Neutrino Physics with Accelerator Driven Subcritical Reactors

Emilio Ciuffoli
IMP, CAS. NanchangLu 509, Lanzhou, 730000, China
E-mail: emilio@impcas.ac.cn

Abstract. Accelerator Driven Subcritical System (ADS) reactors are being developed around the world, to produce energy and, at the same time, to provide an efficient way to dispose of and to recycle nuclear waste. Used nuclear fuel, by itself, cannot sustain a chain reaction; however in ADS reactors the additional neutrons which are required will be supplied by a high-intensity accelerator. This accelerator will produce, as a by-product, a large quantity of \( \bar{\nu}_\mu \) via muon Decay At Rest (\( \mu \text{DAR} \)). Using liquid scintillators, it will be possible to measure the CP-violating phase \( \delta_{CP} \) and to look for experimental signs of the presence of sterile neutrinos in the appearance channel, testing the LSND and MiniBooNE anomalies. Even in the first stage of the project, when the beam energy will be lower, it will be possible to produce \( \bar{\nu}_e \) via Isotope Decay At Rest (IsoDAR), which can be used to provide competitive bounds on sterile neutrinos in the disappearance channel. I will consider several experimental setups in which the antineutrinos are created using accelerators that will be constructed as part of the China-ADS program.

1. ADS Reactors
The main goals of Accelerator Driven Subcritical Systems (ADS) are to produce energy and, at the same time, to provide an efficient method for the disposal of nuclear waste. Used nuclear fuel cannot sustain a chain reaction, however in these reactors the additional neutrons needed are provided by a particle accelerator, where a high-intensity beam collides on a spallation target. Such reactors are being developed all around the world: the China ADS (C-ADS) program is centered on the design and construction of such a facility [1]; in Europe the project MYRRHA also has similar goals.

We will focus on the C-ADS project; here the spallation neutrons are obtained using a proton beam, whose energy will be increased gradually up to 1.5 GeV. Such a machine can also be employed to produce a large quantity of neutrinos, first via Isotope Decay At Rest (IsoDAR), then, when the energy is higher (\( \geq 400 \text{ MeV} \)) also via muon Decay At Rest (\( \mu \text{DAR} \)).

The predicted time-schedule for C-ADS is the following [2]

| ADS time-schedule |
|-------------------|
| R&D: End of 2016  |
| CIADS: 2022       |
| Demo Facility: 2030 |
| Industrial Facility: 203x |
| 10 mA, 25 MeV     |
| 10 mA, > 250 MeV  |
| 15 mA 1 GeV       |

\(^1\) it is currently under consideration to increase the energy of the beam up to 500-600 MeV
2. IsoDAR

$\bar{\nu}_e$ can be produced via IsoDAR from the earlier phases of C-ADS, using the low-energy beam. The target is surrounded by a $^7\text{Li}$-based converter; here the spallation neutrons are absorbed, creating $^8\text{Li}$, that will produce $\bar{\nu}_e$ via $\beta$-decay: the $\bar{\nu}_e$ can be detected using two 20 ton liquid scintillator detectors to search for sterile neutrinos in the disappearance channel.

![Figure 1. Exclusion contours at 2, 3 and 5 $\sigma$'s [3]](image1)

2.1. IsoDAR Converter

In [4] we considered two different beam energies: 25 MeV (that should be available at the end of 2016), where the highest neutron yield is achieved using a Be target, and 250 MeV, where heavy metal targets (Pb, W or Bi) are preferred. The total neutron yield $n/p$ is around $2.2 - 2.4\%$ at 25 MeV; it increases up to $240 - 260\%$ at 250 MeV. We also considered different types of converter:

- Lithium deuteroxide anhydrate (LiOD) and monohydrate (LiOD-D$_2$O): they offer the highest neutrino yields because they act also as a moderator for the neutrons due to the presence of D in the converter. Another advantage is that the converter is reasonably compact, reducing the systematic errors due to the uncertainty on the baseline.
- 9.5\% LiOD solution in heavy water: lower conversion efficiency due to the higher amount of H present in the compound.
- Metallic Lithium: the neutrons are moderated by a heavy water sleeve around the target.
- FLiBe: converter proposed in [5] for IsoDAR@KamLAND

![Figure 2. $^8\text{Li}$ yield with 25 and 250 MeV beam [4]](image2)
2.2. Vacuum Sleeve

When the target is surrounded by other materials (ex: converter, heavy water sleeve, etc...), some of the neutrons can bounce back and be absorbed inside the target. For CIADS, a gravity-driven granular flow tungsten target is being considered [6]. Tungsten was chosen due to its hardness, high heat capacity and melting point; however the neutron loss is particularly high in case of W targets. If the target is surrounded by a vacuum sleeve, it will increase the probability for the bounced-back neutrons to avoid the target, reducing the neutron loss: for example, in the case of W target, n/p can be increased by around 30% using a 20-cm vacuum sleeve [4]. Another possibility is to use different materials, like bismuth or lead (ex: liquid Pb target), however in this case there are serious problems related to heat removal and corrosion of the target [6].

3. $\mu$DAR

When the beam energy is $\geq 400$ MeV, $\bar{\nu}_\mu$ can be produced via $\mu$DAR, using the reactions $\pi^+ \rightarrow \nu_\mu + \mu^+$ and $\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$. While they propagate, $\bar{\nu}_\mu$ oscillate into $\bar{\nu}_e$, that can be detected using liquid scintillators: in this way it is possible to measure $\delta_{CP}$ with good precision and to look for signs of the presence of sterile neutrinos in the appearance channel. The main advantages of $\mu$DAR are that the background in this energy range (30-55 MeV) is very low, moreover both the spectrum (Michel) and the cross secton (Inverse Beta Decay) are known very well. Finally, using two detectors, there is no degeneracy between $\delta_{CP}$ and $\pi - \delta_{CP}$; exploiting the synergy with other experiments, like T2K and NO$\nu$A, even only one detector achieves a good determination of $\delta_{CP}$ ($\approx$15-35 degrees) [3].

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