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A Neutrino Experiment with Decay at Rest source at J-PARC

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After the successful progress of the neutrino oscillation between three active neutrinos, fundamental questions are still remaining. One of the questions include what makes the difference of quark and lepton in mass and mixing, or what is the neutrino properties which is outside of analogs of the quark sector. It has been well established that neutrino has non-zero mass and that the three flavor states are super-positions of three mass eigen-states or vice versa. The standard three-neutrino framework introduces a 3x3 neutrino mixing matrix that is analogous to the quark sector. However, several experiments reported neutrino phenomena outside of three-neutrino framework, indicating the existence of neutrino species other than three neutrinos (ν_e, ν_μ, and ν_τ). Considering number of neutrino determined from Z-boson width, this indicates the existence of a new type of Fermion, i.e., sterile neutrino(s). A series of experiments, using decay at rest (DAR) neutrino source at J-PARC Material and Life Science Facility (MLF), will be possible. As a first step, a definitive search of the appearance oscillation $\overline{\nu_\mu} \to \overline{\nu_e}$ at Δm^2 near eV^2 is described.

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1. Introduction

Among the experimental results, which indicate that there are more than three species of neutrinos, the most notable is the observation of excess of $\overline{\nu_e}$ events in predominantly μ^+ decay by LSND collaboration.[1] The results were first reported in 1998 but is still not confirmed nor refuted at significant confidence level.[2],[3] Recently, deficiency of ν_e events from β source, and $\overline{\nu_e}$ deficiency in nuclear reactor were reported.[4] There is also a indication of excess of electromagnetic shower events in predominantly $\pi^\pm$ decays neutrino beam, reported by MiniBooNE collaboration[5]. If the existence of these phenomena are confirmed and are shown to be due to neutrino oscillation, the corresponding Δm^2 is larger than those of three active neutrino oscillation by a few orders of magnitude. This requires the existence of four or more mass eigen-state. Thus, the existence of more than three neutrino states in nature is required. Considering the Z-boson width of invisible channel[6], the new flavor state does not couple to Z-boson. This is a new kind of lepton, which does not have electromagnetic nor weak interaction, namely sterile neutrino(s).

Sterile neutrinos are naturally present in many theories beyond the Standard Model. An example is see-saw partners of left-handed active neutrino, i.e., ν_R and ν_L^c which do not have weak interaction. Once the existence of sterile neutrino is confirmed, many physics possibilities open. Since neither definite mass scale nor number of sterile neutrino are predicted, one of the sterile neutrinos could be a candidate of dark matter and others could be a source of CP violation in lepto-genesis.[7]

In this paper, as a first step of sterile neutrino physics at J-PARC, a definitive search of the evidence of neutrino oscillation with Δm^2 near 1 eV^2 is described. A proposal has been submitted to J-PARC on September 2,2013.[9] The experiment uses neutrino from muon decay at rest (μDAR) ($\mu^+ \to e^+ + \overline{\nu_\mu} + \nu_e$) in the spallation neutron target at J-PARC Material and Life Science Facility (MLF).[8] The inverse β decay reaction $\overline{\nu_e} + p \to e^+ + n$, followed by γ from neutron capture by nucleus, is used to search for an appearance oscillation $\overline{\nu_\mu} \to \overline{\nu_e}$

The unique features of the proposed experiment at J-PARC MLF, compared with LSND experiment and experiments with conventional horn focused beam, are;

1. The accelerator is a 3 GeV rapid cycling synchrotron (RCS) at J-PARC. The proton intensity is expected to reach 0.33 mA (1 MW) after the major upgrades in 2013. The accelerator is operated with a repetition rate of 25 Hz, where each spill contains two 80 ns wide bunches of protons spaced 540 ns apart. 1 MW beam provides 3×10^{22} protons-on-target (POT) during 4000 hours operation/ year. The bunched beam structure with duty factor of 1.5×10^{-5} allow us to separate neutrinos from μDAR from any other π and K decays by gating out activities for about 1 μsec after the start of the proton spill.

