Directional Antineutrino Detector

Benjamin R. Safdi + ?

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Constructing a directional antineutrino detector is extremely important. Such a detector would have applications across a wide range of scientific fields, and it would also potentially have commercial and humanitarian applications. For fundamental high energy physics, it is useful for a variety of reasons to know the directions that the antineutrinos are coming from. This can help identify the locations of origin (i.e., the specific reactors), which is useful for studying neutrino oscillations. Also, having a directional antineutrino detector is a powerful tool for searching for stellar antineutrinos, which could arise due to neutrino magnetic moment effects. A directional antineutrino detector would also have applications in geology; constructing such a detector is the first step towards spatially mapping geoneutrinos and thus constructing a 3D map of radioactive material inside the Earth. In the future, directional antineutrino detectors may also be used for simultaneously monitoring multiple nuclear reactors from a central location. A large enough directional antineutrino detector could even be used as a monitor for nuclear explosions.

Low-energy antineutrinos, with energies $\mathcal{O}\,(\text{MeV})$, are typically detected in large liquid scintillator detectors. The antineutrino scatters inelasticity with a hydrogen nucleus, converting it into a neutron plus a positron. The positron almost immediately annihilates with an electron, letting off two back-to-back γ rays of known energies. The neutron diffuses for a short time until it reaches thermal speeds, at which point it is captured by hydrogen or perhaps another element, such as Gd. The neutron capture lets of γ rays at known energies.

Before the positron annihilates, it loses energy to the scintillator through a variety of elastic processes. The gamma rays also convert into scintillation radiation. The liquid scintillators are surrounded by photomultiplier tubes to detect the scintillation radiation.

The large liquid scintillator detectors suffer from a major problem; they cannot determine the antineutrino direction on an event-by-event basis. The neutron recoils in approximately the direction of the antineutrino's velocity. One would then think that by measuring the position vector between the positron annihilation location and the neutron capture location, one could measure the direction that the antineutrino came from. This does not work because the neutron diffuses before being captured, and so by the time it is captured it only has a slight preference to end up in the direction it was originally traveling. In fact, it may easily end up in the opposite direction.

The goal of this work it to design a detector that allows the neutron to propagate freely over a large distance before diffusing and being captured. On the other hand, we want the positron to annihilate near the point of the antineutrino capture. Then, the position vector between the antineutrino annihilation point and the neutron capture point will approximately point in the direction of the antineutrino's motion.

I. THE DETECTOR

The experimental design is outlined in Fig. 1. The detector consists of alternating target and neutron conversion layers in a cylindrical topology. Each layer is composed of long and thin plastic scintillator tubes. For convenience, we define r to be the radius of the target-layer tubes and R the radius of the neutron-conversion layer tubes. The neutron-conversion layer tubes are also surrounded in a thin Gadolinium wrapping. The target and neutron conversion layers are separated by a distance D.

The proposed detector utilizes plastic scintillators for the antineutrino target. Plastic scintillators were used in PANDA for antineutrino detection [1]. They also wrapped their scintillators in Gadolinium foil to improve neutron capture, and we propose to do the same on the neutron-conversion layer scintillators. A grid of Gadolinium foil could also be incorporated inside the scintillator material.

The Rexon RP-408 plastic scintillators used in the PANDA experiment have hydrogen and carbon densities

$$\begin{aligned} n_H &\approx 5.23 \times 10^{22}\ \text{cm}^{-3}\,, \\ n_C &\approx 4.74 \times 10^{22}\ \text{cm}^{-3}\,. \end{aligned} \tag{1}$$

The neutrons emitted from the inverse beta decay event have kinetic energies $\mathcal{O}(10\,\text{keV})$. These are fast neutrons, with speeds well above the thermal speed. The fast neutron capture total elastic cross sections on hydrogen and carbon are

$$\sigma_H \approx 4\ \text{b}\,, \qquad \sigma_C \approx 2\ \text{b}\,. \tag{2}$$

Thus, the fast neutrons will on average travel a distance

$$\ell_n = \frac{1}{n_H \sigma_H + n_C \sigma_C} \approx 3\ \text{cm} \tag{3}$$

before their first elastic collisions. With this in mind, we propose to take $r \approx 1$ cm so that most neutrons will not scatter within the target layer; they will travel freely until the neutron conversion layer.

