spotlight/bbn\\_phys/](https://www.einstein-online.info/en/spotlight/bbn_phys/)

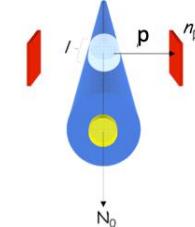


# Neutron Lifetime puzzle

Between two methods of measurement, which measured **decay** and **missing**, there is 8.5 s ( $4.0\sigma$ ) deviation of the value of lifetime.

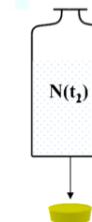


Beam method: Count the decay



$$-\frac{dN}{dt} = \frac{N}{\tau}$$

Storage method : Count the missing

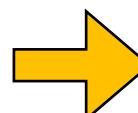


$$\frac{N_1}{N_2} = e^{-(t_1-t_2)/\tau}$$

will be discussed by C.-Y. Liu

Unknown systematic?  
New physics (dark decay, ...)?  
Quantum Zeno effect?  
Measurement in space

arXiv:2011.13272 (2020)  
Mod. Phys. Lett. A 35, 31, 2030019 (2020)  
PRD 101, 056003 (2020)  
arXiv:2011.07061 (2020)

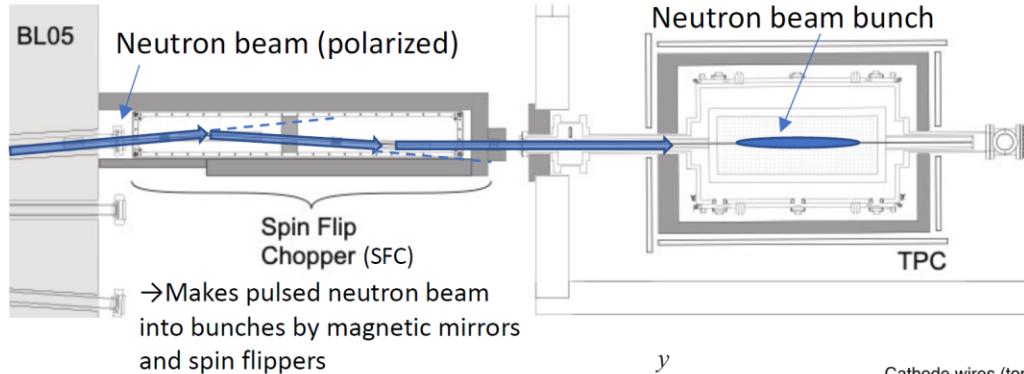


New, and different type of experiment is required.

# Principle of J-PARC experiment

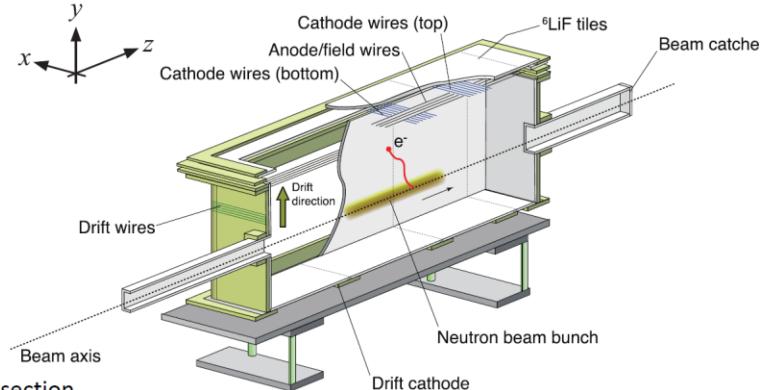
Cold neutrons are injected into a TPC.

The neutron  $\beta$ -decay and the  ${}^3\text{He}(n,p){}^3\text{H}$  reaction are measured simultaneously.



Principle (Kossakowski, 1989)

- Detector: Time Projection Chamber (TPC)
  - Gas :  ${}^4\text{He}$ ,  $\text{CO}_2$ ,  ${}^3\text{He}$   
(~85%, ~15%, 0.5 - 2 ppm, respectively)  
Total pressure: 100 kPa or 50 kPa



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

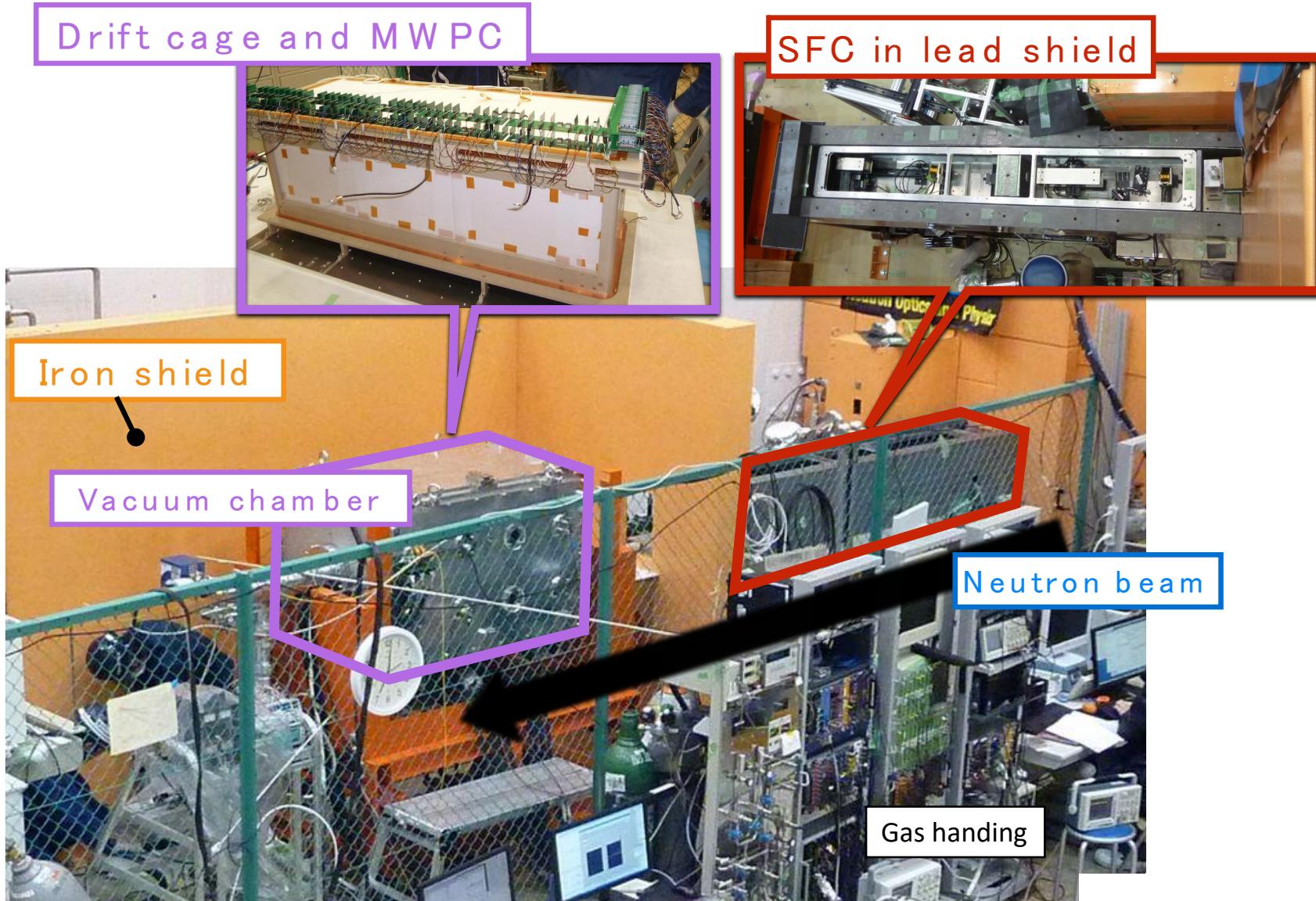
$\rho$  :  ${}^3\text{He}$  density  
 $\sigma_0$  :  ${}^3\text{He}$  neutron absorption cross section  
 $v_0$  : Velocity of neutron  
 $S_{\text{He}}$  : Number of  ${}^3\text{He}$  neutron absorption event  
 $S_\beta$  : Number of neutron  $\beta$  decay  
 $\varepsilon_{\text{He}}, \varepsilon_\beta$  : Efficiency

Hosokawa, RCNP workshop "Fundamental Physics Using Neutrons and Atoms 2022"

This method is free from the uncertainties due to external flux monitor, wall loss, depolarization, etc.

The goal is the experiment is accuracy of 1 sec.

# Experimental Setup @ J-PARC

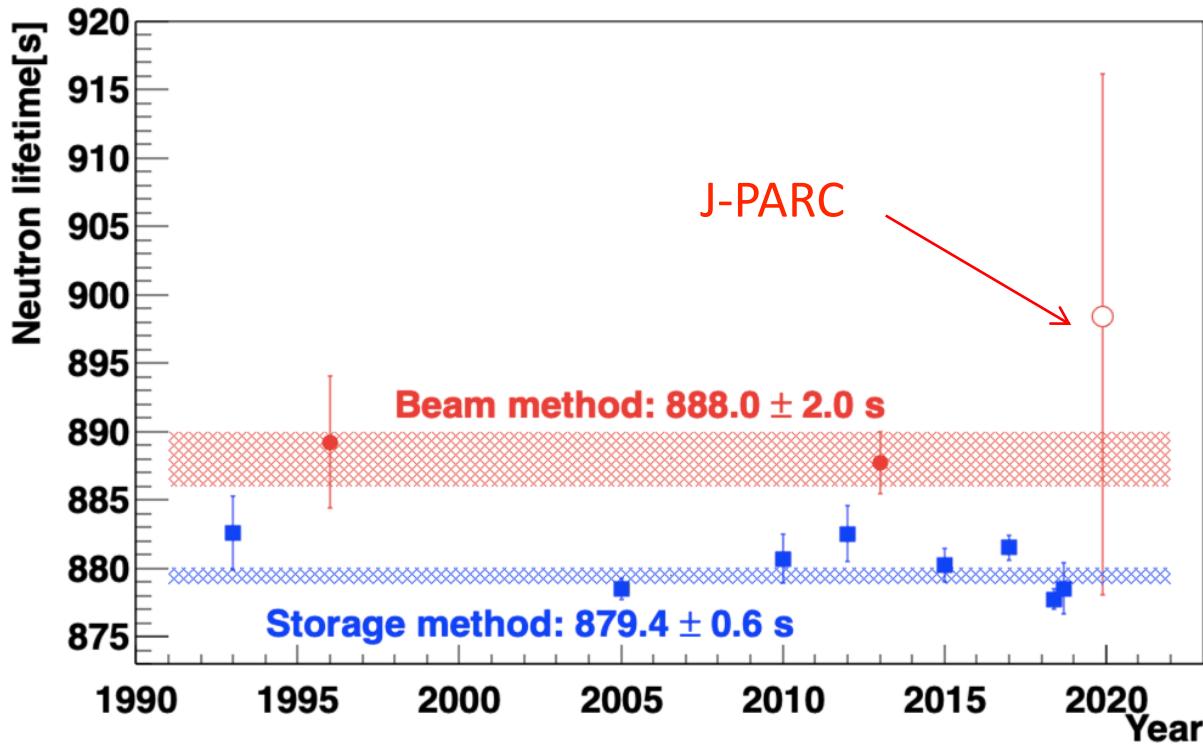


# The first result from J-PARC

The published result by using data using 2014-2016 was

$$\tau_n = 898 +10(\text{stat.})^{+15}_{-18} (\text{sys.}) = 898^{+18}_{-20} \text{ s}$$

[K. Hirota et al., Prog. Theor. Exp. Phys. **2020**, 123C02]

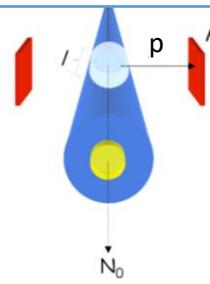


They have taken data of statistical uncertainty of 2 s  
→ Analysis Ongoing

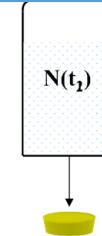
The improvement for better accuracy up to 1 sec is on going

- large aperture SPC
- Background reduction
- Analysis update
- , and so on.