2. Neutrinos from μDAR are dominantly ν_e and $\overline{\nu_\mu}$ with a small (10^{-3} level) contamination of $\overline{\nu_e}$ and ν_μ. This suppression factor of 10^3 is due to π^- and μ^- nuclear absorption. The factor depends on the target, its surrounding material and their configuration. The neutrino spectrum and their cross section are well known for each flavor of neutrino. Especially the cross section of $\overline{\nu_e} + p \to e^+ + n$ is known to a few % level. Also the neutrino beam is 4π symmetric. The intensity can be scaled by $1/(distant)^2$.

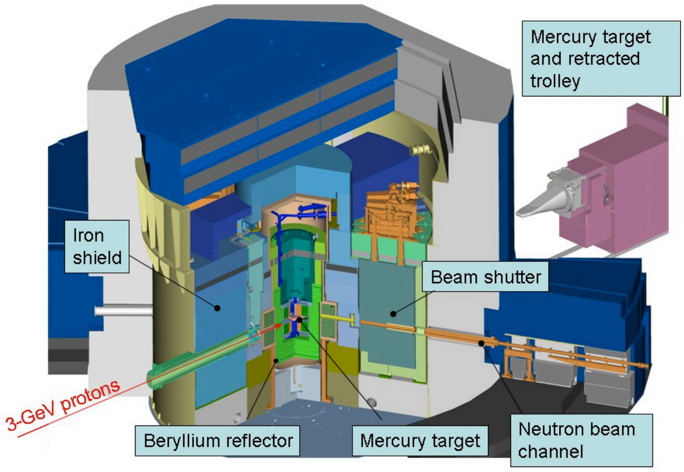

Figure 1: A schematic drawing of the mercury target in the J-PARC is shown.

3. The neutrino energy can be calculated from positron energy by adding 1.8 MeV. In muon decay, $\overline{\nu_\mu}$ and ν_e have different spectrum. This allow us to separate $\overline{\nu_e}$ due to $\overline{\nu_\mu} \to \overline{\nu_e}$ oscillation from those due to μ^- decay contamination. The LSND results can be confirmed or refuted about the $\overline{\nu_e}$ events excess and about the origin of the excess being due to oscillation by examining the $\overline{\nu_e}$ spectrum.

2. The J-PARC MLF as a DAR Neutrino Source

2.1 The RCS beam and the target

The target station of J-PARC MLF is build for a spallation neutron source and is shown in Figure 1. The mercury target has dimensions of 54 cm in width by 19 cm in height by 210 cm in length. Mercury is contained within a multiple wall structure made of stainless steel. Surrounding the target is cooling pipes, beryllium reflectors, and steel shielding. The cryogenic liquid hydrogen moderators are located at the top and bottom of the target. Target and moderators are surrounded by a beryllium reflector and an iron shielding which extends at least to a radius of 5 m around the target. There are 23 neutron channels looking at the moderators, rather than at the target. The target material configuration has been modeled for the neutrino flux calculation.

2.2 Neutrino Beam

Not only spallation neutrons, interaction of 3 GeV protons in the mercury target produce π and K that decay into ν_e and ν_μ and their anti-neutrinos. There are two time structures in the neutrino beam. One is 'On-bunch' neutrino. The duration is beam bunch width plus π,K lifetime. The neutrino are produced by decay-in-flight and decay-at-rest of π and K.

The other is 'Off-bunch' neutrino due to muon-decay-at-rest (μDAR). The duration of the neutrino last for several muon lifetimes. The dominant components are ν_e and $\overline{\nu_\mu}$ from μ^+ decay at rest. The contamination of wrong sign neutrinos are expected from stopping μ^- decay. Once

π^- is stopped, it will be absorbed by nucleus. However, with a small probability (about 1% in our case), π^-'s decay in flight producing μ^-'s. This fraction depends on materials around the target and space between them. Most of the μ^-'s are absorbed by heavy nucleus. Some of the μ^-'s, which stop in a light material, decay by $\mu^- \to e^+ \ \overline{\nu_e} \ \nu_\mu$. This contamination from μ^- decay is estimated by simulation to be 1.7×10^{-3} of the neutrinos from μ^+ decay at rest. The precision of this estimate is suffered from ambiguities in π production, secondary interactions, and detailed geometry of the target. However, one can determine from the data based on the known spectrum shape.

