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Development of a Cylindrical Neutron Counter System for the J-PARC E80 Experiment

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We are developing a cylindrical neutron counter (CNC) system for the J-PARC E80 experiment, which aims to study a kaonic nuclear bound state with three nucleons, $\bar{K}NNN$. To achieve the required timing resolution ($<$ 100 ps), we tested the performance of plastic scintillator modules with various light guide lengths using a positron beam at RARiS-Mikamine, Tohoku University. The best resolution is obtained without a light guide, while the longer light guides degrade timing performance due to signal reduction. Based on this result, a no-light-guide configuration was adopted for the CNC.

§1. Introduction

Given the well-established strongly attractive interaction between an anti-kaon and a nucleon, the existence of nuclear bound states comprising an anti-kaon and a nucleon or nuclei - *i.e.*, kaonic nuclei - is naturally expected. In recent years, the $\Lambda(1405)$, long recognized as an exotic hadron, has been understood as an anti-kaon-nucleon bound state [1]. Additionally, the lightest kaonic nuclear bound state, $\bar{K}NN$, was discovered in the J-PARC E15 experiment [2, 3]. However, the properties of the observed $\bar{K}NN$ state, such as its spin and parity, remain unknown. Furthermore, it is still unclear whether kaonic nuclei beyond $\bar{K}NN$ exist.

To address these questions, we plan to conduct a new experiment: the J-PARC E80 experiment. The primary goal of J-PARC E80 is to search for an anti-kaon and three-nucleon bound state, $\bar{K}NNN$, via the in-flight K^- reaction on ^{4}He. Specifically, we focus on the following reaction: $K^- + {}^4\mathrm{He} \rightarrow K^-ppn + n \rightarrow \Lambda + p + n + n$. K^-ppn is the $\bar{K}NNN$ system with I = 1/2 and $J^P = 0^-$. Our objective is to identify all final-state particles from this reaction. To achieve this, a large-acceptance spectrometer is required. Additionally, since the reaction of interest produces two neutrons, the spectrometer must have excellent neutron detection capabilities.

We have designed a large solenoid magnet-based spectrometer. The solenoid magnet has an inner bore diameter of 2.14 m and a length of 2.92 m. The conceptual design of the spectrometer is illustrated in Fig.1. The target (^{4}He) is placed at the center of the spectrometer. Surrounding the target is the vertex fiber tracker (VFT). Beyond the VFT, a cylindrical drift chamber (CDC) is positioned to track charged particles and analyze their momentum, in combination with the VFT. A cylindrical neutron detector (CNC) is placed outside the CDC. The CNC is also used as a trigger counter and for particle identification of charged particles through time-of-flight (TOF) measurement.

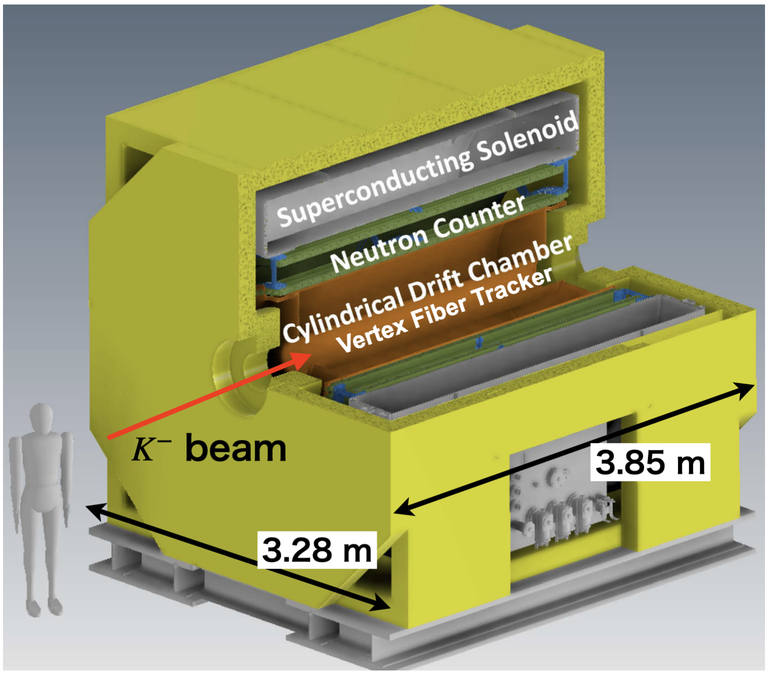

Fig.1. Design of the spectrometer. Details are provided in the text.

