Gadolinium (Gd) and Water

Pablo F. (IFIC-CSIC, UAM)
DUNE Module of Opportunity Workshop
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Outline

- Introduction to Gd-doped water-Cherenkov detectors
- Status of the technology and future steps
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• Higher energy physics potential
  ➢ Proton decay
  ➢ Atmospheric neutrinos
  ➢ Beam neutrinos
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  - Proton decay
  - Atmospheric neutrinos
  - Beam neutrinos
- Higher energy physics potential
- Summary and thoughts
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The resulting excited Gd nucleus de-excites emitting a cascade of photons:

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The neutron propagates for about 2 m in water until it becomes thermal.

This time and spatial coincidences are key to relate the Gd-neutron capture signal with the interaction which originated the neutron.
Gd-doped water-Cherenkov detectors

The produced γ-cascade has a mean multiplicity of 4 photons, with a total energy of $\sim 8 \text{ MeV}$ in average, which can be easily measured.

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Gd-doping provides, in addition to the charged particles detection, a highly efficient way of detecting neutrons by dissolving a salt of this rare earth into a water-Cherenkov detector.
The most recent and ambitious project of this sort is **SuperK-Gd**, that is the doping with Gd of the Super-Kamiokande detector (happening already next year).
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- Which salt to use (sulphate)
- Water purification systems
- Water transparency
- Uniformity of Gd
- Impact on detector materials
- Electronics and DAQ
- Gd-induced backgrounds (from impurities)
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Therefore, Gd-doped water-Cherenkov detectors are a proven and ready technology.

They are also very useful from the physics point of view as this kind of detectors is growing: EGADS, ANNIE, SuperK-Gd, WATCHMAN, XENONnT water shield, WCTEC, IWCD, HyperK (?)
Low energy neutrino physics potential

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A Gd-water-Cherenkov module in DUNE will highly enrich the physics program at low energies with measurements otherwise very challenging for LAr TPCs:

- Standard and NSI solar neutrino physics
- Complementary measurements of supernova bursts with the other modules
- Measurement of the Diffuse Supernova Neutrino Background (DSNB)
- Early supernova warning by measuring the pre-supernova stage
Higher energy physics potential

But Gd-loading also offers benefits at higher energies for proton decay and neutrino physics.

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The main background for proton decay searches are atmospheric neutrinos, which usually (>70%) produce at least one neutron.
Higher energy physics potential

Neutrino physics:

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*NOTE: The following figures and results show simulations for SuperKGd and T2KGd*
Higher energy physics potential

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  This is the natural and most logic continuation of neutron tagging, following the IBD reasoning.
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Despite all this, the neutron multiplicity is still larger for antineutrinos

![Atmospheric ν, μ-like (>1 GeV)](chart1)

![DUNE beam energy range (1.5 ~ 2.5 GeV)](chart2)
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  In this sense, neutron tagging does have some discrimination power to separate between CC, CC-DIS and NC neutrino interactions.
**Higher energy physics potential**

- **Energy neutron correction**
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Invisible energy fraction as function of the Gd-tagged neutrons

\[
E_{\text{rec}}^{Gd} = E_{\text{vis}}(1 + f(Gd - \text{neutron}))
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Atmospheric neutrino oscillations:
All three previous Gd-neutron tagging tools applied improve the atmospheric $\nu$ oscillation analysis as compared with the standard case
- **Neutrino-antineutrino**: performs best at lower energies and improves the sensitivity to $\delta_{CP}$ and MO
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- **Energy neutron correction**: it affects significantly most of the samples, providing an **overall improvement** in the sensitivity to the oscillation parameters

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SuperK-Gd – 155 kton·year
Neutrino beam oscillations:
The T2K neutrino beam is very low energy (0.6 GeV) compared to DUNE’s future beam.

In fact, being the neutrino energy for DUNE ~2 GeV all the three Gd-tagging tools can be applied:
- Detect possible (anti)neutrino backgrounds when the beam is in antineutrino (neutrino) mode
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The largest improvement in sensitivity would come from the ability of detecting beam (anti)neutrino backgrounds.
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In addition of being a novel but developed and proven technology, with the startup of SuperK-Gd and T2KGd (Japan), ANNIE (FNAL) and the possibility of WCTEC (CERN), a lot of knowledge will be acquired:

- Improving Gd-water purification systems
- Development of photo-sensors, like LAPPDs in ANNIE (which would be ideal for DUNE’s module given its geometry)
- Depending on the photo-sensor technology the Gd concentration can be adjusted
- Given the size of the cavern, it would be a ~10 kton FV detector (depends on the possible geometry modifications, outer detector…) aiming for a large photocoverage
- Water source in South Dakota?
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shall we?