The μDAR component can be selected by gating out the first 1 μs from the start of the proton beam. The time distribution from all sources of neutrino and the neutrino fluxes after 1 μs are shown in Figure 2. Note that the resulting $\overline{\nu}_\mu$ and ν_e have different spectrum with endpoint energy of 52.8 MeV. μ^- decay produces ν_μ and $\overline{\nu_e}$ with same spectrum as those of $\overline{\nu}_\mu$ and ν_e, respectively.

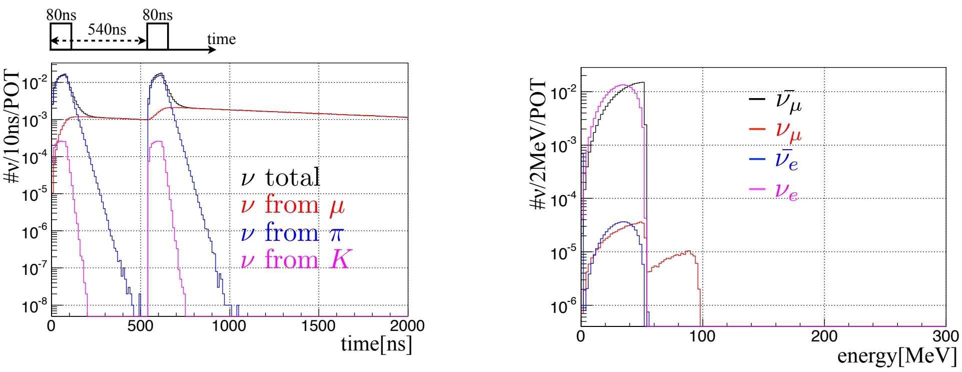

Figure 2: Time distribution of neutrinos from pion, muon and kaon decays and neutrino beams from muon decay at rest only survive after 1 μs from the start of proton beam.(left figure) Estimated neutrino flux after 1 μs from the start of proton beam. The $\mu^+ DAR$ components are selected and main background come from μ^- decays. (right figure)

There are four kinds of neutrino interactions in scintillator detector (CH_2).

1. Inverse beta decay (IBD) for $\overline{\nu_e}$
   The events will be identified by positron (IBD prompt signal) and nuclear capture γ (IBD delayed signal) due to thermalized recoil neutron from $\overline{\nu_e} + p \to e^+ + n$ (IBD) reaction. The cross section is well known.

$$\sigma_{IBD} = \frac{G_F^2 E_\nu^2}{\pi}(g_V^2 + 3g_A^2)\sqrt{1 - \frac{2Q}{E_\nu} + \frac{Q^2 - m_e^2}{E_\nu^2}}\,\theta(E_\nu - Q)$$
$$\sim 9.3 \times 10^{-48} E_\nu^2 (MeV) m^2$$

2. Charged current interaction of ν_e ($\nu_e + C \to e + N^*$)
   The events with N_{gs} (^{12}N ground state) in the final state will be identified by electron (prompt signal) and positron (delayed signal) from N_{gs} β decay. This measurement will serve dual

purposes. One is the measurement of the accumulated number of μ^+ decay. Second, the ν_e disappearance can be searched based on the E_ν shape distortion at 10% level.[10]

3. Neutral current interaction with nucleus for all active neutrinos. ($\nu_{e,\mu} + N \to \nu_{e,\mu} + N'$)
   All active neutrinos interact by neutral current interaction with nucleus. A dominant process in scintillator (CH_2) detector is $\nu_{e,\mu} + C \to \nu_{e,\mu} + C(15.11)$ producing 15 MeV γ.

