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A Plan for Decay at Rest ν_e + Pb Cross Section Measurement: DaRveX

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DaRveX stands for "Decay at Rest ν_e + Pb cross(X) section measurement". So far there has not been good low energy ν_e detection target. Lead is expected to be an excellent low energy ν_e target because the cross section is expected to be very large and the delayed coincidence technique can be used to reduce the backgrounds. If decay at rest $\nu_e + \mathrm{Pb} \to e^- + xn + \mathrm{Bi}$ cross section is measured, it brings new possibilities to the future neutrino experiments, such as low energy ν_e oscillation measurements, flavor specific measurement of the supernova explosion ν_e and understanding of ν_e-nucleus interactions. We are planning an experiment to measure the cross section, energy spectrum and direction of the emitted electron of $\nu_e + \mathrm{Pb} \to e^- + xn + \mathrm{Bi}$ reaction at J-PARC MLF. The beam pulse is very narrow in time and the duty cycle is low at MLF, which help to reduce the backgrounds significantly. In this proceedings, we will explain about conceptual idea of the experiment.

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1. Introduction

In experimental studies of neutrinos, delayed coincidence signal of the inverse beta decay reaction,

$$\overline{\nu}_e + p \to e^+ + n \xrightarrow{\text{thermalize}} n + A(\text{p or Gd}) \xrightarrow{\tau=O(100\mu s)} \gamma + A' \quad (1)$$

has been often used to detect low energy $\overline{\nu}_e$. The reactor neutrino oscillation was discovered and three ($\theta_{12}, \theta_{13}, \Delta m^2_{12}$) out of six neutrino oscillation parameters have been measured most precisely using this reaction[1]. The reaction (1) is excellent because the cross section is large and precisely known, the backgrounds can be reduced much thanks to the delayed coincidence signal and the $\overline{\nu}_e$ energy can directly be known from the energy of e^+.

On the other hand, solar ν_e have been measured with elastic scattering with electron ($\nu_e + e^- \to \nu_e + e^-$) and deuteron disintegrations ($\nu_e + D \to e^- + p + p, \nu_e + n + p$), or radio chemical way (ν_e + (^{37}Cl/^{71}Ga) $\to \cdots$)[1]. However, their cross sections are very small and it is difficult to use for accelerator based low energy ν_e detection. The decay at rest ν_e has been measured using the reaction,

$$\nu_e + {}^{12}\text{C} \to e^- + {}^{12}\text{N}_{\text{gs}} \xrightarrow{\text{EC}(Q=17\text{MeV},\ \tau=11\text{ms})} \gamma + {}^{12}\text{C} \quad (2)$$

However, the cross section is still one order of magnitude smaller than that of the reaction (1).

Fig. 1 shows calculated cross section of various neutrino-nucleus reactions[2]. Lead is expected

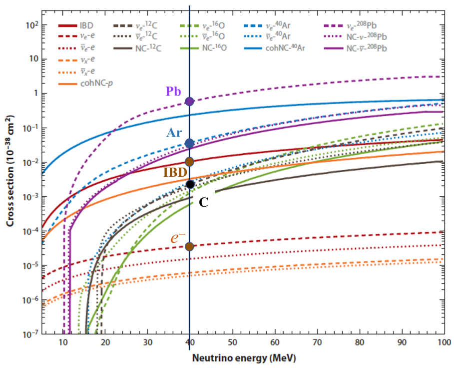

Figure 1: Cross sections of various neutrino- nucleus reactions[2]. 40 MeV is a typical energy of ν_e in μ^+ decay at rest.

to have the largest cross section for the decay at rest ν_e. The cross section of the neutron emission channel;

$$\nu_e + \text{Pb} \to e^- + xn + \text{Bi}; (x = 1 \text{ or } 2) \quad (3)$$

is expected to be equivalent to that of the reaction (1) and 20 times larger than that of (2) if normalized to the target mass. Therefore, lead is a good candidate for low energy ν_e detection. However, the cross section has never been measured yet [1]. Once the cross section of the reaction (3) is measured and proven to be large, it opens a new window to future neutrino studies.