The CNC consists of several layers of detector modules arranged in a cylindrical configuration. The CNC is located at a radius of 530 mm from the beam axis. To achieve sufficient neutron detection efficiency, a total thickness of 15 cm of plastic scintillator is required. In that case, the expected neutron detection efficiency is 15% $\sim$ 45% which depends on the neutron momentum. And in order to collect data over a broader kinematic range, it is desirable to extend the CNC along the beam axis as far as possible, within the limit of 3.32 m, which is decided by the length of solenoid magnet.

As an initial design, CNC consists of 32 modules in a layer whose scintillators were made of Eljen EJ-200 with dimensions of 2.6 m in length, 120 mm in width, and 50 mm in thickness, and these modules were configured in three layers. The signals from the scintillator were planned to be read out by fine-mesh photomultiplier tubes (H8409), which are attached to both ends of each module.

We have two issues to address before constructing the CNC modules. The first is the time resolution of the module. The momentum range of the final-state particles from the decay of the $\bar{K}NNN$ bound state is up to about 800 MeV/c. To separate pions and kaons at a momentum at 800 MeV/c with a 3-standard-deviation time resolution, the CNC module must achieve a time resolution better than 100 ps. Another key consideration is the design of the light guide. Since the cross section of the scintillator is 120 mm $\times$ 50 mm, while the sensitive area of the photon detector is approximately 27 mm in diameter, a light guide must be designed to efficiently collect and transmit light from the scintillator.

A longer light guide is expected to improve the time resolution by enhancing the light collection efficiency as a result of shallower reflection angles. However, increasing the light guide length reduces the solid angle for direct scintillation light to reach the PMT, thereby worsening the time resolution. Additionally, it decreases the effective length of the plastic scintillator, resulting in reduced acceptance.

In this paper, we report the results of a test experiment on the length of light guides for the CNC, conducted using a positron beam at RARiS-Mikamine, Tohoku University.

§2. Setup for the experiment

To evaluate the effect of the light guide length on the CNC, we prepared a plastic scintillator (EJ-200) with dimensions of 120 mm × 50 mm × 1500 mm (width × thickness × length) and three versions of light guides with lengths of 115 mm, 230 mm, and 345 mm. The produced scintillator and light guides are illustrated in Fig.2. Each light guide was attached to the same scintillator with using optical grease, and the performance was tested individually.

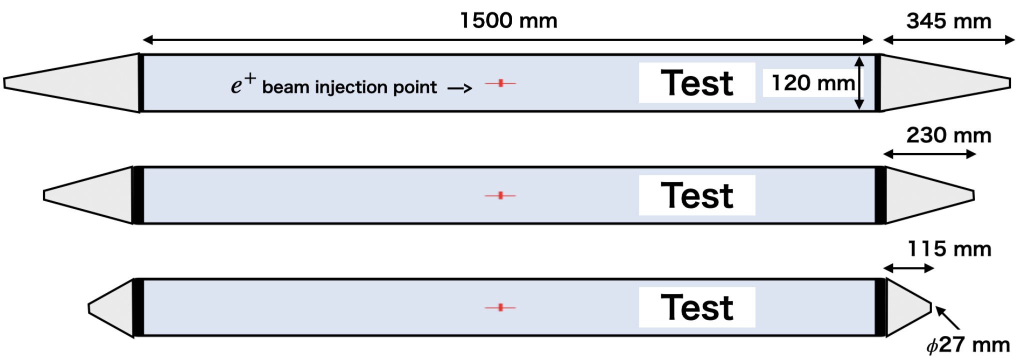

Fig.2. Illustration of the prepared scintillator and the set of light guides with using optical grease.

We conducted a test experiment at the GeV-γ experimental area of RARiS-Mikamine, Tohoku University. A positron beam with a momentum of 584 MeV/c was used for this test. The test setup is illustrated in Fig.3.

Trigger scintillator counters were placed at the most upstream and downstream positions along the beamline. The test counter was positioned just after the first trigger counter (trig1), followed by two scintillator counters: reference counter 1 (ref1) and reference counter 2 (ref2). These reference counters were equipped with timing photomultiplier tubes (PMTs) attached to both ends of the scintillator. The typical time resolution for the reference counters is approximately 30 ps.