4. Atomic electron target reaction
   $\nu_{e,\mu} + e \to \nu_{e,\mu}$. These are negligible contribution.

(1) and (2) are the reactions to be measured and both can be selected requiring delayed coincidence. The time gate for the primary signal should be from 1μs to 10μs, which corresponds to the muon lifetime and avoiding pion decay from both decay at rest and decay in flight. Table 1 is a summary of primary and delayed signal for a Gd-doped liquid scintillator detector. Table 2 is the summary

	primary timing	primary energy	delayed timing	delayed energy
$\overline{\nu}_\mu \to \overline{\nu}_e$	1-10 μs	0-53 MeV	10-100μs	8 MeV
$\nu_e C \to e N_{gs}$, $N_{gs} \to C e^+ \nu_e$	1-10 μs	0-37 MeV	100μs-10 ms	0-16 MeV

Table 1: The expected signal timing relative to proton beam bunch and signal energy

of possible selection criteria and the expected efficiency for detecting signal.

Selection	Detection efficiency	Parameters
1.0$\leq \Delta t_{prompt} \leq$10$\mu$s	74%	time window for prompt signal
6$\leq E_{delayed} \leq$12MeV	78%	energy of delayed signal in Gd-doped scintillator
20$\leq E_{prompt} \leq$60MeV	92%	energy of prompt signal high Δm^2
$\Delta t_{delayed} \leq$100μs	93%	time difference of the prompt and delayed signals
ΔVTX$\leq$60cm	96%	distance between the prompt and delayed signals
Total	48%	

Table 2: IBD Selection criteria and efficiencies for the oscillated signals.

3. Signature of the oscillation

There are two distinct signatures of oscillation signal. One is the energy spectrum of the oscillated signal. The distribution is a convolution of the energy spectrum of the original neutrino (in this case, $\overline{\nu}_\mu$) and the oscillation probability. The signal can be separated from the background due to μ^- decays based on the different energy distribution from oscillated events. The other signature is the distribution of events as a function of distance from the source to prove the oscillation behavior. Measurements with a long detector or measurements at two distances can be used to detect oscillation.

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After examining a possible location of the experiment, the candidate location has been identified in the third floor in the MLF building for the excellent shielding. The baseline is 17m and a 50 ton Gd-loaded liquid scintillator detector is being designed. This short baseline provides a large number of events with a relatively small detector due to $1/L^2$ law. As a result, the sensitivity to search for sterile neutrinos above a few eV is comparable to or better than the experiment using a larger detector at a longer distance. Figure 3 shows $E_{\overline{\nu}}$ distributions of oscillation signals at some typical Δm^2's for a baseline of 17 m. If no definitive positive signal is found by this configuration,

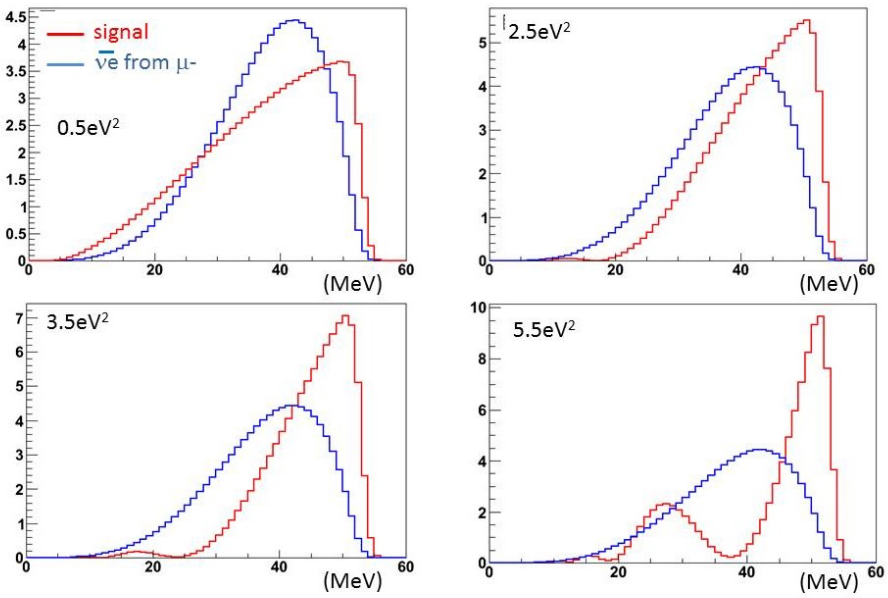

Figure 3: Examples of oscillation signals at typical Δm^2 for a baseline of 17 m are shown. The red graphs are shapes of $\overline{\nu}_e$ appearance signal and the blue graphs are shapes of signal from μ^- decays. Energy resolution is assumed to be $15\%/\sqrt{E}$. All plots are normalized by area.

the small Δm^2 region can be explored by a longer baseline and a larger detector. If a positive signal is found, full explorations of (family of) sterile neutrinos are envisaged.