[1]COHERENT group is measuring the inclusive cross section by detecting final state neutron[3] , while DaRveX is going to measure the differential cross section with respect to the electron energy and emission angle.

2. Physics potentials with low energy ν_e

If the lead target is proven to be effective to detect low energy ν_e, it will become possible to measure oscillation of Decay at Rest (D@R) neutrinos, to perform flavor specific detection of supernova explosion ν_e, to study ν_e-nucleus interactions, etc. [4]. Since there is a space limitation, we focus on the D@R ν_e oscillation in this proceedings.

Fig. 2 shows possible ν_e productions in π^+ and μ^+ decay at rest and related physics. Studies

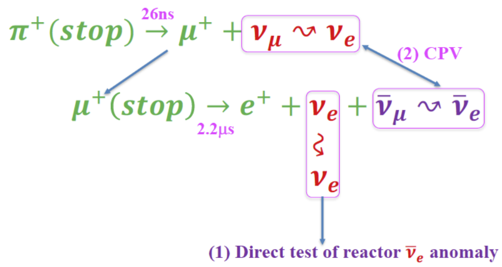

Figure 2: ν_e produced in π^+ and μ^+ decay at rest and possible physics to explore[4].

of D@R neutrinos are very important now because several experiments suggest existence of sterile neutrinos which could cause oscillation of the D@R neutrinos at a baseline of a few tens of meters. For example, LSND group reported μ^+-D@R $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation at a baseline ~30 m[5]. JSNS^2 group is trying to measure the same $\overline{\nu}_e$ appearance at J-PARC MLF[6]. This oscillation can also be checked by measuring π^+-D@R $\nu_\mu \to \nu_e$ appearance measurement as shown in Fig. 2. Moreover, the $\nu_\mu \to \nu_e$ oscillation is CP inverted process of $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation and CP violation could be measured from difference between the two oscillation probabilities, once the sterile neutrino is confirmed. In this measurement, the number of parent ν_μ and $\overline{\nu}_\mu$ are the same and their energy spectra are precisely known. The oscillation probability of $\overline{\nu}_e$ appearance can be measured precisely using the IBD reaction (1) and the oscillation probability of ν_e appearance can be measured precisely from the ratio to the number of ν_e events produced in μ^+ decay at rest (Fig. 2). Therefore, very accurate CPV measurement is expected to be possible. In addition, ν_e produced in μ^+ decay at rest can be used to measure ν_e disappearance from baseline dependence of its flux. This measurement can test the reactor neutrino anomaly[7] using different systematics. Figs. 3 show expected sensitivity to $\nu_\mu \to \nu_e$ appearance oscillations and $\nu_e \to \nu_e$ disappearance in a dedicated future experiment[4].

3. Concept of the ν_e + Pb experiment

We will use the ν_e produced in the μ^+ decay at rest at J-PARC MLF. At MLF, a 3GeV proton beam hits mercury target and produced π^+ stops in the target and decays. μ^+ is produced in the π^+ decay and stops within the mercury target and decays and produces ν_e with 2.2μs lifetime. The time structure of the proton beam is that two 100 ns wide pulses, 540 ns apart comes every 40 ms (25 Hz). Therefore, by setting the ν_e timing window as $1.5\mu s < t < 5.5\mu s$, it is possible to escape from the instantaneous beam associated backgrounds and the natural backgrounds are reduced to

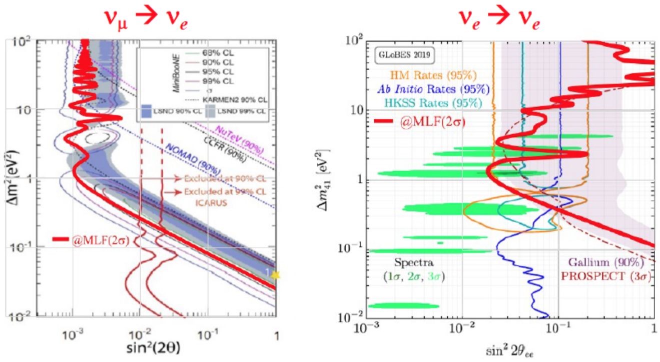

Figure 3: Statistical sensitivity to $\nu_e \to \nu_e$ disappearance and $\nu_\mu \to \nu_e$ appearance oscillations[4] of D@R neutrinos. Thick red lines show statistical 2σ significance $\sin^2 2\theta$ upper limit. A far detector with 75 ton lead target at 30 m baseline and a near detector with 8.5 ton lead target at 10 m is assumed as the detector configuration. 3GeV proton beam with 1MW power and 5 years of data taking are also assumed.