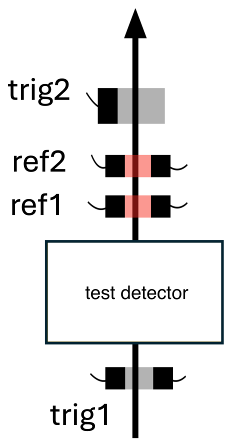

Fig.3.Schematic view of the experimental setup at ELPH.

Signals from the PMTs were delivered to an analog-to-digital converter (ADC) module (CAEN V792) to record charge information, while timing information was recorded by a time-to-digital converter (TDC) module (CAEN V1290). The lowest bit resolution of the TDC is approximately 25 ps. The typical trigger rate during the data-taking period was approximately 1 kHz. We recorded data with the three light-guide-length settings and also without a light guide; PMTs are directly attached to the scintillators.

§3. Results

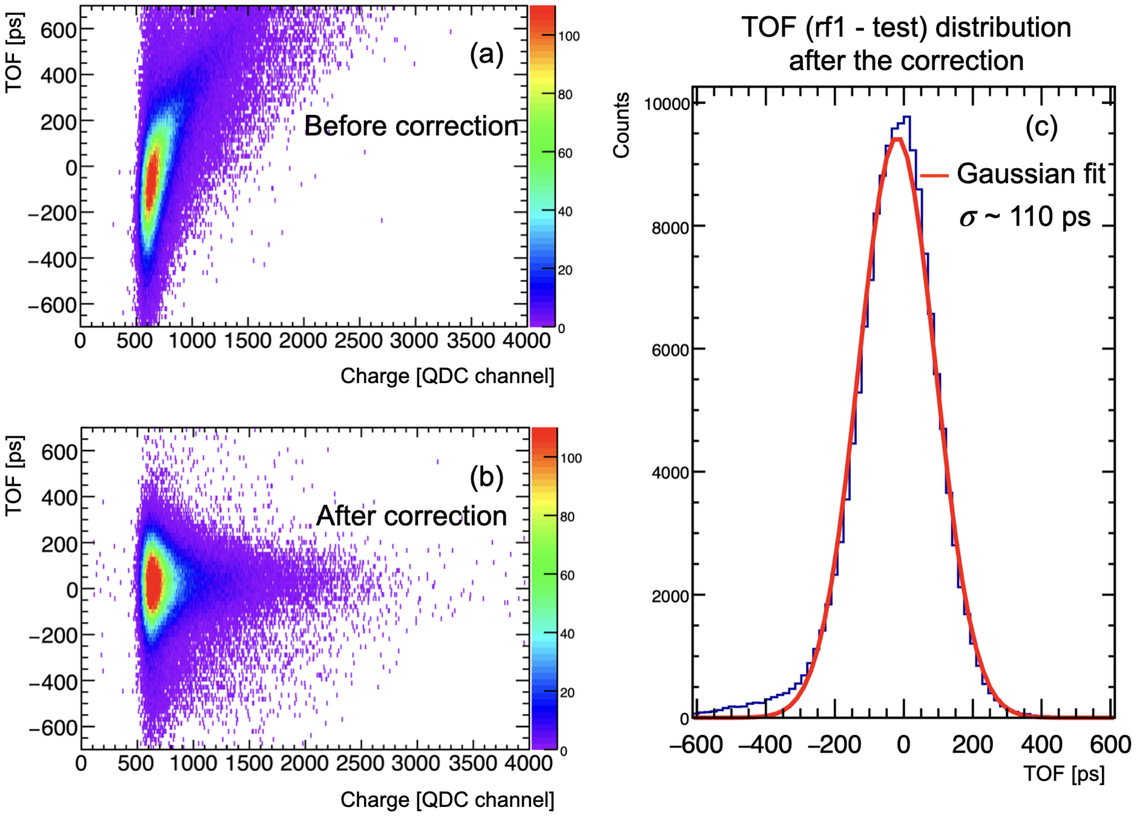

Fig.4. Time-of-Flight distribution between the reference counter(rf1) and the test counter, along with charge information from the readout. Details are provided in the text.