In-beam method  
Count the dead



Storage method  
Count the living



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# Gravity

- Hierarchy problem
  - Gravity is too small compared with other interactions
    - Strong  $\sim 1$
    - Electro-Magnetic  $\sim 10^{-2}$
    - Weak  $\sim 10^{-5}$
    - Gravity  $\sim 10^{-40}$
- Large Extra Dimension model was proposed to solve the problem
  - The gravity force is escaping to the other dimension
  - gravity become strong in the short distance
- in this theory, gravity is modified as

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

correction term

$\alpha$ : coupling,  $\lambda$ : range

# Quantum states in earth gravity

- Gravity

potential well

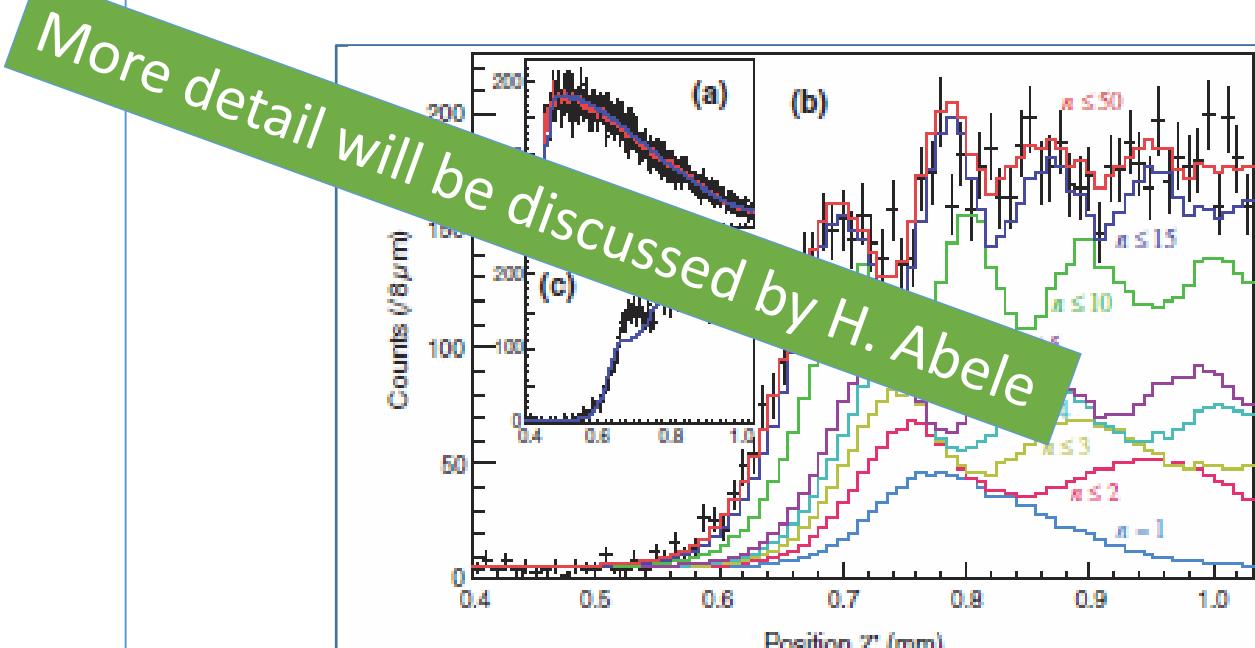
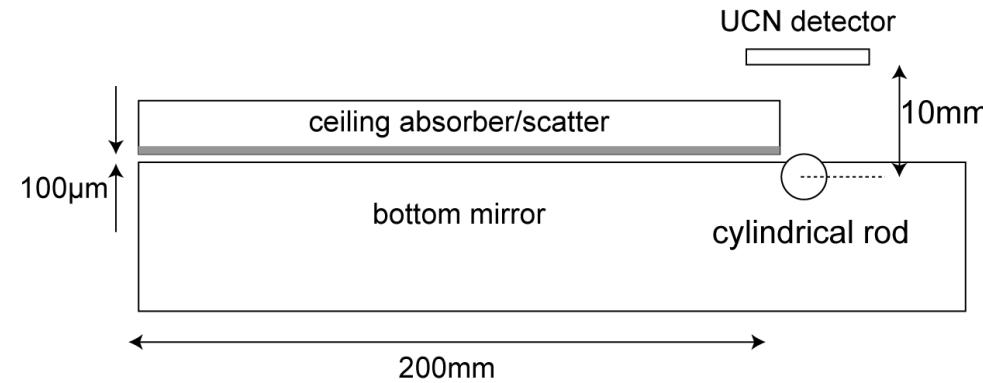
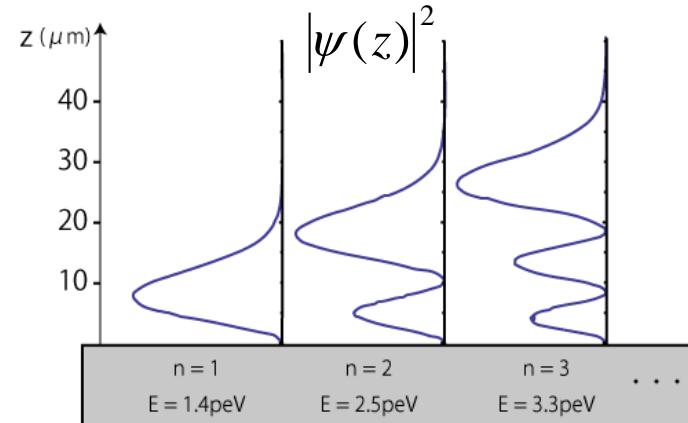
$$V(z) = \begin{cases} mgz & (z \geq 0) \\ \infty & (z < 0) \end{cases}$$

Schrödinger equation

$$\left( -\frac{\hbar^2}{2m} \frac{d^2}{dz^2} + V(z) \right) \psi(z) = E \psi(z)$$

$$\psi(z) = A \varphi(z)$$

$\varphi(z)$ : Airy function



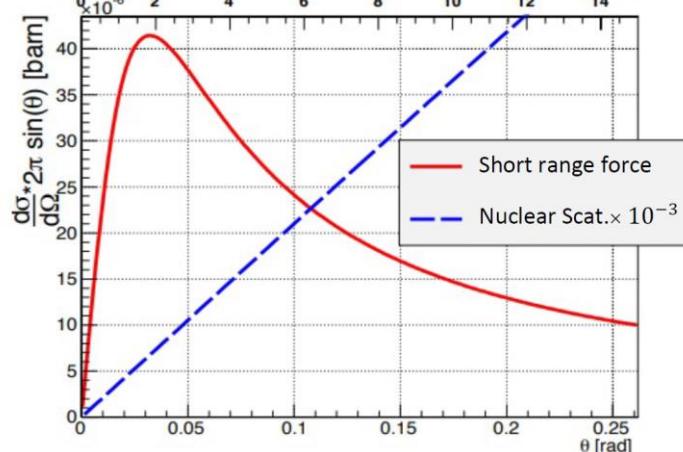
Ichikawa et al., PRL 112, 071101 (2014)

# Small angle scattering with noble gas

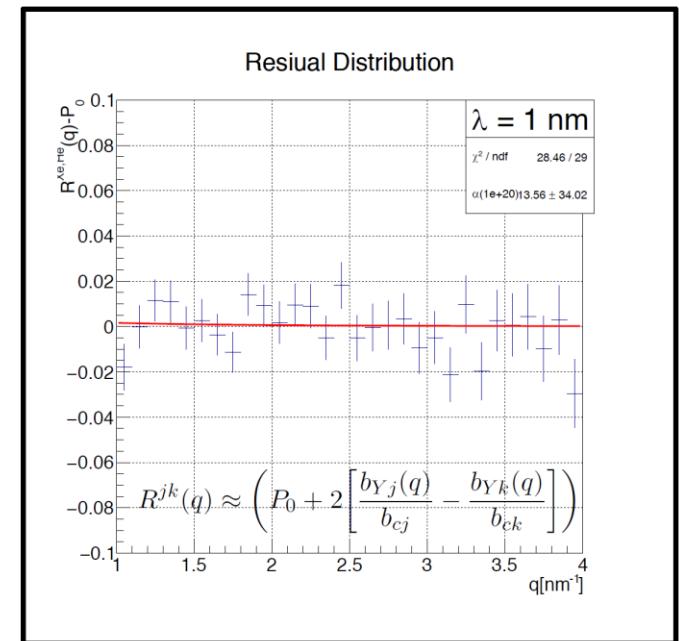
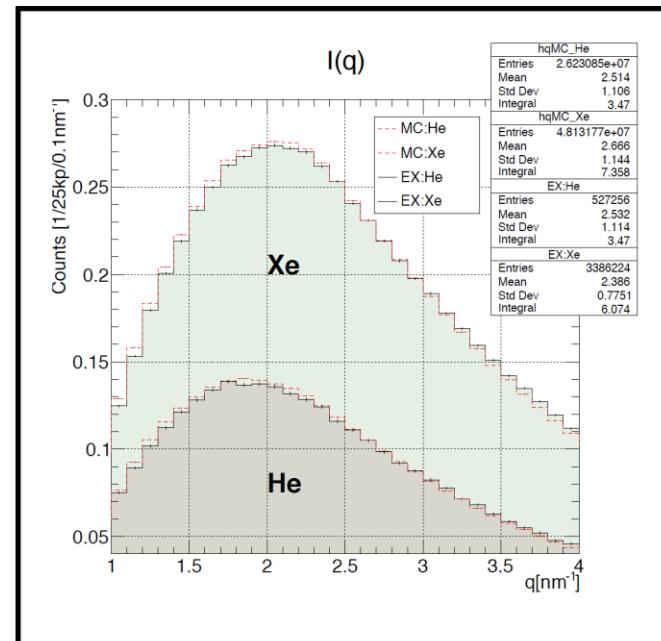
Scattering cross section is modified by short range force

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

$b_N$  : nuclear scattering (isotropic)  
 $\alpha_G F_G(\theta)$ : short range interaction  
(angular dependence)