4. Neutron and gamma backgrounds

In addition to the $\overline{\nu_e}$ from μ^- decay, beam associated and natural sources of backgrounds (gammas, neutrons etc.) exist. To estimate amount of background, a test measurements were carried out at one of the MLF beam lines, BL13 with a 1 ton scintillator detector. Figure 4 shows the top view of BL13 beam line and a 1 ton segmented scintillator. Followings are a summary of the measurements.

- Beam associated fast neutron : Michel electrons from muon decays were observed as a background for "IBD prompt signal". The events are consistent with being made by fast neutron in the beam. Namely, a fast neutron interacts in the scintillator, producing π, and stop in the scintillator. Then electron or positron from $\pi^\pm \to \mu^\pm \to e^\pm$ are observed.

- Gammas ($6 < E[\mathrm{MeV}] < 12$) made from neutron captured around the 1 ton detector, which constitute the background of "IBD delayed signal".

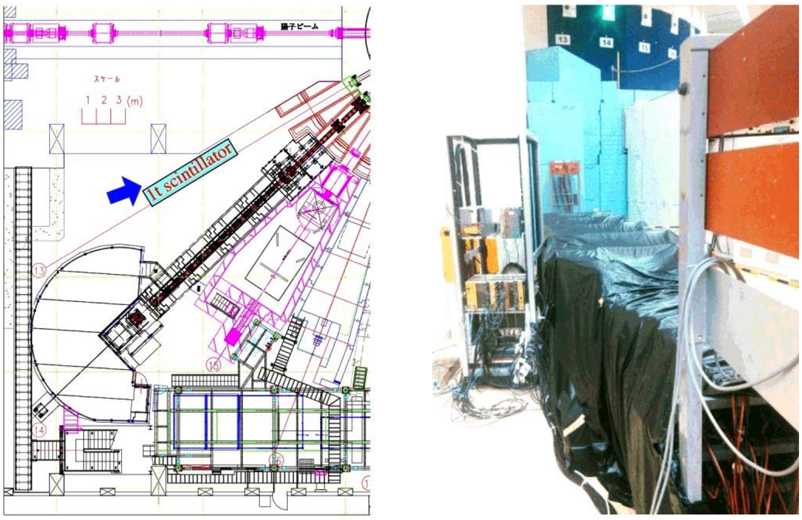

Figure 4: Top view of the BL13 and the location of the scintillator detector (left), and a photograph of the scintillator detector at BL13 (right). This photograph was taken at the blue arrow shown in the left figure.

- The amount of the neutrons below 1 MeV are also estimated.

The expected amount of background at the candidate location (3rd floor of MLF) was estimated from the measurements at BL13 and by using the Monte Carlo simulation for the ratio of backgrounds at two locations.

In addition, cosmic ray induced fast neutron was considered. These may recoil proton with sufficient energy to fake "IBD prompt signal"and neutron(s) from the interaction captured to produce gamma to fake "IBD delayed signal". With 1 MW beam power, 50 ton detector at 17 m from the mercury target in 4 years the signal and the backgrounds are estimated as shown in Table 3.

	Contents	/4years/50tons	Assumptions
Signal	$\overline{\nu}_\mu \to \overline{\nu}_e$	811	$\Delta m^2 = 3.0eV^2$, $sin^2 2\theta = 3.0 \times 10^{-3}$ (Best Δm^2 for MLF exp.)
		337	$\Delta m^2 = 1.2eV^2$, $sin^2 2\theta = 3.0 \times 10^{-3}$ (Best fit values of LSND)
Backgrounds	$\overline{\nu}_e$ from μ^-	377	
	$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	38	
	Beam associated fast neutron	0.3	
	Cosmic ray induced fast neutron	42	
	Total accidental events	37	

Table 3: Numbers of events of the signal and backgrounds with total fiducial mass of 50 tons after applying IBD selection efficiency for 4 years measurement.

