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Neutrino Source for Sterile Neutrino Searches

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The J-PARC MLF neutron target is suitable as an intense neutrino beam from μ decay at rest (μDAR) for the sterile neutrino. Pure $\bar{\nu}_\mu$ beam can be available thanks to the low duty factor of beam spill and 1 MW proton beam power of the MLF. Estimation of the pion production rate is one of the significant challenges in the sterile neutrino search. And therefore, several MC simulations are carried out to understand the uncertainty. In addition to the sterile search, neutrino from kaon decay at rest (KDAR) is also an interesting channel to probe neutrino interaction with monogenic energy. The environmental background related to the proton beam was measured using a plastic scintillator detector. Finally, we confirmed that there is almost no environmental background expected for the sterile neutrino search at a distance of 20 m behind the mercury target.

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1. Introduction

Search for the fourth-generation neutrino, so-called ”sterile” neutrino, is one of the major targets in the recent neutrino physics. The existence of the sterile neutrino was firstly indicated by the LSND experiment in the 1990s with 3.8σ of significance[1, 2]. The JSNS^2 (J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source) experiment [3, 4] starts in early 2020, to search for the existence of neutrino oscillations with Δm^2 near 1 eV^2 at the J-PARC Materials and Life Science Experimental Facility (MLF). A 1 MW beam of 3 GeV protons on the mercury spallation neutron target produces a powerful neutrino beam from muon decay at rest in the target. A liquid scintillator based neutrino detector is located at 24 m away from the target to detect $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation. Therefore, the JSNS^2 experiment is a direct test to the $\bar{\nu}_e$ anomaly in the LSND result. In addition to the sterile neutrino search, there are also interesting channels in JSNS^2 for measurements of the neutrino cross sections with a few ten MeV energy neutrinos from muon decay at rest and with monochromatic neutrino of 236 MeV from kaon decay at rest[5].

2. JSNS^2 experiment

A search for the existence of neutrino oscillation with Δm^2 near 1 eV^2 at the J-PARC MLF is proposed in 2013. The 3 GeV proton beam from the Rapid Cycling Synchrotron (RCS) and the mercury spallation neutron target provide an intense neutrino beam from μ decay at rest (μDAR) via a decay chain of pion and muon, available at a distance of a few ten meters from the target. A search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation will be carried out via inverse β decay (IBD) interaction ($\bar{\nu}_e + p \to e^+ + n$) followed by gammas from the neutron capture by Gadolinium, loaded in the liquid scintillator.

3. J-PARC MLF as Neutrino Source

JSNS^2 adapted the same technique of $\bar{\nu}_\mu$ beam. $\bar{\nu}_\mu$ is obtained by the following decay chain in equation (3.1) of pion produced by the proton beam:

$$\pi^+ \to \mu^+ \nu_\mu, \mu^+ \to e^+ \nu_e \bar{\nu}_\mu. \tag{3.1}$$

The muons are stopped and decay at rest (DAR) into neutrinos. The LSND experiment used the 800 MeV proton beam into a water target. There are several advantages in μDAR compared to neutrino beams using pion decay in flight (DIR), adapted in other sterile neutrino searches. The energy spectrum of the neutrino beam is well known since the maximum energy of the spectrum is determined by muon mass; Background can be suppressed more than the DIR beam thanks to heavy materials of the target itself and around the target (irons). On the other hand, the DIR beam can be focused by horn, and therefore, the statistics in the DAR might be worse than that in the DIR.

The J-PARC MLF is the best site in the world to study the sterile neutrino using the DAR beam, as shown in Figure 1. Proton beam with 1 MW will be available in a few years. A trial operation of the 1 MW beam was continued for 1 hour in the last summer, while 500 kW of the beam power is operational in 2019. The low duty factor of the beam spill, which has two bunches with 100 ns level timing resolution, helps to purify $\nu_\mu(\bar{\nu}_\mu)$ from μ DAR. The JSNS^2 experiment adapted the "OFF bunch" scheme in Figure 2. The μDAR neutrinos are continuously created in a few ten μs after beam spill ("OFF bunch") while neutrinos coming from hadrons such as kaons and pions are concentrated in 1 μs ("ON bunch"). And then, a pure μDAR neutrino beam is selected in the OFF bunch. Besides, the heavy materials of the target and surrounding the target also contributes to suppress $\bar{\nu}_e$ background in μ^- decay from π^- by capturing π^- before decaying.