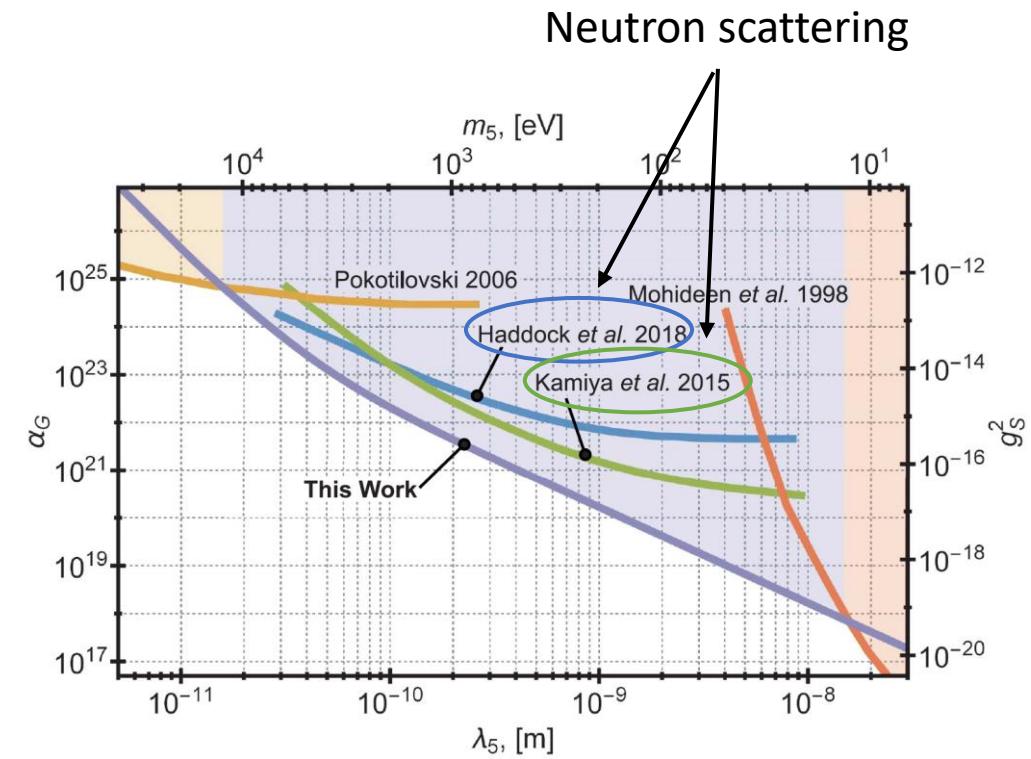
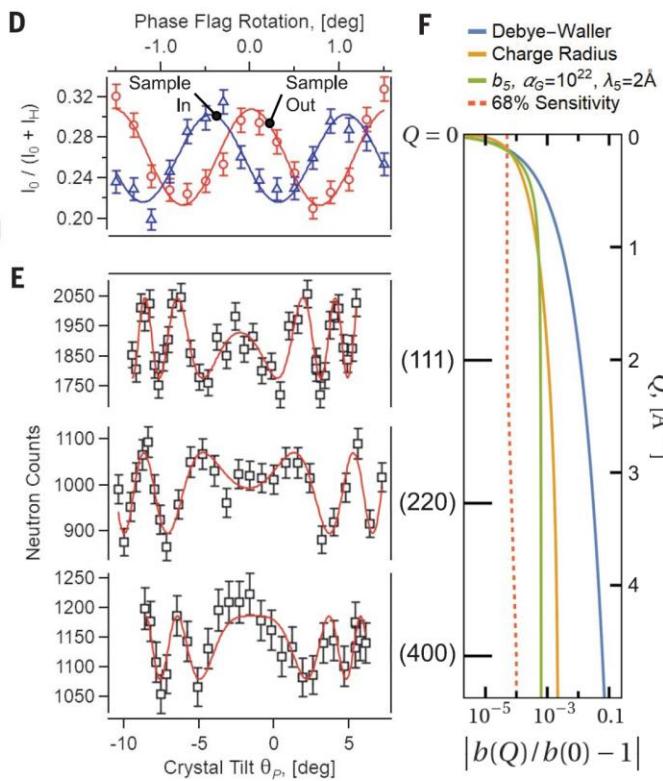
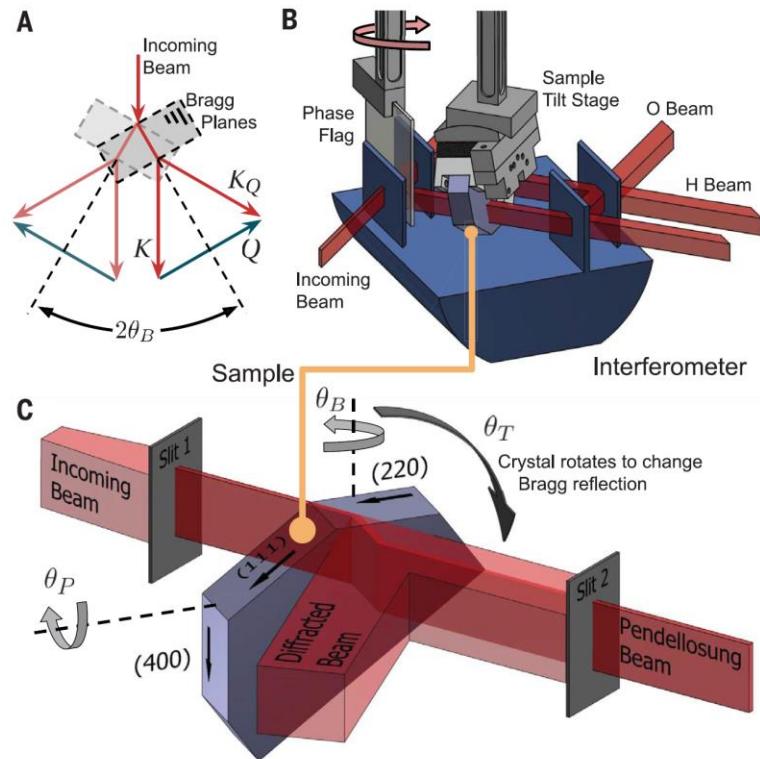
## Results



1. The experimental data is normalized by the corresponding simulation data for each gas species to remove any  $q$ -dependence.
2. The ratio of two gases (He and Xe) was taken.

# Neutron Interferometer

The phase shift of the sample can be measured by the neutron interferometer



Heacock et al., Science 373, 6560 (2021)

Experiment at NIST

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# n-nbar oscillation

- Baryon number violation

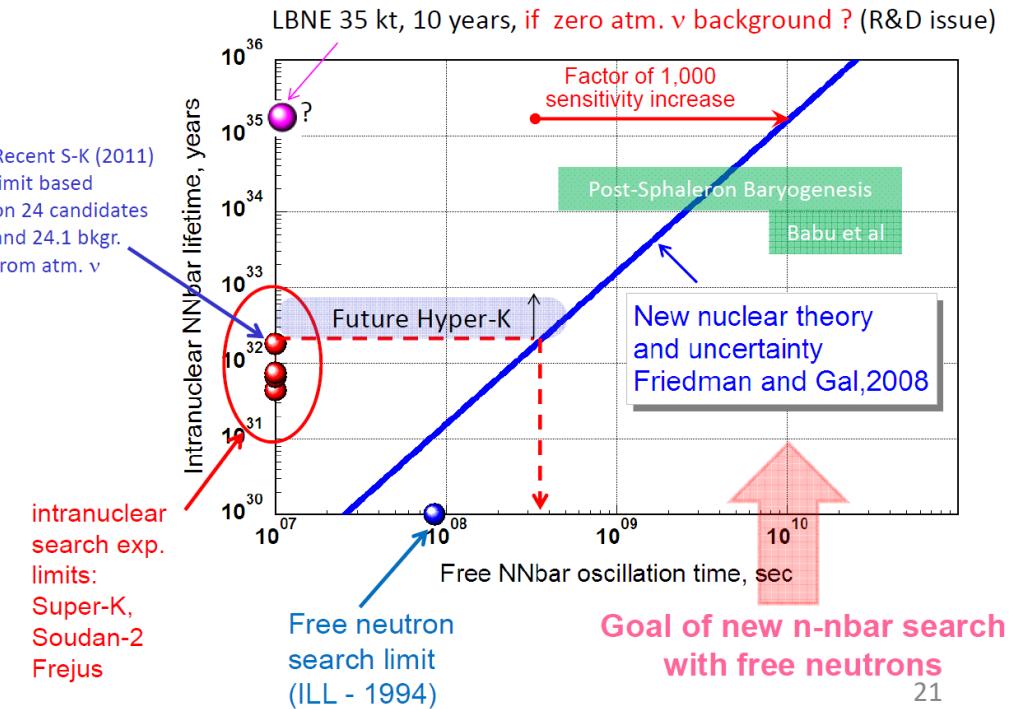
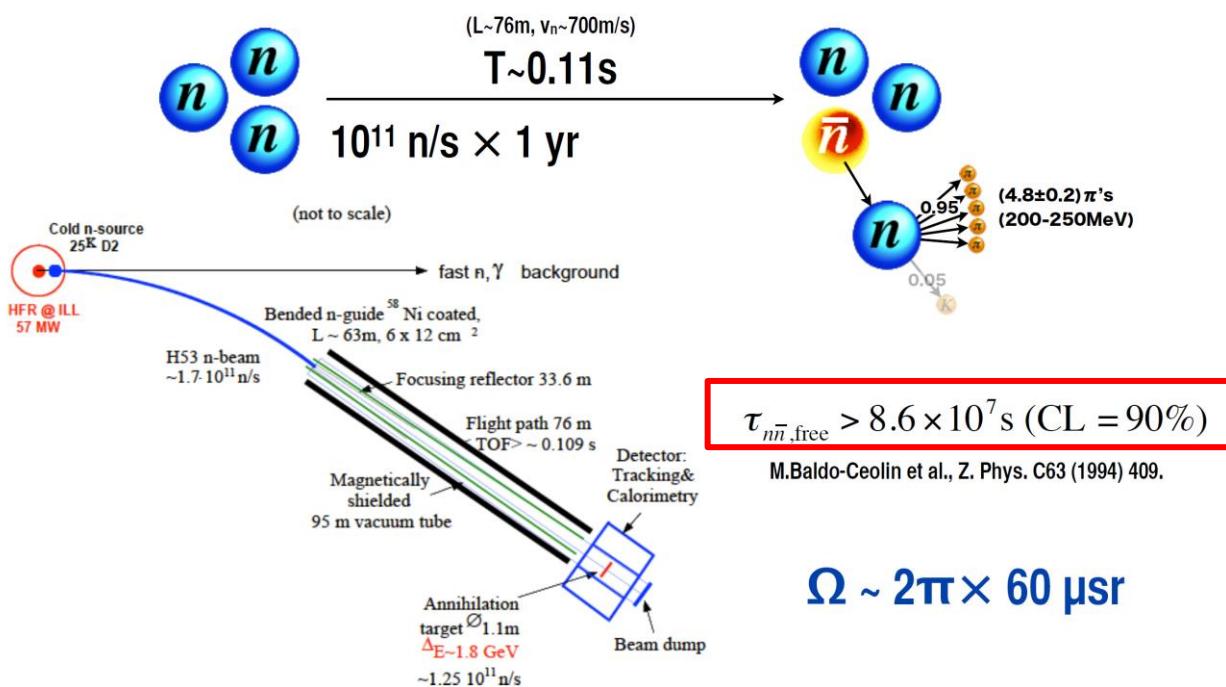
$$n \rightarrow \bar{n} : \Delta B = -2$$