The neutron conversion layer may be made similar to the PANDA scintillators, with $R \approx 10$ cm and $\sim$25 μm-thick Gd foil. The distance D should be great than R; the

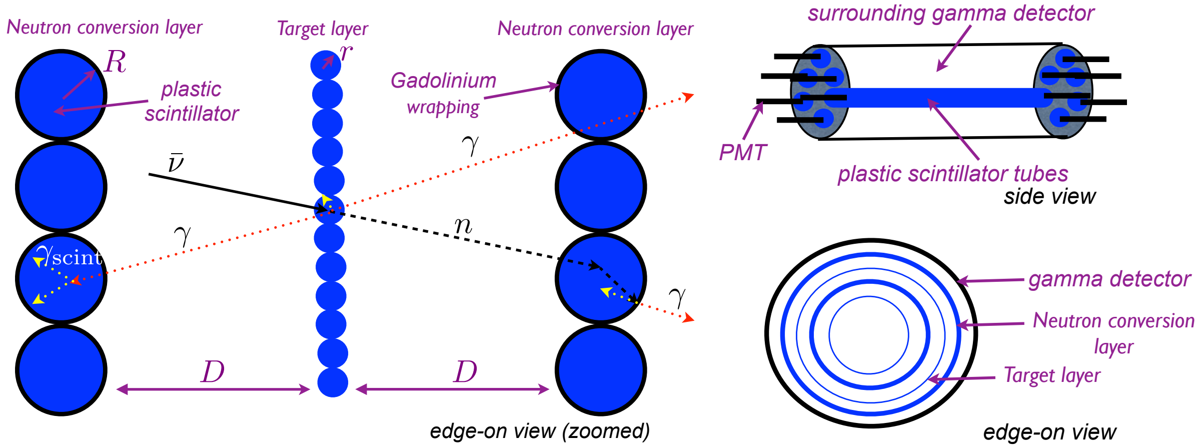

FIG. 1: The antineutrino detector has a cylindrical topology, with alternating "target" and "neutron conversion" layers. Both layers are made of plastic scintillator tubes, but the latter type of layer is surrounded by a thin Gd foil. A grid of Gd foil could also be incorporated inside the scintillator. The target tubes have radius $r \sim 1\,$cm, while the conversion layers have radius $R \sim 10\,$cm. The layers are separated by a distance $D > 10$ cm. PMTs are attached to the ends of the scintillator tubes, and the whole apparatus may be wrapped in a surrounding gamma ray detector.

greater the distance D, the better the angular resolution. We consider $D \approx 50$ cm.

The cross section for positron annihilation is high enough that the positron annihilates within the target. Moreover, before the positron annihilates, it releases energy within the scintillator in the form of scintillation radiation. This radiation is detected by attaching PMTs to both ends of the tubes, like in PANDA. These measurements help identify the location of the event and the positron energy.

The high-energy γ rays propagate through the detector. Depending on how many neutron conversion layers there are in the detector and where the event takes place, it is possible that the γ rays make it to the edge of the detector, where they are detected by γ ray detectors. Then, just like in a PET scanner, the two γ rays may be used to draw a line on which the initial event took place. Advancements in time-of-flight techniques for PET scanners could further help identify the location along this line. Combined with the initial scintillation signal, this should be sufficient to accurately determine the initial event's location.

It is also possible that the γ ray converts into scintillation radiation in one of the scintillator tubes. In this case, the scintillation radiation may be observed from the PMTs attached to the ends of the tube. The location along the tube where the γ converted is found by comparing the radiation at both ends of the tube, as in PANDA.

We propose a $\sim$100 kg H detector as a prototype. This is the amount of hydrogen in the target scintillators; there will also be $\sim$10 tones of H in the neutron-capture scintillators, since their radii are a factor $\sim$10 larger. Antineutrinos will also be captured in the neutron-capture scintillators. These events can be measured and recorded, though they will not have directionality.

As an example, if the target tubes are 5 meters long and 1 cm in radius, then each tube will contain $\sim$140 g of hydrogen. Then, to reach 100 kg of H in the target, we need $\sim$730 target tubes. This could be arranged by having a single target shell (see the edge-on view in Fig. 1) at a radius $\sim$1 m. Then, there should be two neutron conversion layers; one at a radius $\sim$0.5 m and the other at a radius $\sim$1.5 m. The experiment would then fit inside a cylinder of radius $\sim$2 m and length $\sim$5 m.

II. SIMULATIONS

Coming soon!

[1] Y. Kuroda, S. Oguri, Y. Kato, R. Nakata, Y. Inoue, C. Ito, and M. Minowa, Nuclear Instruments and Methods in Physics Research A **690**, 41 (2012), 1206.6566.