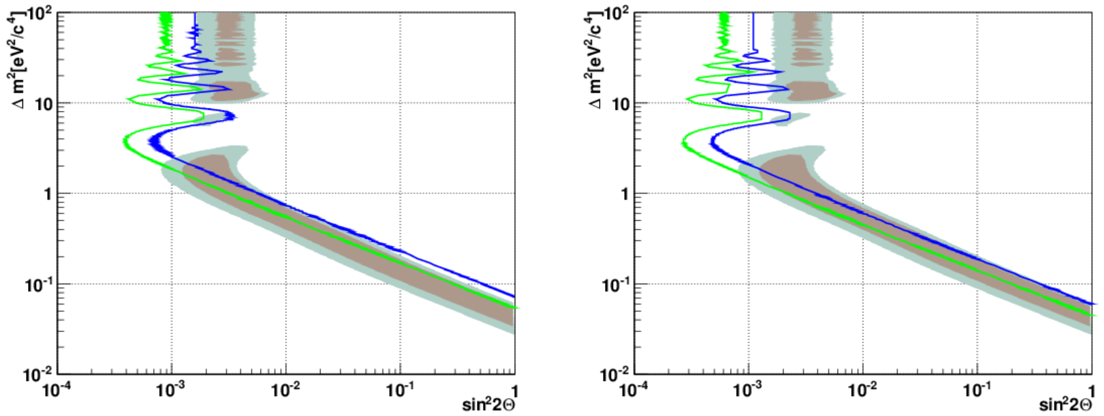

Figure 5: The sensitivity of the MLF experiment assuming 2 and 4 years operations (4000 hours / year), ∼50% detection efficiency and 17 m baseline. The blue line shows the 5 σ C.L., while green one corresponds to 3 σ. Left plot shows the case with 2 years exposure, while the right plot shows that with 4 years.

5. Expected sensitivity

The background other than $\overline{\nu}_e$'s from μ^- decay is expected to be well suppressed with good shielding at the detector site and after the various cuts. Only $\overline{\nu}_e$'s from μ^- is considered to estimate the sensitivity and asigned 50% uncertainty for this background.

The $\nu_e + ^{12}C \to e + ^{12}N_{gs}$ can be measured directly and provides the normalization factor for the oscillated signal ($\overline{\nu_e} + p \to e^+ + n$). Note that the determination of the normalization factor can be done at the 10% level. Even if ν_e disappearance occur as reported in reactor and β source measurements, it should be smaller than 10% in total number of events.

The binned maximum likelihood method is used for the analysis. The method fully utilizes the energy spectrum of each background and signal components. Figure 5 shows the sensitivity of our experiment with 3 (green) and 5 σ (blue), respectively. The left plot shows the case with 2 years exposure, while the right plot shows the that with 4 years. If no definitive positive signal is found by the experiment, a future option exists to cover small Δm^2 region. This needs a relatively long baseline and requires a large detector to compensate for the reduced neutrino flux.

6. Outlook

The above sensitivity critically depends on the amount of backgrounds. It has utmost importance to confirm the simulation of the backgrounds estimates by actual measurements at the proposed location as soon as possible.

In the future, if the backgrounds can be controlled and if sufficient motivations of further study of sterile neutrino exist, J-PARC MLF offers more opportunities such as,

- An explicit demonstration of the oscillation $\nu_\mu \to \nu_{sterile}$ by disappearance of ν_μ neutral current interaction. The best possible neutrino will be 35 MeV monochromatic ν_μ from $\pi^+ DAR$. The oscillation can be identified by geometrical periodicity of the disappearance of the events $\nu_\mu + C \to \nu_\mu + C(15.11)$.

- Since J-PARC RCS is 3 GeV, a large number of K can be produced. A rough estimate shows 10^{20} K^+ could be stopped in the target per year, which offers an attractive opportunity for a study of very rare K^+ decay process.

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