- post-sphaleron baryogenesis

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

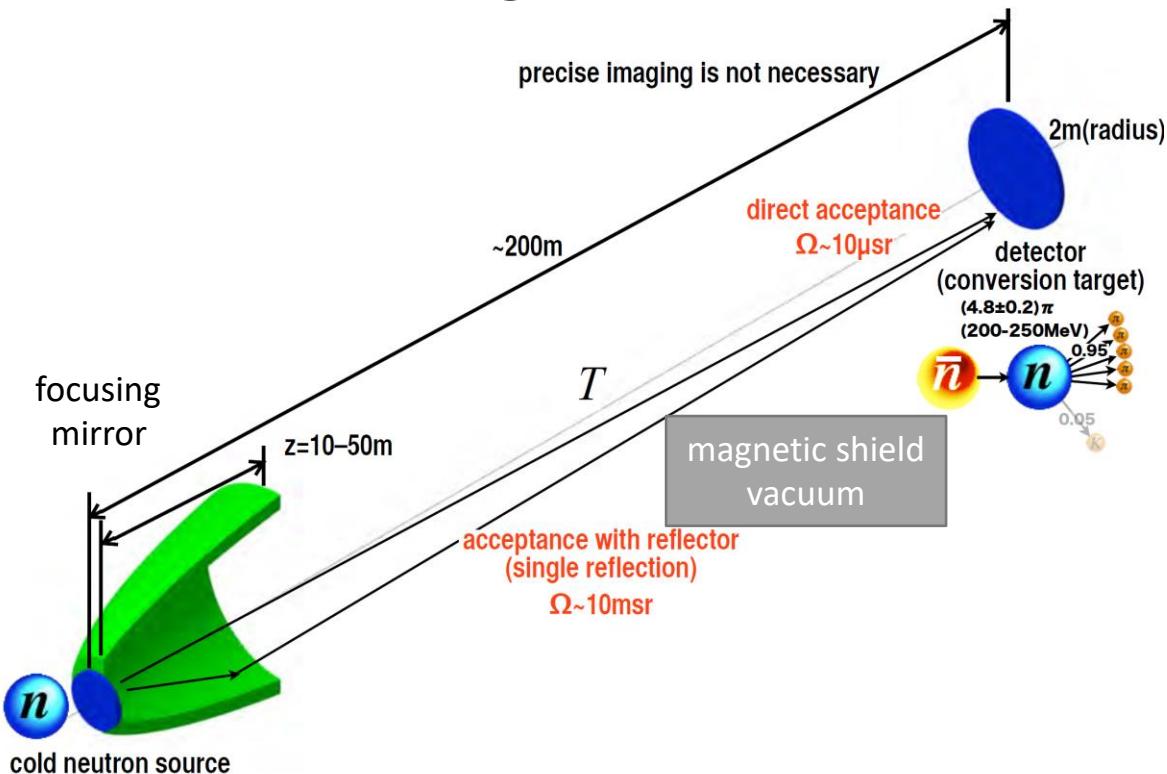
$$\tau_{n\bar{n}} \leq 5 \times 10^{10} \text{ sec}$$

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

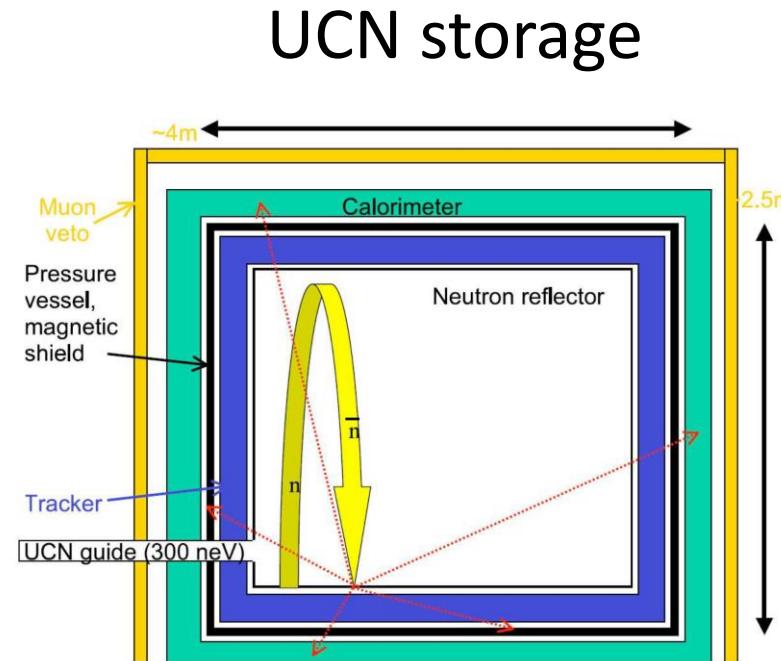


# n-nbar oscillation experiments

## Proposal @ ESS free flight cold neutron



- > few 10 times better sensitivity than ILL
- strongly depend on the cold neutron source performance



D.G. Phillips II et al., Phys. Rep. 612, 1-45 (2016)

UCN beam intensity ;  $\Phi_n = 10^8 \text{ n/sec}$

Storage time ;  $T_s = 500 \text{ sec}$  Flight time ;  $t_{\text{TOF}} = 1 \text{ sec}$

Detector efficiency ;  $\varepsilon = 0.5$

Measurement time ;  $T_{\text{mes.}} = 2 \times 10^7 \text{ sec}$

$$\rightarrow \tau_{n-n\bar{n}} \sim 7 \times 10^8 \text{ sec}$$

# Summary

Slow neutrons are unique probe

- to test standard model
- to search new physics
- There is a plan to build a new research reactor (10 MW) in Japan
  - we are designing to the slow neutron source to conduct the rich science programs

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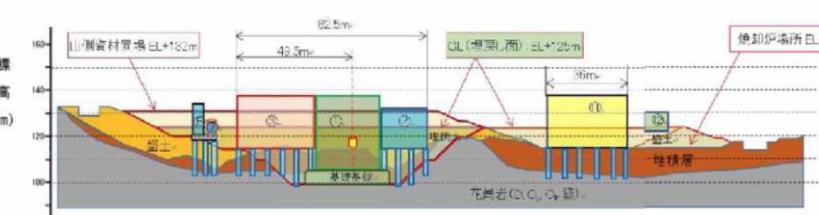
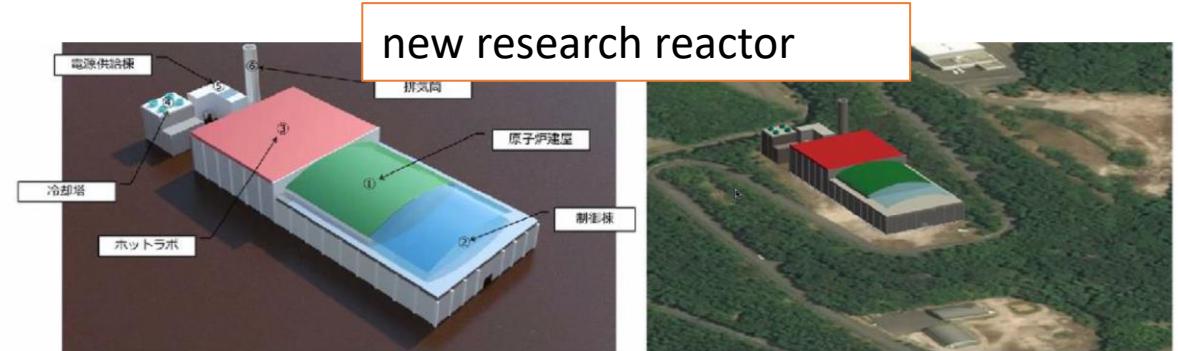
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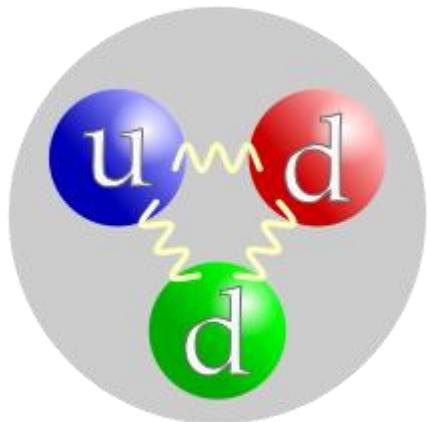
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# BUCKUP

# property of neutron



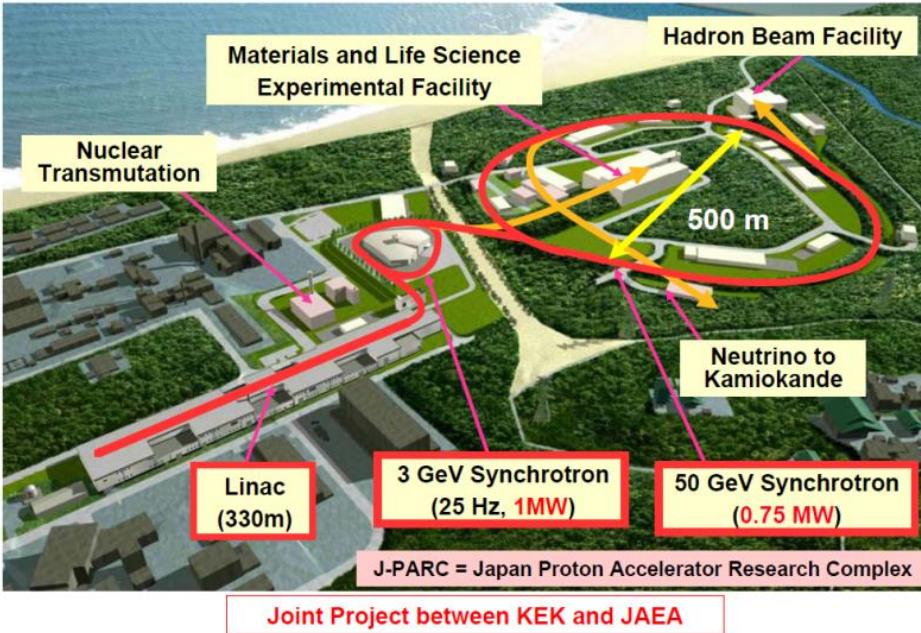
- Electro-magnetic interaction
  - electrically neutral
  - magnetic moment :  $60 \text{ neV/T}$ 
    - spin  $1/2$
- Strong interaction
  - Scattering length
- Weak interaction
  - $\beta$ -decay
    - lifetime:  $878.4 \pm 0.5 \text{ sec}$
- Gravity
  - mass:  $939.6 \text{ MeV/c}^2$
  - gravity

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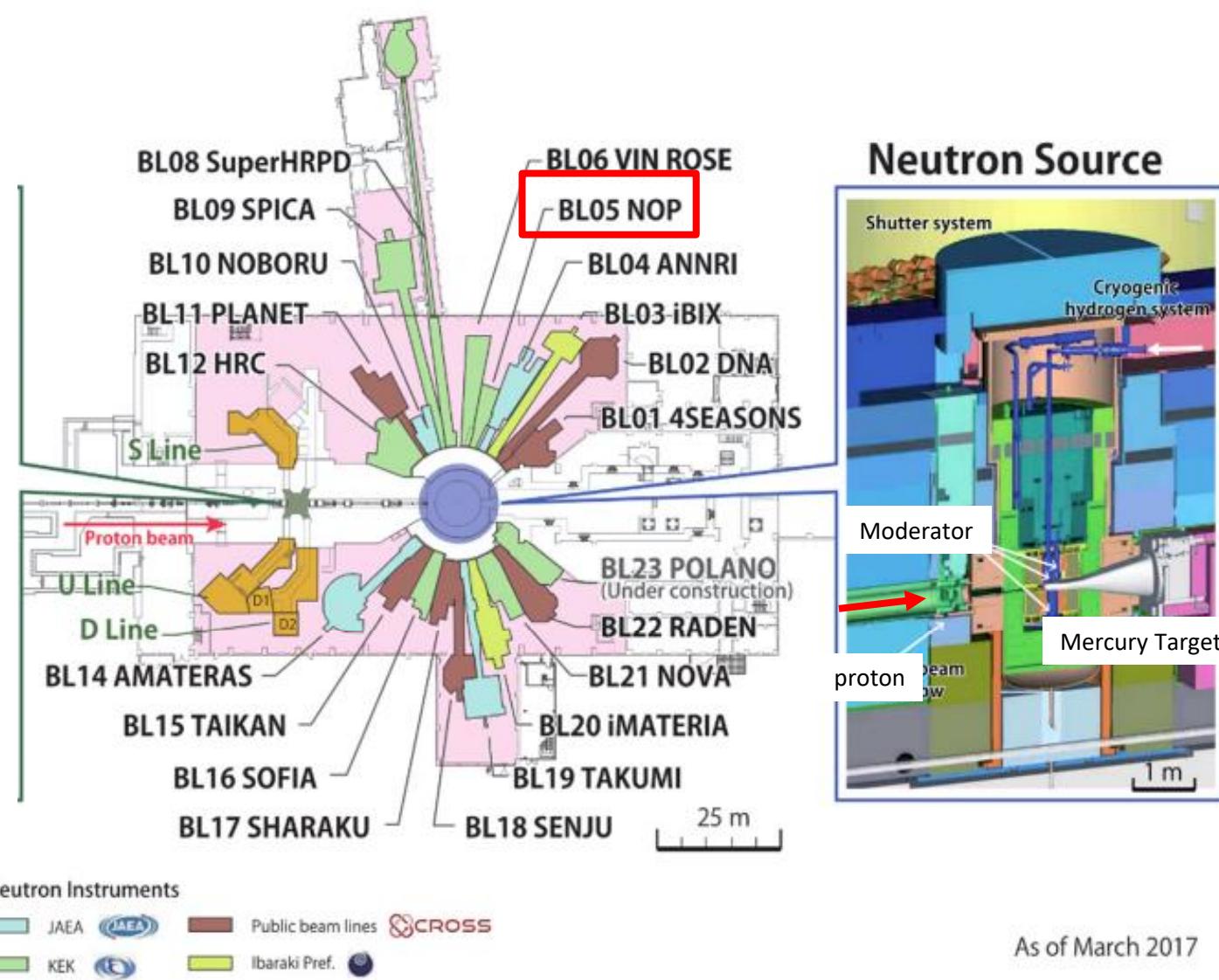
# J-PARC

