Fundamental Physics with Pulsed Cold Neutrons at J-PARC

Kenji MISHIMA (IMSS)
for the NOP collaboration
J-PARC / MLF / BL05

J-PARC
Materials and Life Science
Experimental Facility (MLF)

Spallation neutron target (designed for 1MW)

Pulsed neutron Beam line BL05
Neutron optics and physics (NOP)
Neutron Lifetime Puzzle

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

Beam method: Count the decay

\[ \frac{dN}{dt} = \frac{N}{\tau} \]

Storage method: Count the missing

\[ \frac{N_1}{N_2} = e^{-\frac{(t_1-t_2)}{\tau}} \]

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

PRD 101, 056003 (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 $^3$He(n,p)$^3$H reaction are measured simultaneously.

Principle (Kossakowski, 1989)

Neutron bunch shorter than TPC

Count events during time of bunch in the TPC

- $\tau_n = \frac{1}{\rho \sigma_0 v_0} \left( \frac{S_n/\epsilon_n}{S_\beta/\epsilon_\beta} \right)$  
  \[ \beta\text{-decay} \]

- $S_\beta = \epsilon_e N \frac{L}{\tau_n v}$  
  \[ \text{neutron density} \]

- $S_n = \epsilon_n N \rho \sigma L$  
  \[ \text{cross section of } ^3\text{He reaction} \]

- $\sigma_v = \sigma_0 v_0$  
  \[ \text{cross section at } v_0, v_0=2200\text{[m/s]} \]

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

- Drift cage and MWPC
- SFC in lead shield
- Iron shield
- Vacuum chamber
- Neutron beam
- Gas handing
The first result from J-PARC

The published result by using data using 2014-2016 was

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

Multi layer type
Neutron interferometer

Neutron interferometer is an instrument that measures the interference of the wave function of a single neutron.

Interferometer from silicon crystal
- Only mono-energetic neutrons are available.
- Mainly used in nuclear reactors.
- Limited by the size of Si crystal
- Phase shift can be obtained by rotating a phase plate (several minutes)
- Very sensitive for temperature and vibration, which causes system errors.

Interferometer with neutron mirrors attached to an optical element
- Compatible with white (pulsed) neutrons
- TOF directly shows the phase difference
- No limit to the size, in principle
- Good matching with highest peak intensity neutron at J-PARC

Conventional type : Single crystal Si neutron interferometer

Available with pulse source: Multi layer type neutron Interferometer

http://www.neutroninterferometry.com/
Demonstration at BL05

- Demonstration of the multilayer interferometer was succeeded.
  - Clear oscillation with TOF
  - Stable operation in an half day
  - Phase difference with samples

\[ \Delta \phi = 2\pi \frac{mL}{h^2} \Delta E \lambda \propto t_{\text{tof}} \]
Doppler shifter type
Pulsed UCN source
Ultra Cold Neutron (UCN)

UCN:
- Energy $\sim 200$ neV
- Velocity $\sim 5$ m/s
- Wavelength $\sim 50$ nm

An UCN feels the averaged material potential and is totally reflected on the material surface.
Ex. : 252 neV for Ni

UCN can be stored more than 100 s in a material or magnetic bottle, and applied to many fundamental physics experiments.
Ex. nEDM, lifetime, gravitational quantization, etc.
Doppler shifter is on the Beamline. Pulsed UCNs are provided.

Monochromatic supermirrors of $m = 10 \, (68 \, \text{m/s})$ is used.

Mirror velocity should be half of the neutron velocity to produce UCN.

Moving mirror reduce velocity of neutrons.

$|V_r \perp| = |V_{n \perp} - 2V_{m \perp}|$

Mirror sys.  Lab sys.

Elastic reflection  Doppler shift

Doppler shifter
\[ v_n = 136 \text{ m/s} \pm 8\% \text{ extracted} \]

**Setup**

- Pb & B\(_4\)C shield
- Monochromatic mirrors
- \(^3\)He detector
- \(^2\)D detector
- Cold neutron
- \(136 \text{ m/s} \pm 8\%\)

**UCN Production**

- \(^{136}\text{m/s} = 20\text{ cm}\)
- \(80\text{ cps} \Rightarrow 1.4\text{ UCN/cm}^3\)

---

Summary

- Various fundamental physics experiments are ongoing using pulsed neutron at J-PARC
  1. Neutron lifetime with pulsed neutron beam
  2. A multi-layer type neutron interferometer
  3. Doppler shifter type pulsed UCN source
  4. Search of short-range unknown intermediate force
  5. Position sensitive neutron detector using nuclear emulsion with sub-micron resolution
backup
Why is gravity so weak?

Currently discovered interactions are

- Strong $\sim 1$
- Electromagnetic $\sim 10^{-2}$
- Weak $\sim 10^{-5}$
- Gravity $\sim 10^{-40}$

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.

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

Nima Arkani-Hamed, Savas Dimopoulos and Gia Dvali
Experimental Setup

- Physics run has been started in late 2016.
- J-PARC beam power : 150 kW
- 2 atm Xe and He with gas circulation
Results

- Set new limit below 0.1 nm.
- Degradation > 0.1 nm is due to background caused by scattered neutron from beam stopper.
- < 0.01 nm is dominated by “Schwinger effect”.
Nuclear emulsion - a high position resolution tracking detector for ionizing particles.

Emulsion gel (AgBr·I crystals dispersed in gelatin)

Cross sectional view

- 44μm Emulsion layer
- 210μm Base (plastic)
- 44μm Emulsion layer

Microscopic view (after development)

A track of minimum ionizing particle
: Grain Density (GD) ~30/100μm

10GeV \( \pi^- \)

Fog (chemical noise)
Fog Density (FD) ~3/(10μm)^3

N. Naganawa et al., UCN workshop at Mainz (Mar.2016)
Neutron detector with sub-micrometer spatial resolution neutron detector using nuclear emulsion

Detection principle: neutron absorption by $^{10}$B

\[ n + ^{10}\text{B} \rightarrow \alpha + ^{7}\text{Li} + 2.79 \text{ MeV (6\%)} \]
\[ \alpha + ^{7}\text{Li} + 2.31 \text{ MeV (94\%)} \]

Tracks by UCN absorption were successfully observed.

Efficiency:

\[ \epsilon_{\text{UCN}} = 12\pm2\% \text{ (expected 11\pm3 \%)} \]
\[ \epsilon_{\text{cold}} = 0.16\pm0.02\% \text{ (expected 0.11\pm0.03\%)} \]

By extrapolating linear-fit grains (40 nm diameter) of a track to the B4C layer, we can determine the neutron reaction position with an ambiguity of the thickness of the layer.
Estimation of spatial resolution using tracks

Position data of grains of alpha tacks from absorption

- Transverse: independent to angles → resolution: 11 nm
- Longitudinal: depend on angles (θ) whole acceptance (0 ≤ tanθ ≤ 13.8) → resolution: 11 nm ~ 1μm tanθ < 1.9 (34% of whole statistics) → resolution: 11 - 99 nm