Outline

- ADS
- IsoDAR
- $\mu$DAR
- Conclusions
The main purposes of an Accelerator Driven Subcritical System (ADS), of the kind being developed in China (C-ADS), are

- recycle the used nuclear fuel
- produce electricity

The byproducts of nuclear fission are still radioactive but cannot sustain a chain reaction. In the C-ADS nuclear reactor the additional neutrons will be provided by a linear accelerator, where the energy of the beam will be gradually increased up to 1.5 GeV. Z.H. Li et al., Phys.Rev.ST Accel.Beams 16 (2013) 8, 080101

<table>
<thead>
<tr>
<th>ADS time-schedule</th>
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<td>12 mA, 26 MeV</td>
<td>10 mA, 250-500 MeV</td>
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Also Europe is working on the development of an ADS system: MYRRHA
Neutrino Research at ADS

Even in the earlier phases of ADS, neutrinos can be produced first via Isotope Decay At Rest (IsoDAR), then via muon Decay At Rest ($\mu$DAR).

- **IsoDAR**: the accelerator is used as source of spallation neutrons. They are absorbed in a $^7$Li converter placed around the target, producing $^8$Li $\Rightarrow \beta$-decay $\Rightarrow \bar{\nu}_e$.
  
  Possible to search for **sterile neutrinos** in the **disappearance channel** (energy higher than reactor neutrinos).

- **$\mu$DAR**: when the energy is higher (> 400 MeV), $\bar{\nu}_\mu$ can be created via $\mu$DAR, using the process

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \\
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu
\]

Studying $P_{e\mu}$ is it possible to search for **sterile neutrinos** in the **appearance channel** and to **measure $\delta_{CP}$**.
IsoDAR
Comparison with Reactor Neutrino Experiments

Many other proposed experiments using $\bar{\nu}_e$ from nuclear reactors to search for the same effect.

- **Shape of the expected spectrum is known more precisely** (uncertainties for reactor neutrino spectrum)

- Due to our higher energy:
  A) Longer baselines (for the same oscillations) $\Rightarrow$ easier for near detector
  B) More shielding *and* sensitive to higher $\Delta M^2$
  C) Different energy range $\Rightarrow$ complementary to reactor neutrino experiments

However

- Reactor neutrino experiments will get an higher neutrino flux
- No need of additional facilities to produce neutrinos
Target Station

Neutrino Research at ADS Facility
IsoDAR - Converters

$^8\text{Li}$ production from the reaction $^7\text{Li} + n \rightarrow ^8\text{Li}$

The neutrons from the spallation target must be slowed down by a moderator.

We considered several possibilities for the converter

E. Ciuffoli et al., arXiv:1606.09451 [physics.ins-det]

- **Metallic Lithium**: the neutrons are moderated by a heavy water sleeve around the target.

- 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 ($\Rightarrow$ reduce 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.

- **FLiBe**: converter proposed for IsoDAR@KamLAND

M. Abs et al., arXiv:1511.05130 [physics.acc-ph]
Converter Efficiency

Neutrino Research at ADS Facility

- LiOD
- LiOD-D2O
- Solution
- Metallic Li
- FLiBe

FLUKA Simulations
Geant4 Simulations
Converter Efficiency

Neutrino Research at ADS Facility
Figure: $^8$Li yield for different proton beam energies, using a Be target (25 MeV) or W target (250 MeV)
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. This effect is particularly important 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.

- 25 MeV: Be target preferred
- 250 MeV heavy metal targets give better performances (used W in the current simulations, however also depleted U under study)
Figure: Exclusion contours in the disappearance channel using IsoDAR

EC, J. Evslin, F.Y. Zhao, JHEP 1601 (2016) 004
Using $\mu$DAR it is possible to measure precisely $\delta_{CP}$.

Advantages:

- Spectrum (Michel) and cross section (IBD) known very well
- Using two detectors, no degeneracy between $\delta_{CP}$ and $\pi - \delta_{CP}$
- Synergy with other experiments, like T2K and NO$\nu$A. Exploiting this synergy, even only one detector achieves a good determination of $\delta_{CP}$ ($\sim$15-35 degrees)
- Low background in this energy range (30-55 MeV)
The first proposal along these lines was the DAEδALUS project. J. Alsonso et al., arXiv:1006.0260 [physics.ins-det]

**μ Decay At Rest with Two Liquid Scintillators (μDARTS)**

- Our idea is to use a single accelerator to produce neutrinos and two detectors at different baselines.
- With one small detector near the accelerator it is possible to fix the flux normalization (and test LSND anomaly).
- In our simulations, we considered 20 ktons liquid scintillators, and a neutrino flux equivalent to the one generated by a 10 mA, 800 MeV proton beam.
- This is equivalent to 650 IBD events expected a 10 km with $\delta_{CP} = 0$