## Materials and Life Science Experimental Facility(MLF)



### Neutron Beam Line at MLF

- 21 Beam line (+ 2 vacant port)
- Mainly for Material and Life Science
  - imaging
  - diffraction
  - Reflectometer
  - spin echo
- One Fundamental Physics Beam line
  - BL05 : NOP



# BL05: Neutron Optics and Fundamental Physics (NOP)



View of the Optics from Upstream

## High Polarization Branch

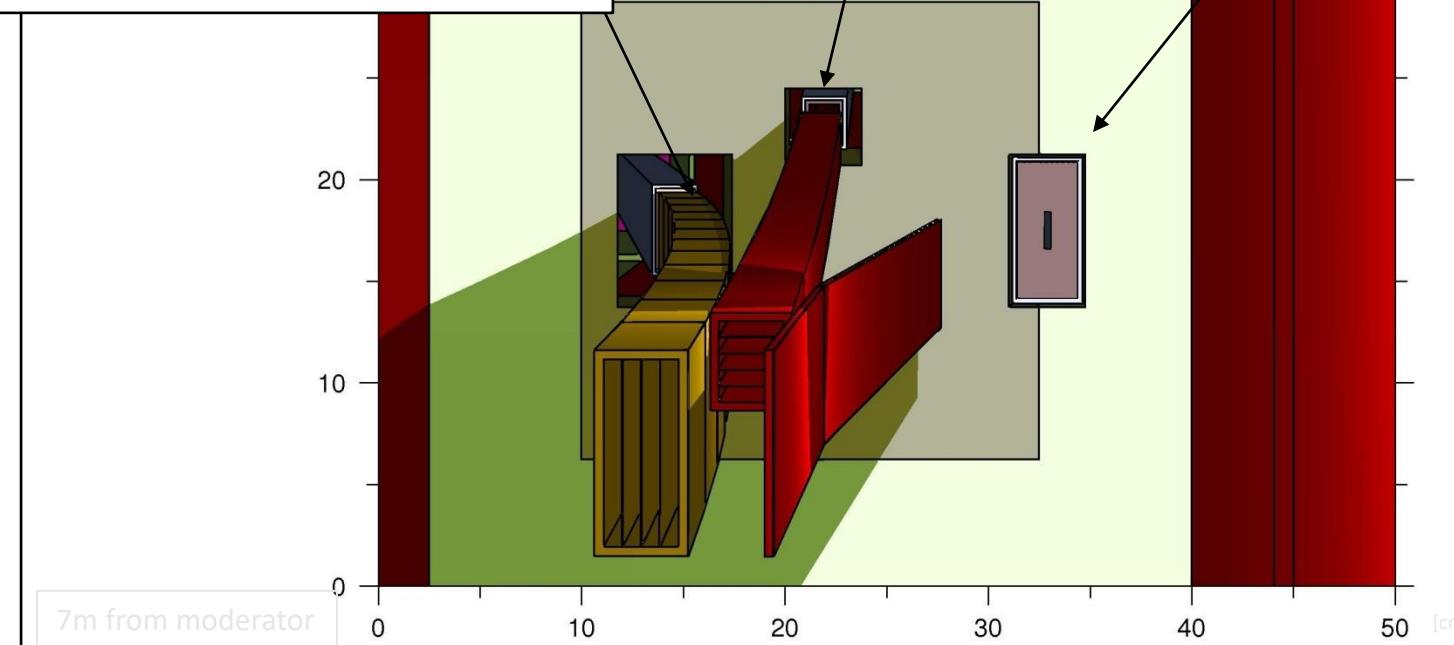
Experiment **Beta decay**  
Mirror Magnetic Supermirror(2.8Qc)  
Configuration Polygonal approximation  
12unit  $\times$  0.262 deg. ( $R=82m$ )  
Cross-section 40mm  $\times$  100mm  
Channel 4ch  
Bender Length 4.5 m (375mm  $\times$  6  $\times$  2)  
**Bending Angle** 3.14 deg.

## High Intensity Branch

Experiment **Scattering**  
Mirrors Supermirror (3Qc)  
Configuration Real Curve  
Curvature 100m  
Cross-section 50mm  $\times$  40mm  
Channel 5ch  
Bender Length 4.0 m (2.0m  $\times$  2)  
**Bending Angle** 2.58 deg.

## Low Divergence Branch

Experiment **Interferometer**  
Mirrors Supermirror (3Qc)  
Configuration 2 mirrors  
Critical Angle 0.95 deg.  
**Bending Angle** 3.85 deg.

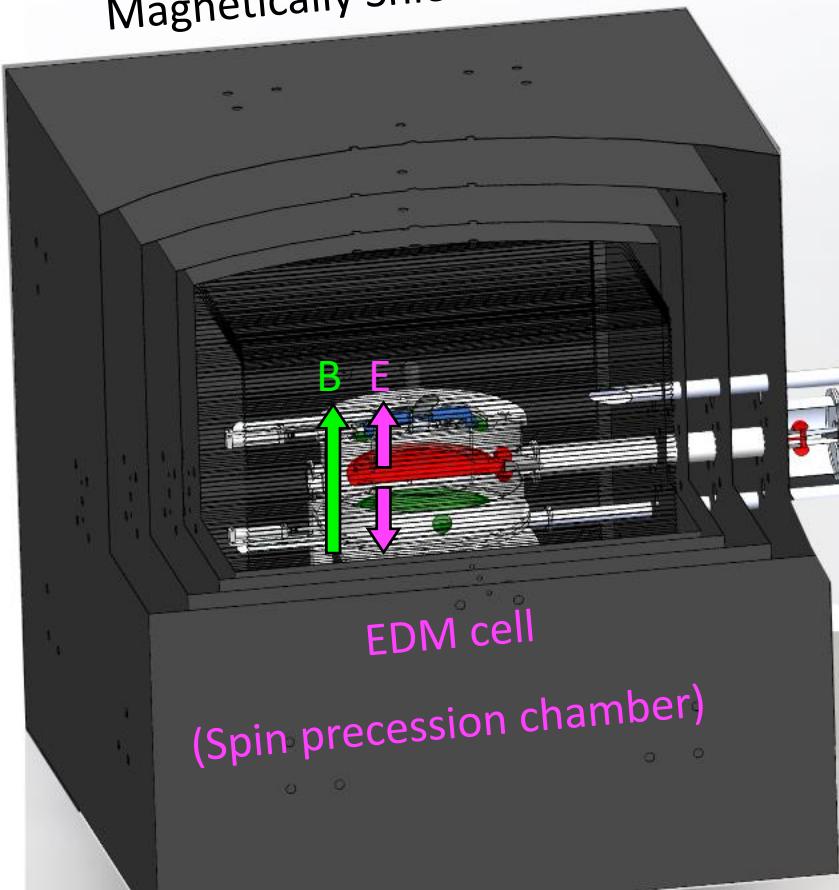


Mishima et al.,  
NIMA 600 (2009)  
342–345

# Overview of the TUCAN apparatus and KEK contribution

## nEDM Spectrometer

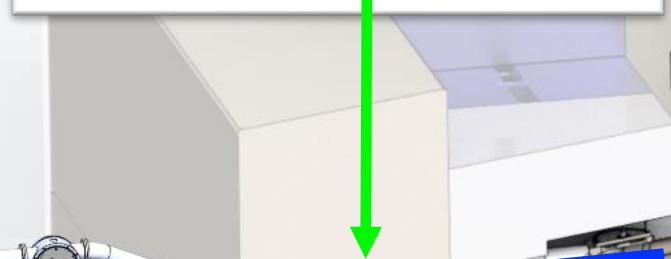
Magnetically Shielded Room



EDM cell  
(Spin precession chamber)