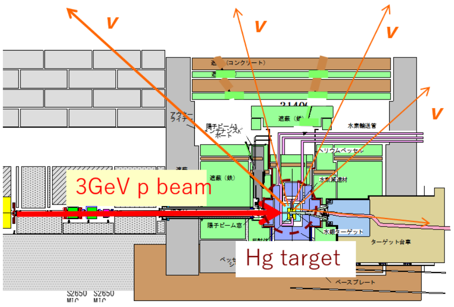

Figure 1: A drawing of the MLF neutron source. The 3 GeV proton beam (red line) hits the mercury target and then, the neutrino beam are produced around the target to fly isotropically (orange lines).

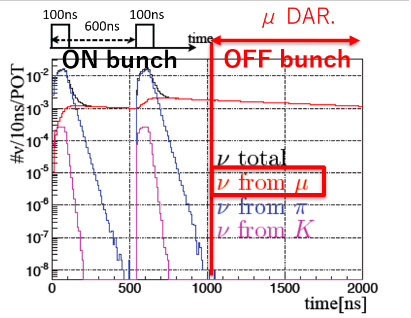

Figure 2: The OFF bunch scheme. ν_μ of μ decay (red plot) can be separated from ones from π and K (blue and purple plots) after 1μs shown in the red line.

3.1 Estimation of Neutrino Flux

Estimation of the neutrino flux from μDAR is a big challenge. $\nu_\mu(\bar{\nu}_\mu)$ flux is roughly determined by the following equation (3.2):

$$\#\nu = \#\text{P.O.T.} \times R(p \to \pi) \times R(\pi \to \mu) \times R(\mu \to \nu) \times \Omega. \tag{3.2}$$

Here, Ω is the solid angle to the target from the neutrino detector. The number of protons on the target, #P.O.T., is estimated to be 3.8×10^{22} / 5000 hours in one year for 0.33 mA (1 MW) of the proton beam in the J-PARC MLF. The pion production rate from 3 GeV proton, $R(p \to \pi)$, is essential for neutrino flux. Not only the target, but the neutron beam line components must be taken into account for the pion production while there is no experimental input available. There are some differences in the production rate of muon, $R(\pi \to \mu)$, between from π^+ and π^-; π^+ decays into μ^+ in 26 ns while π^- is absorbed in nuclei of the heavy materials. Therefore, behavior in the nuclei of hadrons must be understood. Finally, the production rate of ν_μ, $R(\mu \to \nu)$, depends on absorption rate into the nucleus. Then, muon interaction with the nucleus also is needed to be considered.

Three kinds of Monte Carlo simulations based on FLUKA, Geant4 (with QGSP_BERT), and PHITS are studied in the JSNS^2 experiment. In the simulation, geometries of the surrounding materials such as Fe (heavy reflector of the neutron) and Be (light reflector) are entirely constructed in addition to the mercury target. As a result, about 1.7 times difference of the flux among the simulation models is obtained as uncertainties in the prediction of ν flux. The reduction of the π production uncertainty is a crucial point for the sterile ν search. Therefore, a real measurement using proton beams with an energy of 1-10 GeV will powerfully help the sterile search.

3.2 Neutrino Components in the ON Bunch

There are also many interesting channels in the ON bunch neutrino beams, consisting of various components from hadron decays and μ absorption. Two monogenic 30 and 236 MeV energies of ν_μ come from $\pi^+ \to \mu^+\nu_\mu$ and $K^+ \to \mu^+\nu_\mu$, respectively. $K^+ \to \mu^+\pi^0\nu_\mu$, $K^+ \to e^+\pi^0\nu_e$, and $\mu^-A \to \nu_\mu A$ have continuous spectrum with the endpoints of 218, 228 and 105MeV, respectively. ν_μ from kaon decay at rest (KDAR), possible to study using the early JSNS^2 data, which is a unique tool to measure neutrino cross section and interaction to nuclei with fixed energy. The sites for studies of KDAR are very limited in the world, and then the J-PARC MLF is also the best site thanks to the 1 MW beam power. As a primary concern in JSNS^2, 3 GeV of the proton energy is almost the threshold energy of kaon production. The production rate of KDAR neutrino is also challenging to estimate since there is also no experimental input, and MC predictions have more than two times fractions between Geant4 and MARS.