Fig.4 presents the correlation between the charge of the test counter and the time-of-flight (TOF) between the reference counter (rf1) and the test counter when the light guide length is set to 115 mm. Fig.4(a) shows the data before the slewing correction, while Fig.4(b) displays the data after the correction. Fig.4(c) represents the projection of Fig.4(b) onto the timing axis. The TOF resolution in this case was found to be approximately 110 ps. Three timing counters, named rf1, rf2, and test, allow the measurement of three time-of-flights (TOFs): (1) rf1 - rf2, (2) rf2 - test, and (3) test - rf1. The timing resolution of each detector ($\sigma_{\mathrm{rf1}}, \sigma_{\mathrm{rf2}}$ and σ_{test}) can be derived from the measured three TOF resolutions (σ_1, σ_2 and σ_2) by solving the following system of equations:

$$\sigma_1^2 = \sigma_{\mathrm{rf1}}^2 + \sigma_{\mathrm{rf2}}^2 , \quad \sigma_2^2 = \sigma_{\mathrm{rf2}}^2 + \sigma_{\mathrm{test}}^2 , \quad \sigma_3^2 = \sigma_{\mathrm{test}}^2 + \sigma_{\mathrm{rf1}}^2 .$$

Fig.5 shows the timing resolution of test (σ_{test}) and the geometric mean of the charge of signals

(QDC) from the two PMTs as functions of the light guide length. A length of zero corresponds to data taken without a light guide. The results clearly show that the photon detected by the PMT decreases and the timing resolution deteriorates as the light guide length increases.

Considering the results obtained above, we decided to choose a no light guide configuration for the CNC. Without a light guide, the prototype used in this experiment would have inadequate coverage of the plastic scintillator by the PMT, resulting in low light collection efficiency. Therefore, we modified the scintillator cross-section to 60 mm × 60 mm, which is about half the width of the originally designed scintillator. And we will try to evaluate performance of that new CNC proto-type.

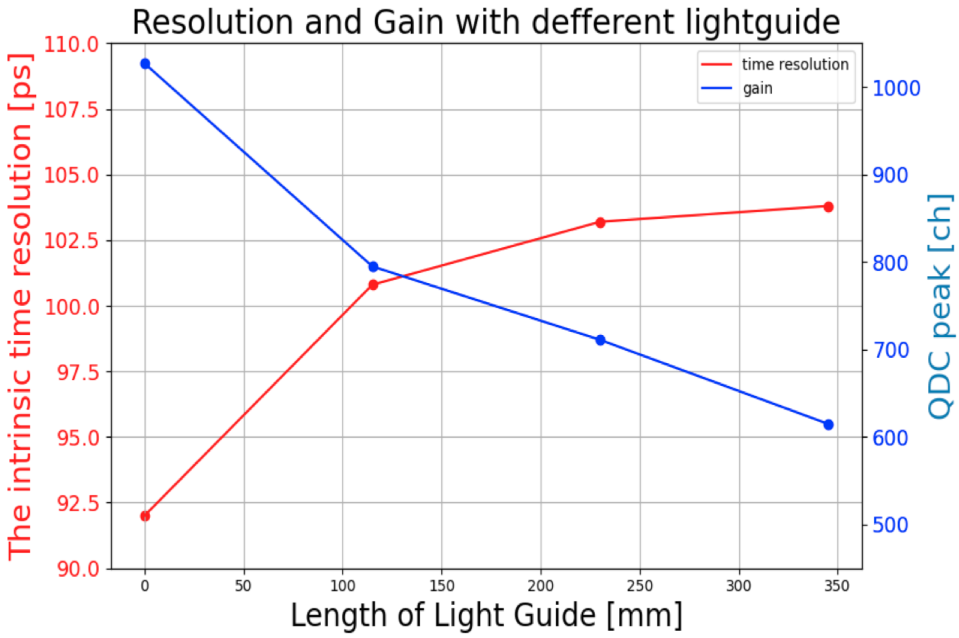

Fig.5. The timing resolution and the charge of the signal (QDC) as functions of the light guide length.

§4. Summary and prospect

We are preparing the J-PARC E80 experiment to investigate kaonic nuclei, particularly three-body and four-body anti-kaon bound states. Since neutron detection is crucial for this measurement, we are developing Cylindrical Neutron Counter (CNC) for the experiment.

A test experiment was conducted at the GeV-γ experimental area of RARiS-Mikamine, Tohoku University. In this test, we focused on the effect of light guide length and collected data by varying it. The results demonstrated that the best timing resolution was achieved in the absence of a light guide.

Based on these findings, we refine the design of the CNC, and plan to evaluate its performance in 2024 toward the fixing final design for the mass production for the J-PARC E80.

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