UCN guide development at J-PARC

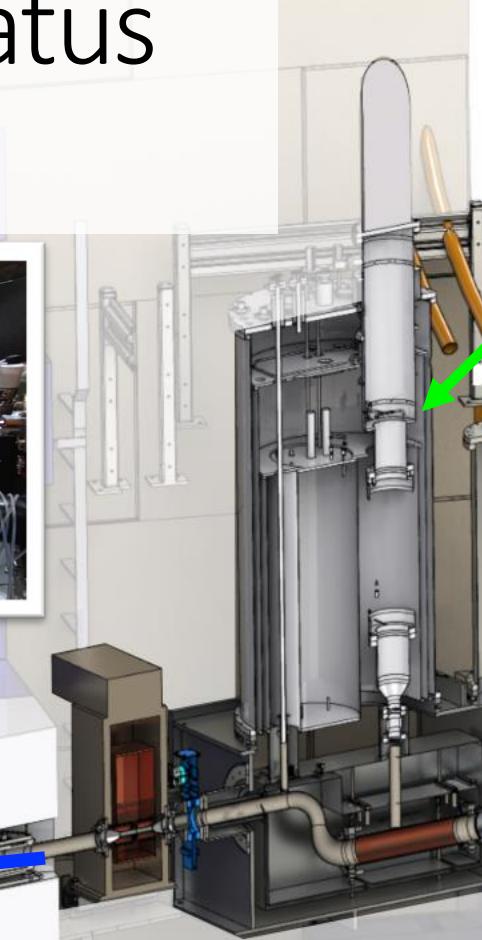


Polarized UCNs

Spin analysis &  
UCN detection



Spin Analyzer Development at J-PARC

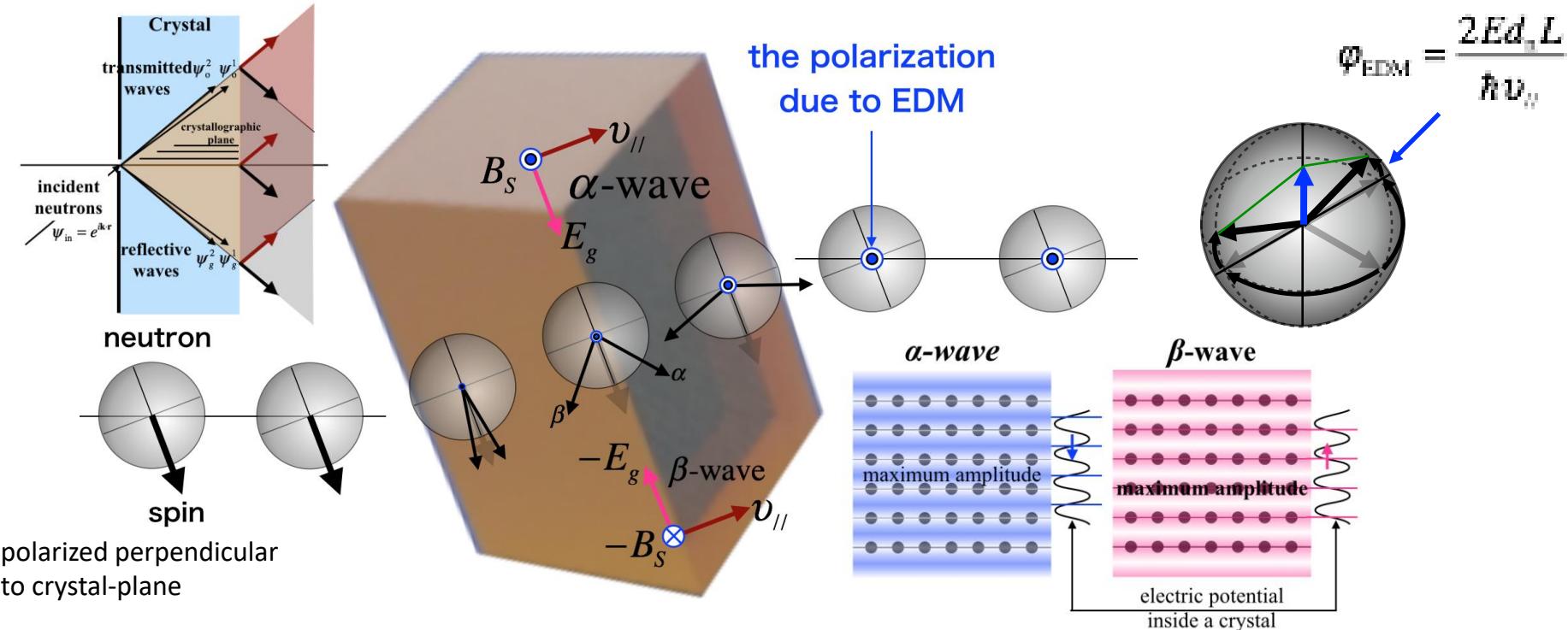


W target

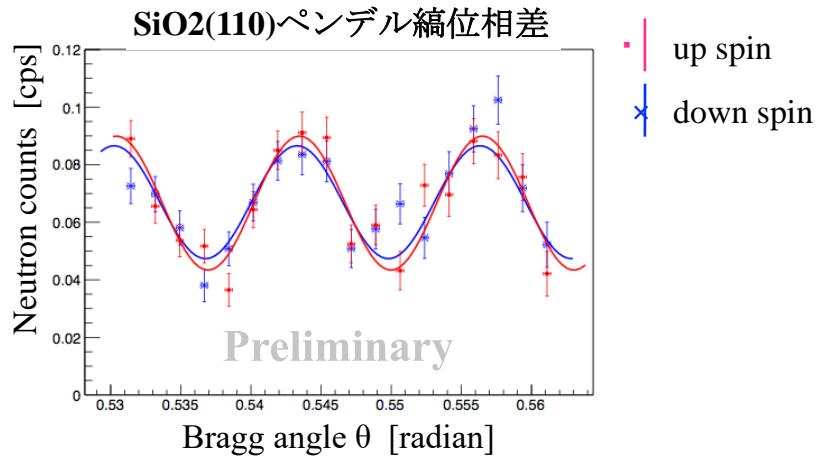
Proton Beam  
(480 MeV, 40  $\mu$ A)



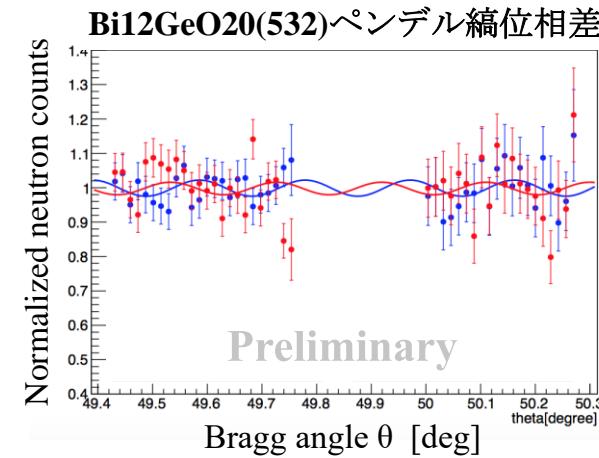
Helium-3 cryo. development  
at KEK/Tsukuba



### ペンドル縞を用いた結晶内電場の測定



$$E_g = (0.40 \pm 1.47) \times 10^{-8} [\text{V/cm}]$$

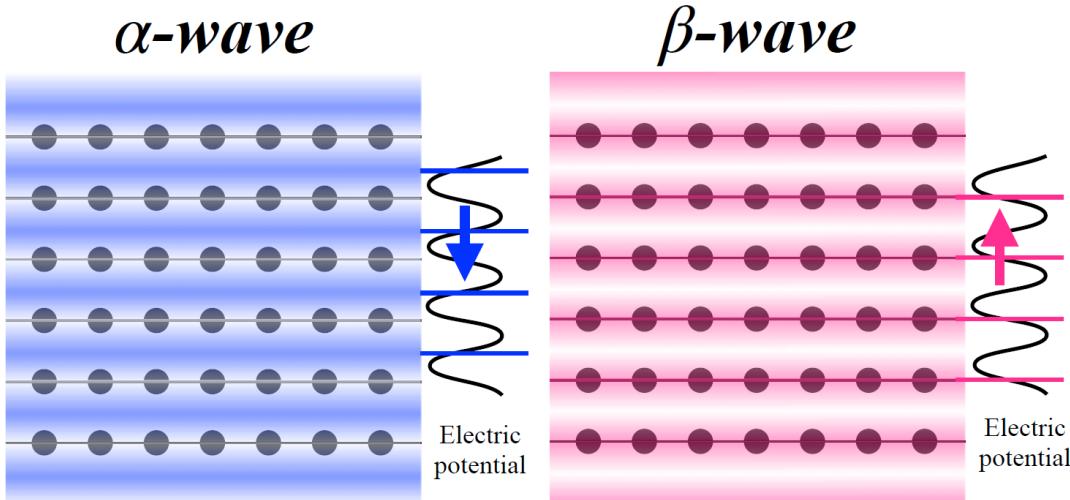
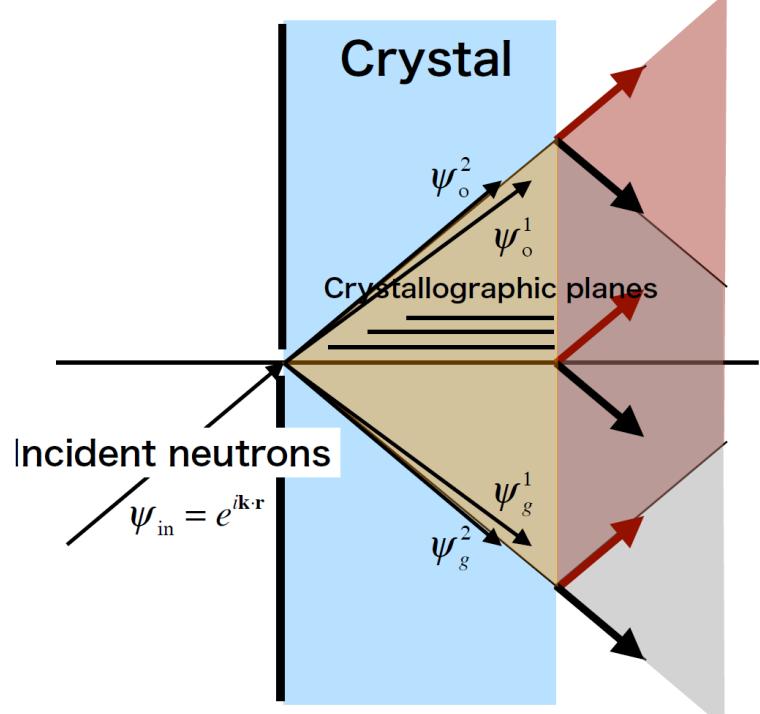


$$E_g = (3.5 \pm 2.0) \times 10^{-8} [\text{V/cm}]$$

# Dynamical Diffraction Theory

$$\psi_{\text{cry}} = \psi^1 + \psi^2 = A_o^1 e^{i\mathbf{k}_o^1 \cdot \mathbf{r}} + A_g^1 e^{i\mathbf{k}_g^1 \cdot \mathbf{r}} + A_o^2 e^{i\mathbf{k}_o^2 \cdot \mathbf{r}} + A_g^2 e^{i\mathbf{k}_g^2 \cdot \mathbf{r}}$$

$$\psi^1 = \psi_o^1 + \psi_g^1 = A_o^1 e^{i\mathbf{k}_o^1 \cdot \mathbf{r}} + A_g^1 e^{i\mathbf{k}_g^1 \cdot \mathbf{r}} \quad \psi^2 = \psi_o^2 + \psi_g^2 = A_o^2 e^{i\mathbf{k}_o^2 \cdot \mathbf{r}} + A_g^2 e^{i\mathbf{k}_g^2 \cdot \mathbf{r}}$$

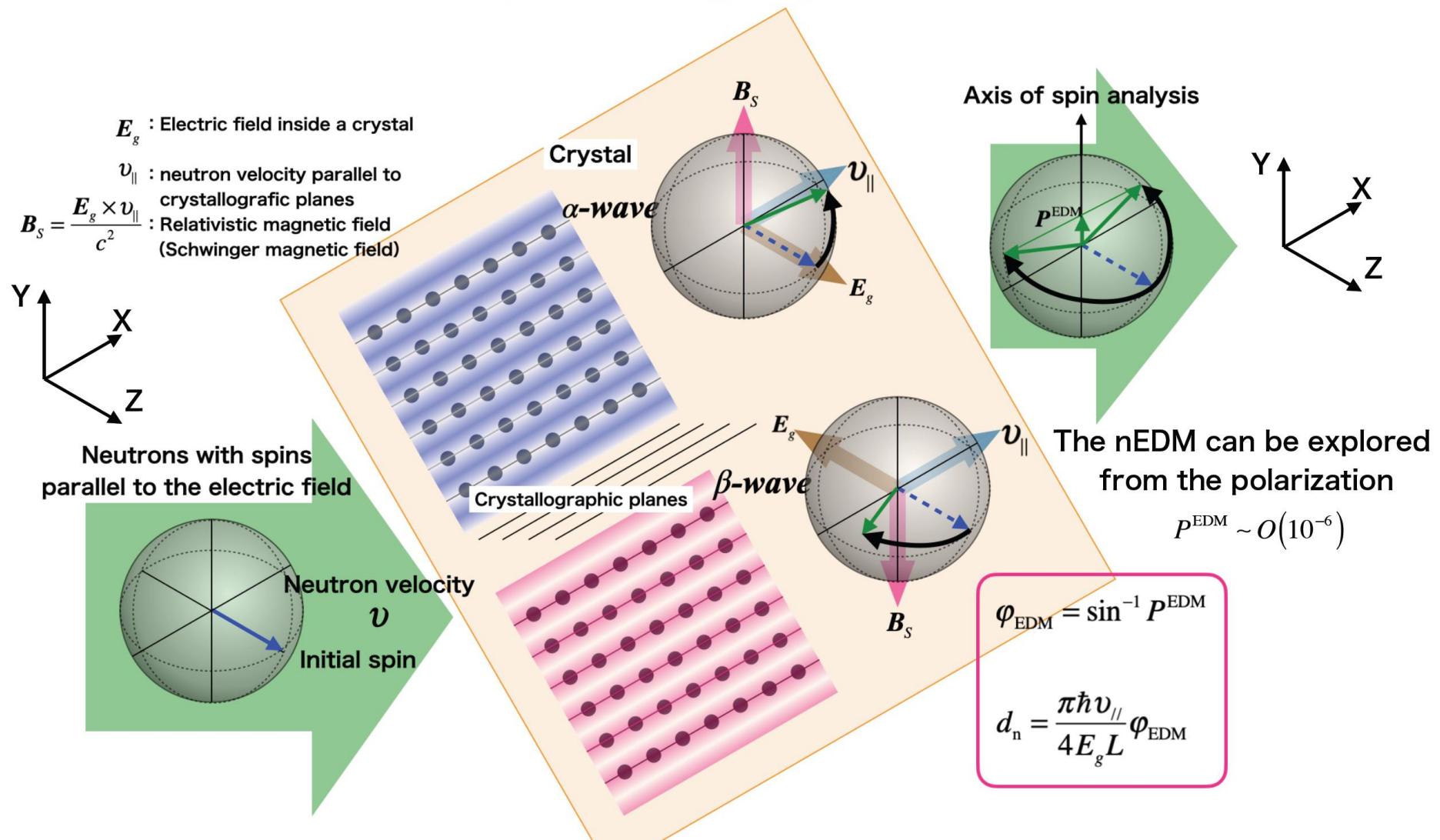


The superposition of transmitted and reflected waves with the same wavenumber can be described by two standing waves:  $\alpha$  waves with maxima between crystal lattices and  $\beta$  waves with maxima on the crystal lattice  
In the case of non-centrosymmetric crystals, the  $\alpha$  and  $\beta$  waves experience opposite electric fields.