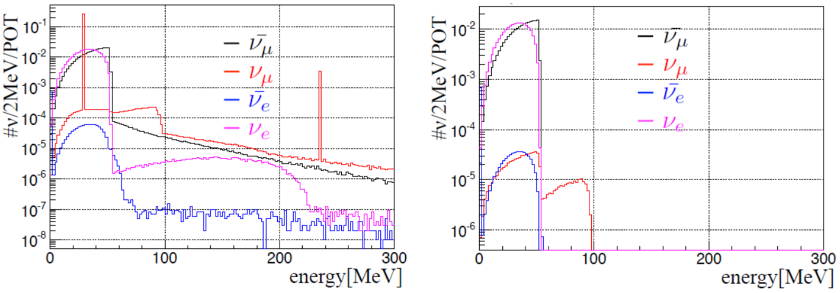

Figure 3: A simulation results of neutrino flux at the detector [4]. The left and right plots show the ON and OFF bunch neutrino beams, respectively. The black, red, blue and purple lines indicate fluxes of $\bar{\nu}_\mu$, $\bar{\nu}_\mu$, $\bar{\nu}_e$ and $\bar{\nu}_e$, respectively. Two monogenic peaks in the left plots show the energy peak of 30 and 236 MeV ν_μs.

4. On-site Environment Background

The most critical concern in the actual experiment is the background from the experimental environment, especially for fast neutrons from the proton beam. High energy neutrons with more than 200 MeV produce pion inside the neutrino detector, and they become a source of crucial background decaying into extra neutrinos. A plastic scintillator detector with 500 kg target volume was located at three measurement points (shown in Figure 4) of the third floor in the J-PARC MLF, the experimental space of the JSNS^2 experiment to measure the beam related backgrounds [6]. According to the comparison of the results between Point 1 and the others, fast neutron seems created by large halo from multiple proton scattering at 2 cm carbon graphite of the muon target in front of the neutron target. The background is found to be easy to avoid by placing the neutrino detector behind the mercury target since the halo is reflected or stopped in the surrounding massive materials. Finally, we concluded that almost no background is possible in the signal region shown in Figure 5 at the Point 2 (20 m behind the mercury target).

5. Summary

The MLF neutron source is suitable as an intense neutrino beam from μ decay at rest (μDAR)

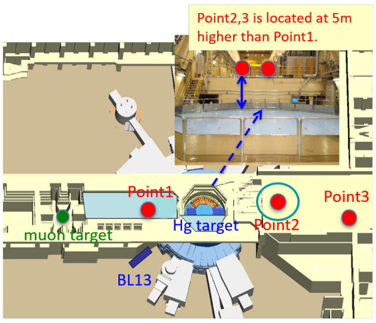

Figure 4: A drawing of the measurement points in third floor of the MLF. The plastic scintillator detector was located at Point 1, 2 and 3 in the red points while the blue and green points indicate location of mercury and muon targets in the first floor.

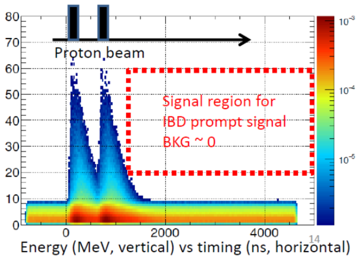

Figure 5: The 2D distribution of background events in the energy and timing phase space in the Point 2. The red square shows the target region of energy and timing for the sterile neutrino search.

for the sterile neutrino. Pure $\bar{\nu}_{\mu}$ beam can be observed thanks to the low duty factor of beam spill and 1 MW proton beam power. Estimation of the pion production rate is one of the significant uncertainties in the sterile neutrino search. Neutrinos from kaon decay at rest (KDAR) are also interesting in the JSNS^2 experiment to probe neutrino interaction with the monogenic energy in addition to the sterile search. An investigation of the environmental background related proton beam was carried out. Finally, it is turned out that there is almost no environmental background for the sterile neutrino search at a distance of 20 m behind the mercury target.

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