NOTE: Exploiting the synergy with LBNE it is also possible to obtain a reasonable precision even with just one detector.
Expected Precision

Neutrino Research at ADS Facility
ADS facilities will be able to produce a large amount of neutrinos. Even from the first phases of the project it will be possible to produce $\bar{\nu}_e$ via IsoDAR, searching for experimental signs of the presence of sterile neutrinos. LiOD and LiOD-D$_2$O give the best $^8$Li yield in most of the cases. Using heavy metal target, bounce back can significantly decrease neutron yield (reduced with vacuum sleeve). When the energy is higher, $\bar{\nu}_\mu$ can be produced via $\mu$DAR and be used to determine $\delta_{\text{CP}}$ with good precision.
Backup Slides
If almost all the neutrons are absorbed inside the converter, the expected ratio $^{8}\text{Li}/n$ can be calculated analytically.

\[ \rho_i = \text{fraction of atoms of the isotope i present in the compound} \]
\[ \sigma_i = \text{absorption cross section for thermal neutrons} \]

\[ P_{\text{Li8}} = \frac{\sigma_{\text{Li7}} \rho_{\text{Li7}}}{\sum \sigma_i \rho_i} \]

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>D</th>
<th>$^6\text{Li}$</th>
<th>$^7\text{Li}$</th>
<th>Be</th>
<th>O</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{abs}}$</td>
<td>0.33</td>
<td>$5.2 \times 10^{-4}$</td>
<td>940</td>
<td>0.045</td>
<td>0.008</td>
<td>$1.9 \times 10^{-4}$</td>
<td>0.01</td>
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</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>$\text{Li}$</th>
<th>$\text{LiOD}$</th>
<th>$\text{LiOD} \cdot \text{D}_2\text{O}$</th>
<th>solution</th>
<th>F$\text{LiBe}$</th>
</tr>
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<tbody>
<tr>
<td>$P_{\text{Li8}}$</td>
<td>0.326</td>
<td>0.317</td>
<td>0.300</td>
<td>0.208</td>
<td>0.280</td>
</tr>
</tbody>
</table>

**NOTE**

Since $\sigma_{\text{Li6}} \gg \sigma_{\text{Li7}} \left(\sim 2 \times 10^4 \sigma_{\text{Li7}}\right)$, the main limiting factor in the $^{8}\text{Li}$ yield is the isotopic purity of Li.
The CP-violating angle $\delta_{CP}$ appears only in the oscillation probability (no $\delta_{CP}$ in the disappearance channel); e.g.:

$$P_{\mu \rightarrow e} =$$

$$\sin^2(\theta_{23}) \sin^2(\theta_{13}) \sin^2(\Delta_{31})$$

$$\pm \sin(\delta_{CP}) \sin(2\theta_{13}) \sin(2\theta_{23}) \sin(2\theta_{12}) \sin^2(\Delta_{31}) \sin(\Delta_{21})$$

$$+ \cos(\delta_{CP}) \sin(2\theta_{13}) \sin(2\theta_{23}) \sin(2\theta_{12}) \sin(\Delta_{31}) \cos(\Delta_{31}) \sin(\Delta_{21})$$

$$\cos^2(\theta_{23}) \sin^2(\theta_{13}) \sin^2(\Delta_{21})$$

$$\Delta_{ij} = 1.27 \Delta m^2_{ij} L/E; + \ (-) \text{ for antineutrinos (neutrinos).}$$
Expected spectra at near and far detectors for $\delta_{CP} = 0^\circ, 90^\circ, 180^\circ, 270^\circ$; normal hierarchy, 10 years lifetime.

With $\delta_{CP} = 0$, 650 expected events between 30 and 55 MeV
Sensitivity to $\delta_{CP}$ for $\delta_{CP} = 0^\circ, 90^\circ, 180^\circ, 270^\circ$.

Solid curves: synergy with NO$\nu$A is taken into account.
In our energy range (30-55 MeV) we can neglect the spallation, reactor or geoneutrinos background ⇒ main source of background: atmospheric neutrinos. A strong horizontal geomagnetic field defects low energy cosmic rays, reducing the low energy atmospheric flux.

China (0.38 G), RENO 50/Kamioka mines (0.31 G)

vs

DUNE (0.17 G), LENA in the Pyhasalmi mine (0.13 G)

Low background: \( \simeq 50 \) events in 10 years (compared to 650 events at 10 km wth \( \delta_{CP} = 0 \))

J. Evslin, S.F. Ge, K. Hagiwara; arXiv:1506.05023