→nEDM search

# Principle of nEDM measurement of crystal diffraction

Neutrons with spins parallel to the electric field are subject to spin polarization by the EDM at right angles to it



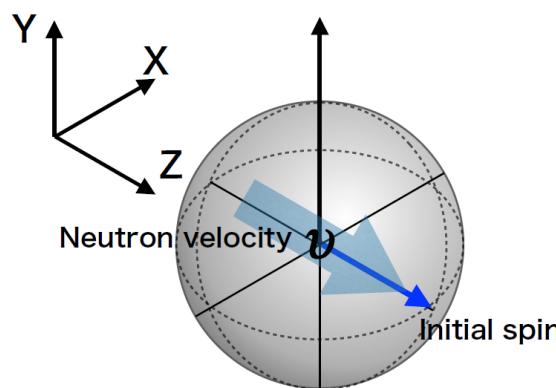
# Electric Field inside a Crystal

Crystal Diffraction Method	
相互作用時間 $\tau$ [s]	$\sim 10^{-3}$
電場 $E$ [V/cm]	$\sim 10^8$
カウント数 $n$ [n/s]	$\sim 10^4$
実験感度 $\sigma(d_n)$	$\sim 10^{-25}/\sqrt{\text{Day}}$

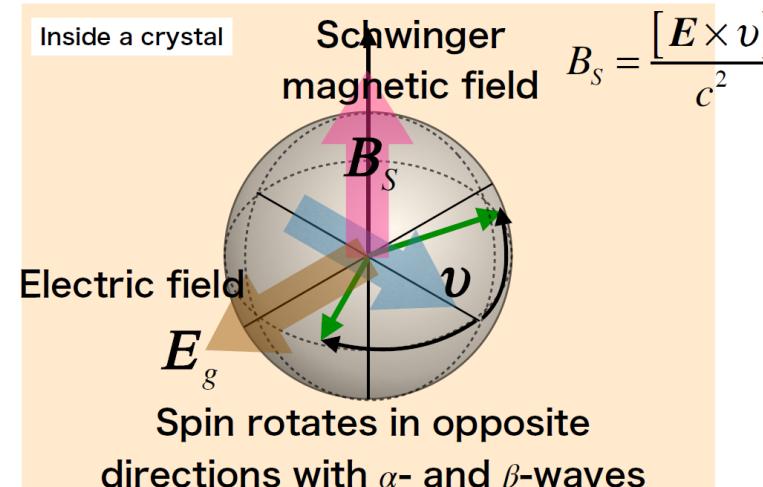
Documented value (calculated)		
Crstal	Plane(hkl)	Electric Field [V/cm]
SiO <sub>2</sub>	110	2.00
Bi <sub>12</sub> GeO <sub>20</sub>	433	5.20
Bi <sub>12</sub> GeO <sub>20</sub>	312	2.40
Bi <sub>4</sub> Si <sub>3</sub> O <sub>12</sub>	132	4.60

## Measurement of electric field in crystal by spin rotation

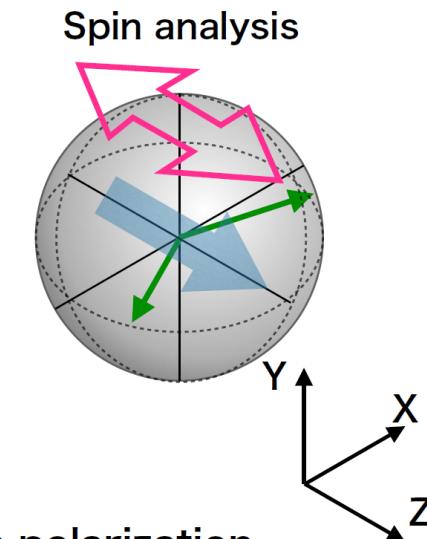
Neutrons with spins parallel to the electric field



Neutrons interact with Schwinger magnetic field inside a crystal.



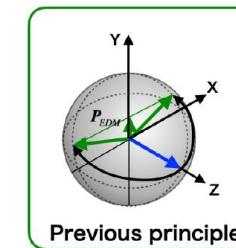
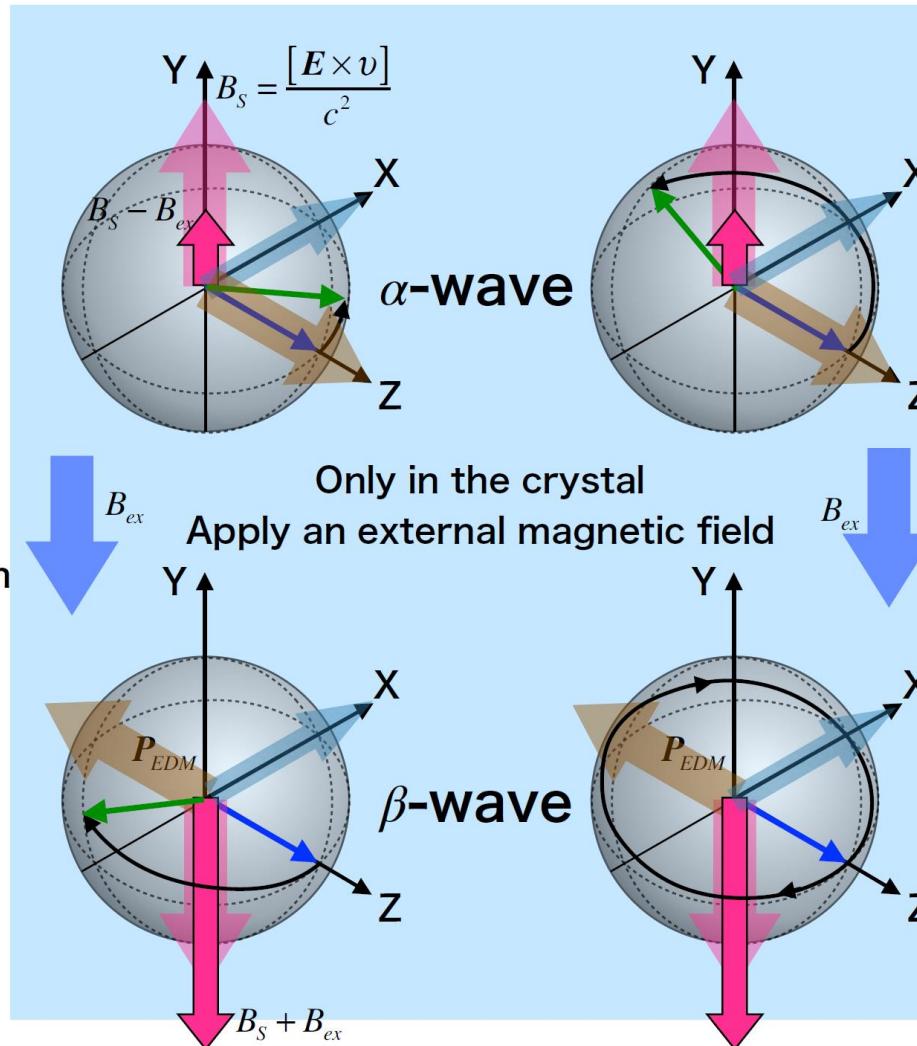
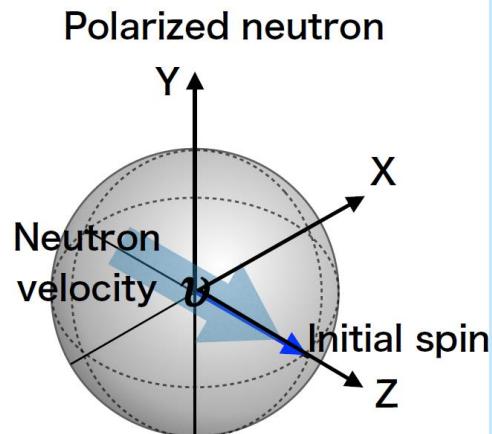
Measuring polarization



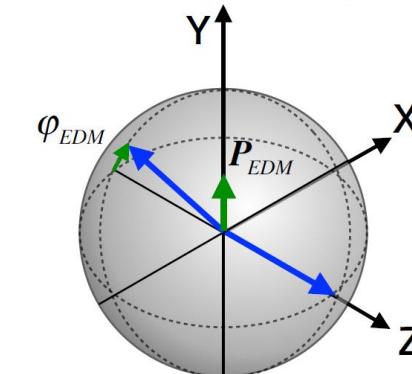
The electric field can be determined by examining the change in polarization

# Extend Interaction Time

Add an external magnetic field (inside the crystal only) to the Schwinger field to the Schwinger field to increase interaction time



