論文の内容の要旨

Precise Neutron Lifetime Measurement Using Pulsed Neutron Beams

（パルス中性子ビームを用いた中性子寿命の精密測定）

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The neutron beta-decay lifetime (τ_n～880 s) is an important parameter in the Standard Model of particle physics, cosmology, and astrophysics. For example, τ_n is a parameter which can be used to determine the V_{ud} parameter of the Cabibbo-Kobayashi-Maskawa quark mixing matrix. The neutron lifetime is also one of the input parameters for the Big Bang Nucleosynthesis, which predicts the light element synthesis in the early universe.

Since the discovery of a neutron by James Chadwick in 1932, various experiments have been conducted to measure τ_n. They are mainly divided into two independent methods. One is to measure the number of protons from neutron beta-decays, which was conducted at National Institute of Standards and Technology Center for Neutron Research. The other is to store ultra cold neutrons (UCNs) in a chamber and count the number of remaining UCNs after a certain period of time. The average result of the in-flight method gives (888.0±2.2) s, while that of the UCN storage method gives (879.6±0.6) s. As a result, there exists a significant discrepancy of 8.4 s (corresponding to 4.0 σ) between the results of these two methods, which is recognized as the “neutron

lifetime puzzle".

In order to resolve this problem, we conducted a new type of experiment using the pulsed neutron beams at Japan Proton Accelerator Research Complex (J-PARC). We set our eventual precision of 1 second for measuring τ_n, which is comparable to the current best precision measurement. The experiment was carried out at the polarized beam branch of the beamline BL05 in Materials and Life Science Experimental Facility at J-PARC. The neutron beams from the polarization beam branch first enter a spin flip chopper, which is composed of radio-frequency coils and magnetic super mirrors. The magnetic super mirror can selectively reflect neutrons depending on the neutron polarization direction. By adjusting the radio-frequency coil operation, a neutron bunch with an arbitrary length can be formed.

A time projection chamber (TPC) made of polyether ether ketone is developed for a beta-decay counter to realize the low-background condition. The inside walls are completely covered by ^{6}LiF plates to absorb scattered neutrons without prompt γ-ray emission. There is a two-dimensional multi wire proportional chamber in the upper part of the TPC, which can reconstruct the three-dimensional track of charged particles. Helium and CO_2 gases are used as an operation gas. In addition to these gases, a small amount of ^{3}He gas, which typically amounts to 100 mPa pressure, is injected into the TPC. The neutron flux can be evaluated by counting the number of the ^{3}He(n, p)^{3}H events in the TPC. Since the length of each neutron bunch is about half of the TPC length, the TPC can detect both beta-decays and the ^{3}He(n, p)^{3}H reactions with a 4π solid angle acceptance and the good signal-to-noise ratio. The neutron lifetime can be expressed using the number of beta-decays (S_β)and the ^{3}He(n, p)^{3}H events (S_{3He}) as

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\frac{S_{3He}/\varepsilon_{3He}}{S_\beta/\varepsilon_\beta} ,$$

where ε_{3He} and ε_β are the respective selection efficiencies, σ_0=(5333±7) barn is the ^{3}He(n, p)^{3}H cross section for a neutron with a velocity of v_0 = 2200 m/s, and ρ is the ^{3}He number density in the TPC.

The detector response is simulated using the Geant4-based Monte Carlo simulation software. The simulation result is used to evaluate the signal selection efficiencies and expected background amount in the signal region. The difference of the signal selection efficiencies between beta-decays and the ^{3}He(n, p)^{3}H events can be corrected. The simulation procedure is divided into two processes: the particle simulation and the detector response simulation. In the particle simulation process, the detector setup at the BL05 polarization beam branch is implemented. The particle transportation and the ionization process in the TPC is simulated, and the corresponding energy deposit from charged particles is calculated as a function of its position. In the detector simulation, the energy deposit is converted into anode, field, and cathode wire waveforms.

We started the data acquisition in May 2014, and we have continuously taken data every year through 2018. In total, we obtained 1094 hours of beam-incident data, and 6.6×10^{11} neutron have entered the TPC. The overall combined data gives a statistical error of about a few seconds on the neutron lifetime. The signal events are counted only when each of the neutron bunches are completely inside the TPC sensitive region. As a result, the systematic uncertainties originating from the TPC insensitive region can be eliminated.

There are several kinds of backgrounds expected for the neutron beta-decay events. The constant background, such as cosmic rays and environmental radiation, can be subtracted using the shutter-closed data. In the shutter-closed data, the neutron beams are stopped by a ^{6}LiF plate at the entrance of the TPC, thus the TPC events without the presence of the neutron beams can be obtained. There also exists the backgrounds related the neutron beams. For example, scattered neutrons interact with the TPC wall, which emits prompt γ-rays and undergoes Compton scattering in the TPC. This kind of backgrounds cannot be subtracted using the shutter-closed data. Since the background mainly originates at the TPC wall, it can be separated based on how far the track starting point is from the TPC center. Using this parameter, the simulated background events are normalized, and the total background amount in the signal region is subtracted. Finally, the result combining all the data is evaluated to be 894.6 ± 4.4 (stat.) +7.6 (sys.) s. This is the first result of the neutron lifetime measurement that obtaining a 1%-level of the precision using the pulsed neutron beams.

Although our result is closer to the averaged result of the in-flight method, it is also consistent with the averaged result of the UCN storage method. We do not yet know what causes the discrepancy between the in-flight method and the UCN storage method: whether it is simply caused by missing some systematic effects or it indicates new physics beyond our understanding. Our result is not precise enough to give any indication of the discrepancy puzzle, hence further precise measurement is required. Several upgrade plans to reduce both the statistical and systematic uncertainties are ongoing, such as the spin flip chopper upgrade and the low-pressure operation of the TPC.