Cl Loaded Antineutrino Detector

[The Straight Dope on Doping]

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The Past

Water Cherenkov detectors such as Kamiokande, IMB, SNO, and Super–Kamiokande have been used for many years as inexpensive, effective detectors for neutrino interactions and nucleon decay searches.

Many important measurements have been made with these detectors — discovery of neutrino oscillations, non-observation of nucleon decay, confirmation of the Standard Solar Model, and of course

discovery of neutrinos from stellar collapse!
BUOYANT

So successful has this technique been that now there is serious talk about megaton-scale underground water Cherenkov detectors (Hyper-Kamiokande, UNO, M$^3$) and even larger projects (TITANIC, NESTOR, ANTARES, NEMO, Ice-Cube).

I’m not sure what John wants to call his giga-ton array, but for now I’m going to refer to it as BUOYANT:

- Balloons
- Underwater
- Observing
- Yellowcake
- Antineutrinos from Nuclear Technology
The Missing Signal

For all their successes, a major drawback of the water Cherenkov technique has been the difficulty of such detectors in detecting the production of neutrons.

Of course, detecting neutral particles is not what Cherenkov detectors are designed to do...

Is there a way around this limitation?
The Physics of Neutron Capture

Neutrons liberated in water by the inverse beta reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

(and other processes) are quickly thermalized.

On average it takes about twenty collisions with the water’s free protons over \(\sim 10 \ \mu s\) to bring a neutron emitted with a few MeV down to room temperature (0.025 eV).
Once thermalized, and after bouncing around for another 100 $\mu$s or so, the neutron is captured by a proton or oxygen nucleus in the water.

The cross sections for these capture reactions are 0.33 barns and 0.19 millibarns, respectively, so to first approximation every thermal neutron is captured on a free proton via the reaction

$$n + p \rightarrow d + \gamma.$$
The resulting gamma has an energy of 2.22 MeV and makes very little detectable light since the Compton scattered electron is rather close to Cherenkov threshold.

Hence, in traditional water Cherenkov detectors (which tend to have trigger thresholds around 5 MeV) these neutron captures are generally not recorded.
Competitive, Aren’t We?

In order to observe reactor antineutrinos, we need something which will compete with the hydrogen in capturing neutrons.

Such a process is very similar to resistors in parallel, and can be exactly calculated:

![Diagram of resistors in parallel]

\[
\begin{align*}
V & \quad R_1 \quad R_2 \\
\text{NEUTRONS} & \quad H \quad ?
\end{align*}
\]
The Briny Deep

Couldn’t we put salt into BUOYANT to help collect neutrons, just like SNO has already done? Chlorine’s neutron capture cross section is 33 barns, yielding a nice 8.6 MeV gamma cascade.

But there’s a complication: in SNO the heavy water’s deuterium did not aggressively grab neutrons. In light water, to collect 50% of the neutrons on chlorine and 50% on hydrogen you’d need to put 6% NaCl by mass into BUOYANT. That’s double the salinity of seawater!
The Stopping Power of Chlorine

Here’s how the concentration of Cl in the water affects detectable neutron absorption:

Note that at 25.8% salt crystals start to form!
Another Option?

You may have heard that John Beacom and I have been working on putting gadolinium into Super–Kamiokande:

While Gd has great advantages over NaCl in Super–K or Hyper–K, it is not the right choice for BUOYANT.
That’s About the Size of It

So, why use NaCl in BUOYANT?

As is often the case, size matters:

BUOYANT is so large that efficiency can be traded for volume and cost-effectiveness.
Economies of Scale

Remember that one has to keep BUOYANT from being too buoyant.

The obvious solution is to put locally purified, low $^{40}\text{K}$ salt into the balloons to nearly match oceanic salinity, $\sim 3.5\%$.

Note that present world NaCl production is 210 megatons/yr... BUOYANT will require a total of 35 megatons of NaCl.
You Light Up My (Half)Life

Also, in a giant detector where light must travel long distances (~200 meters) every Cherenkov photon is going to matter!

Neutron capture on Cl gives off somewhat more Cherenkov light than does capture on Gd, as their gamma cascades liberate 8.6 MeV and 8.0 MeV respectively.
Mixology 101

Okay, but what about tossing in a little Gd with its astonishing neutron capture cross section of 49,000 barns?

In order to raise BUOYANT’s observable neutron fraction from, say, 33% to 66% you’d need to add just 0.005% Gd by mass. That’s a total of 50 kilotons of Gd.

Unfortunately, the entire world production of Gd is about 3 kilotons per year!
Need A Few Kilotons of Dysprosium?

Well, maybe production of Gd could be stepped up if such an enormous demand suddenly arose...

However, it is not possible to just produce more Gd. All other rare earths must be mined (if not refined) at the same time!
I May ♡ My Dog, But I ♣ My Baby Seal

What’s more, such a huge detector system in open waters will inevitably attract negative attention from the environmental lobby.

It’s clearly much better to be able to say that in case of a leak there’s nothing sloshing around in the balloons not found in regular seawater!
Pass the Salt!

So, it looks like BUOYANT is pretty much stuck with pure NaCl, as well as a modest neutron capture efficiency of about 33%.

Still, if such a gigantic detector can actually be built this will surely allow some remarkable measurements to be made!