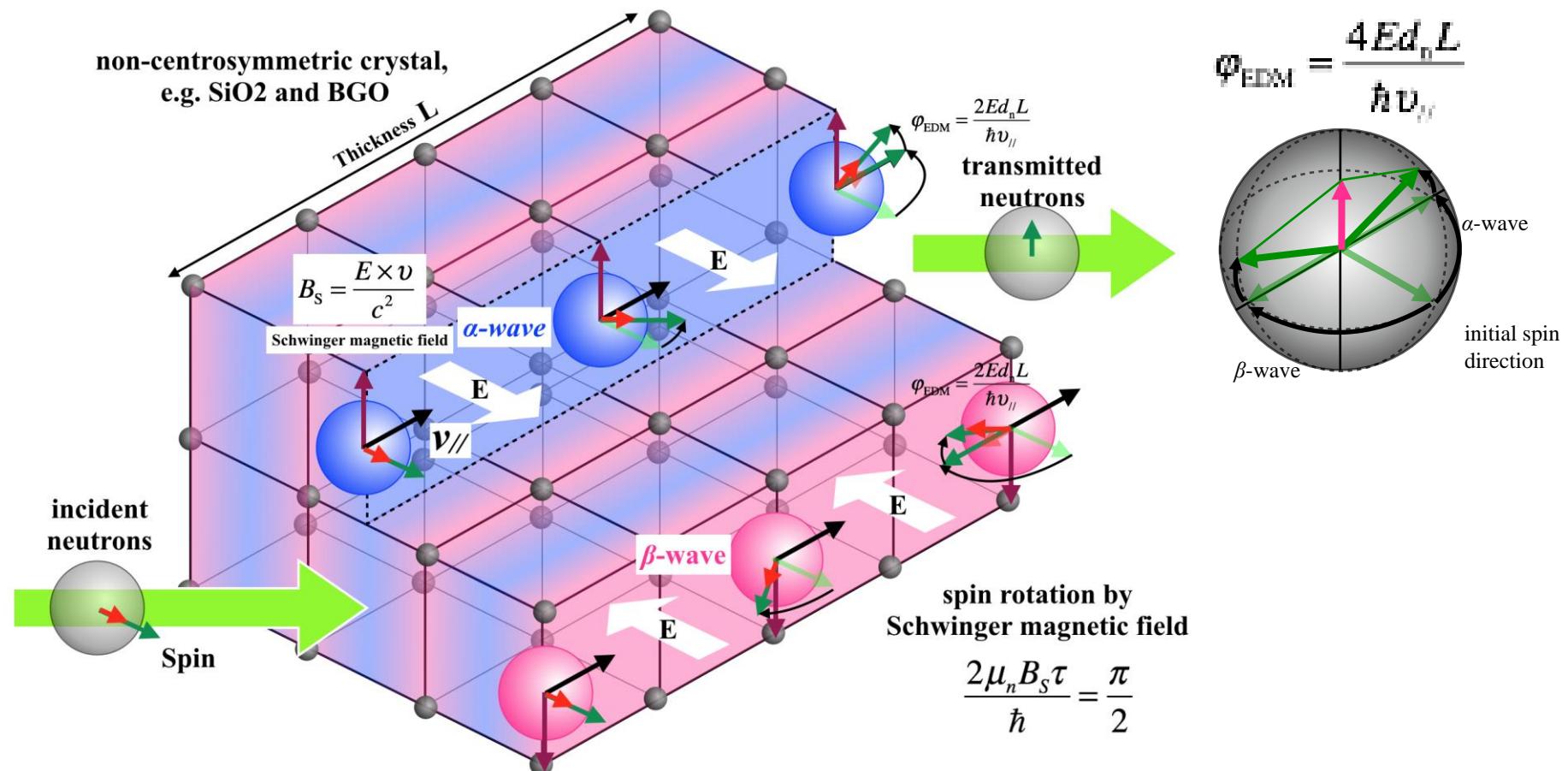
Axis of spin analysis



For example, If we add a magnetic field 9/11 times of  $B_S$ , the  $\beta$ -wave will rotate 5 times while the  $\alpha$ -wave rotates  $\pi$ .

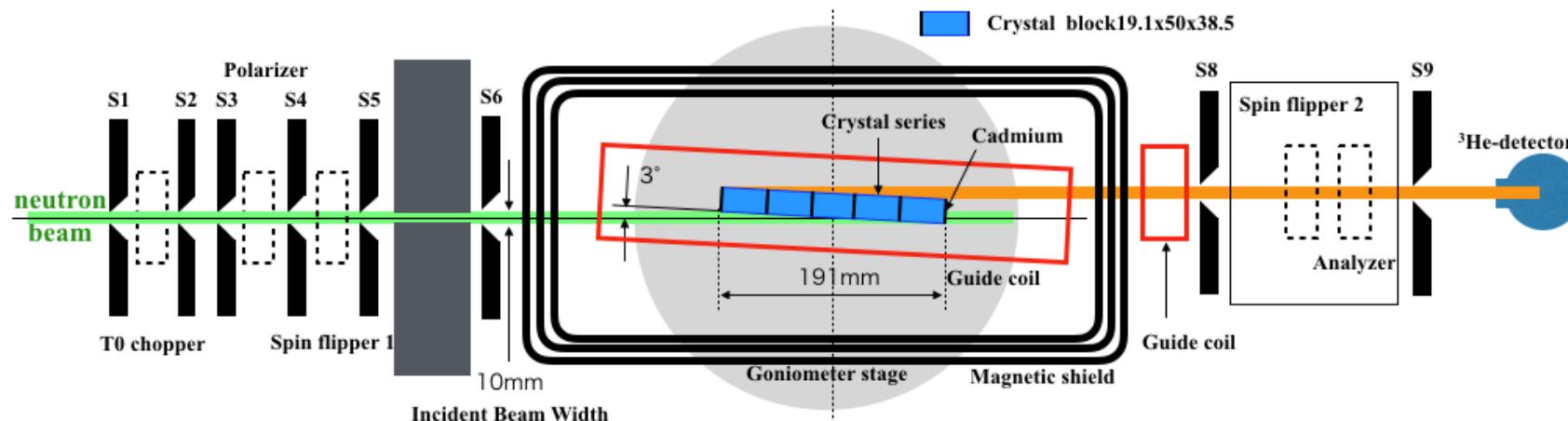
Measurement principle of the crystal diffraction method  
in the Laue geometry

Neutrons with parallel spin to the  $E$ -field will get a spin polarization perpendicular to initial spin direction by the inversive electric field and Schwinger magnetic field of  $\alpha$ -wave and  $\beta$ -wave respectively.



Conceptual setup for nEDM search experiment  
with SiO<sub>2</sub> in Laue geometry

J-PARC MLF BL17(Sharaku)



10 crystal blocks is seriesed, but only 5 blocks is showed in this figure.

**Design of magnetic condition.**

Schwinger magnetic field ~0.1G

Corresponding magnetic field to the false EDM of  $1 \cdot 10^{-26}$  ecm ~10<sup>-7</sup>G

**Practical use of poli-chromatic analysis.**

Use of multi crystal-planes and TOF method

**The most advantageous crystal and geometry.**

Another candidate; Bi<sub>12</sub>Ge<sub>0.20</sub>

**Use of the refractive neutrons, and so on.**

**Our first milestone is the upper limit ~10<sup>-24</sup> ecm by the crystal diffraction method.**

まずは、結晶法による最高感度 $1e-24$ を目指して

想定 : J-PARC MLF BL17(Sharaku) 1MW運転

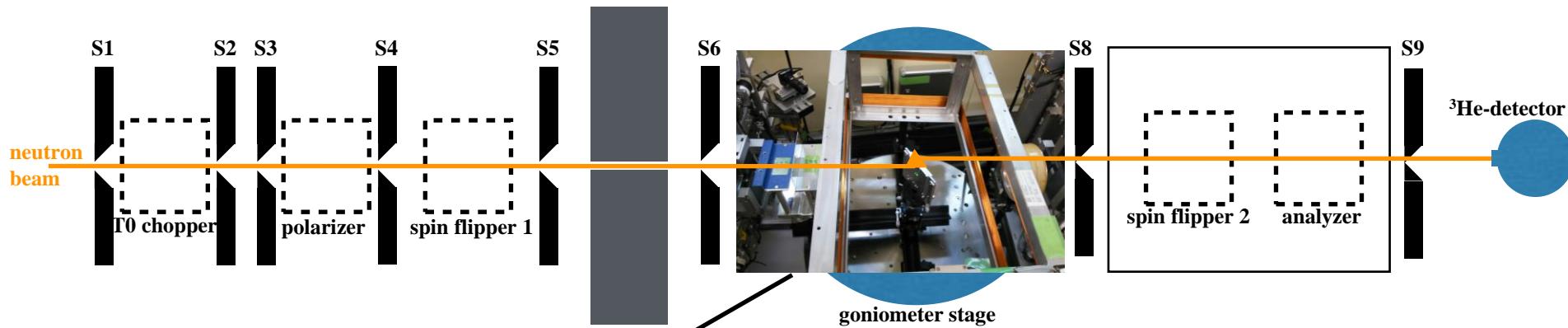
	V/cm	2.0E+08 注 : 文献値	5.2E+08 注 : 文献値	3.5E+08 注 : 現在の測定値
	mm	38.52	14.82	7.70
	mm x mm	50x382	50x382	50x382
	fm	15.6546	23.6949	133.52
	degree	88.5	88.5	88.5
	Å	4.91	3.29	3.48
	msec	1.83	0.50	0.70
	Gauss	0.047	0.172	0.123

$\text{SiO}_2(110)$ 約11日で $1e-24$ に到達する

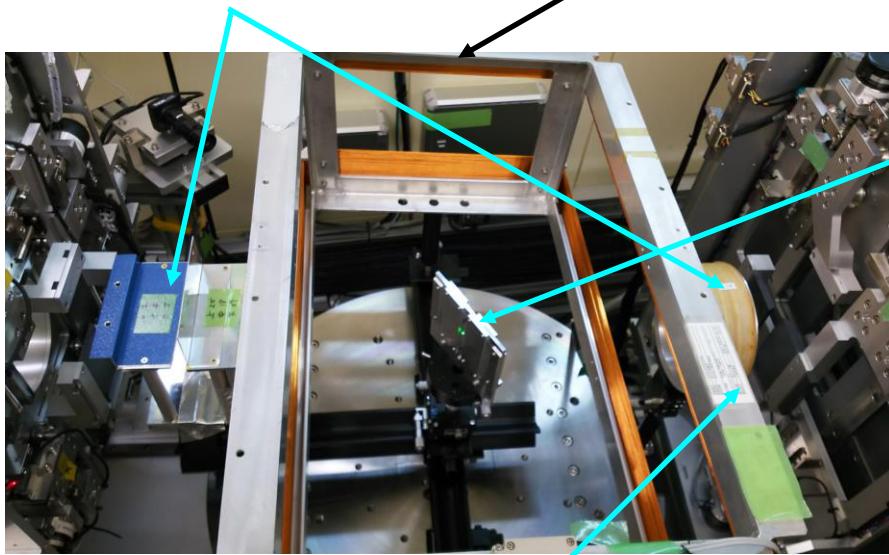
BGO(532)の良い結晶ができれば約1日で $1e-24$ に到達する

## Setup for the measurement of pendellösung fringes

J-PARC MLF BL17(Sharaku)



Magnets for adiabatic spin rotation

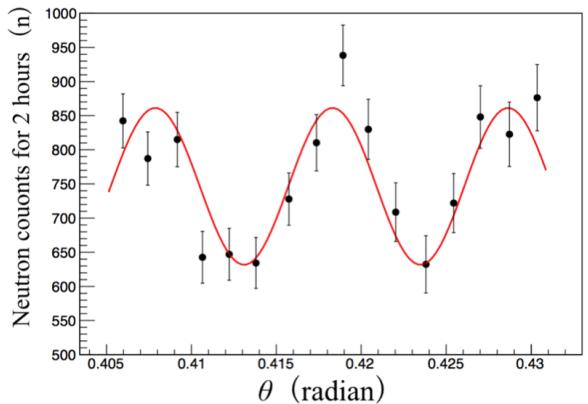


Crystal holder  
and slit system



Guide coil

**1. (2017/11) we had achieved to observe the Pendellösung fringes of a single Si crystal and established the technique**



Nuclear Inst. and Methods in Physics Research, A 908 (2018) 78–81

Pendellösung interferometry by using pulsed neutrons

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Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan

Pendellösung interferometry is one of the technique for accurate determination of the structure factors of crystals. Observation method of Pendellösung fringes by using pulsed cold neutrons and the time-of-flight analysis were established. We measured the nuclear scattering length of silicon by the Pendellösung fringes with pulsed neutrons as  $(4.125 \pm 0.003(\text{stat.}) \pm 0.028(\text{syst.}))$ . This indicates the applicability of Pendellösung interferometry at high-intensity pulsed neutron facilities for various precision measurements.

**2. (2018/12) The observation of the Pendellösung fringes with a non-centrosymmetric crystal, SiO<sub>2</sub>, by using non-polarized pulsed neutrons had been achieved.**