10^{-4}.

Fig. 4 shows the conceptual structure of the ν_e detector to measure the cross section of the reaction (3). We will convert existing reactor neutrino detector PANDA (Plastic AntiNeutrino Detector

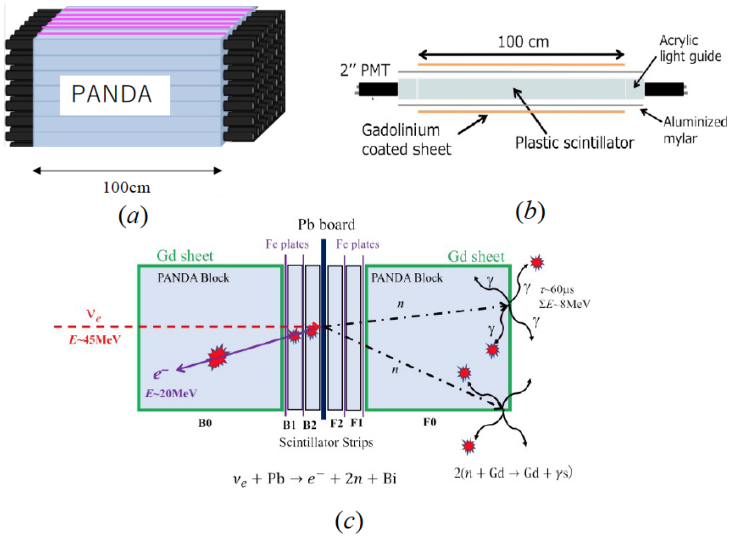

Figure 4: (a) PANDA detector (b) A plastic scintillator module. (c) Sandwich structure of the lead target, thin plastic scintillators and PANDA blocks,

Array)[8]. The PANDA detector is an array of 10 cm $\times$ 10 cm $\times$ 100cm scintillator blocks shown in Fig. 4(a). The scintillator block is surrounded by a Gadolinium coated sheet. The Gd captures the thermal neutron produced in the reaction (3) and generate delayed signal. A 4 mm thick lead sheets and 2+2 1cm thick thin plastic plates are sandwiched within the vertical space between the PANDA scintillator array (Fig. 4(c)). The thin iron plates between the scintillator is to stop the proton generated by the recoil of fast neutron. The electron produced in the reaction (3) is identified by the triple coincidence of two thin scintillators and a PANDA block in the same direction. In order to reduce backgrounds, energy deposits within the two thin scintillator is required to be consistent with the passage of minimum ionizing particle. The ν_e signal is identified by the delayed coincidence of e^- signal and the Gd signal. With 250 kg of the lead target at 10 m baseline, the expected number of ν_e reaction is 2,400/year. Assuming the ν_e detection efficiency is 5%. the number of ν_e events to detect is 120/year. The ν_e flux will be measured by JSNS^2 experiment using ν_e + ^{12}C interaction with precision ~10%. Assuming the signal to background ratio to be 1:1 and 10% systematic error, the cross section is expected to be measured with precision 20 % with one year of data taking.

4. Summary

DaRveX is planning to measure differential cross section of D@Rν_e + Pb $\rightarrow$ e^- + xn + Bi at J-PARC MLF. Once the cross section is measured, D@R ν_e oscillation measurement, flavor specific detection of supernova explosion ν_e and measurements of low energy ν_e-A interactions will become possible. We have measured on site backgrounds at MLF in 2021 and are hoping to start the experiment in 2022 or 2023.

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