A New Detector for Electron Antineutrinos

F.D. Brooks, University of Cape Town
M. Drosg, University of Vienna
F.D. Smit, iThemba LABS, Somerset West

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A Direction-Sensitive Detector for Electron Antineutrinos

F.D. Brooks, University of Cape Town, South Africa  
M. Drosg, University of Vienna, Austria  
F.D. Smit, iThemba LABS, Somerset West, South Africa

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Interest in $\bar{\nu}_e$ detection from:

- Weak-interaction physics
- Astrophysics (next supernova)
- Geophysics (geoneutrinos)
- Nuclear material surveillance

Figure 2. (left) Ratio of the observed number of neutrino events with respect to the no-oscillation case for all reactor neutrino experiments. The source-detector distances are displayed on the x-axis. Among all experiments, only KamLAND has observed a disappearance thanks to its very long source-detector average distance [24]. (right) Measurement of neutrino oscillation with KamLAND and long baselines for several reactors. The green band represents statistical uncertainties in the fitted value.
Supernova emitted $10^{57}$ neutrinos in a few seconds -10 times the total number of neutrons and protons in the Sun

Of these, about $10^{16}$ passed through the detector and 12 were detected

Provides the first experimental proof of stellar collapse

Pulse shape remarkably well reproduced by Bethe-Brown theoretical model based on nuclear phenomena

Pulse duration sets upper limit of 15 eV on the neutrino mass.
Evidence for geoneutrinos – Borexino data

Figure 3: Light yield spectrum for the positron prompt events of the 21 $\bar{\nu}_e$ candidates and the best-fit with Eq. (5) (solid thick line). The horizontal axis shows the number of p.e. detected by the PMTs. The small filled area on the lower left part of the spectrum is the background. Thin solid line: reactor-$\bar{\nu}_e$ signal from the fit. Dotted line (red): geo-$\bar{\nu}_e$ signal resulting from the fit. The darker area isolates the contribution of the geo-$\bar{\nu}_e$ in the total signal. The conversion from p.e. to energy is approximately 500 p.e./MeV.
Average no. of antineutrino interactions per year in a 1 kiloton detector
(estimated, from all known nuclear reactors)

Figure 21: The *predicted* average antineutrino flux worldwide arising from known nuclear reactors. The color contours show the antineutrino interaction rate per $10^{32}$ proton per year, or about that of a 1000-ton detector per year. The red indicates areas where there are dense concentrations of reactors in France, the eastern United States, and Japan. Data are modeled based on known reactor powers, and are not from antineutrino flux measurements.
Production of plutonium during a typical reactor fuel cycle

The graph shows the fractions of the different isotopes of uranium and plutonium over time. The isotopes 235\text{U}, 239\text{Pu}, 238\text{U}, and 241\text{Pu} are represented with different lines.

't). Percentage of fissions of the main fissile elements during a fuel cycle.
Figure 16: Left: a cutaway view of the plastic scintillator/Mylar sandwich detector SONGS2. Mylar sheets, covered with a Gd-doped paint, are interleaved between the 2 centimeter thick plastic scintillator blocks. Light collection is accomplished with 4 photomultiplier tubes. Right: initial data from the plastic detector showing sensitivity to the antineutrino signal.
Neutrinos/antineutrinos

- Postulated by Pauli (1930). (Pauli “apologized” to physicists for “inventing” a particle that “could not” be detected!)

- Fermi’s theory, incorporating Pauli’s hypothesis, was successful in explaining features of beta decay (1934).

- Antineutrino detected by Reines, Cowan et al (1953)
First detection of antineutrino – Reines and Cowan (1953)

Liquid scintillator
75 cm x 75 cm diam.
90 PM tubes.
$\bar{\nu}_e$ from Hanford nuclear reactor
Double-pulse “signature”.

Fig. 2. The Hanford neutrino detector (1953).
\overline{\nu}_e \text{ signature in a Cd-doped scintillator (1)}

1) **Pulse #1** from inverse beta decay of the neutron:

\[ \overline{\nu}_e + p \rightarrow e^+ + n \quad (Q = -0.8 \text{ MeV} \quad \sigma \sim 10^{-43} \text{ cm}^2) \]

\[ e^+ + e^- \rightarrow \gamma + \gamma \quad (Q = 1.02 \text{ MeV}) \]

sum of pulses from e\(^+\) and 2 \(\gamma\)

2) **Delay** of 1-2 \(\mu\)s while the neutron thermalizes

3) **Pulse #2** from neutron capture by Cd:

\[ ^{113}\text{Cd} + n_{\text{th}} \rightarrow ^{114}\text{Cd}^* \quad (Q \sim 9 \text{ MeV} \quad \sigma = 20 \text{ kb}) \]

\[ ^{114}\text{Cd}^* \rightarrow ^{114}\text{Cd} + \gamma\text{-cascade} \quad (\Sigma E_\gamma \sim 9 \text{ MeV}) \]

sum of pulses from 4-6 \(\gamma\)
An improved $\bar{\nu}_e$ signature (2)

1) **Pulse #1 from inverse beta decay of neutron:**

\[
\bar{\nu}_e + p \rightarrow e^+ + n \quad (Q = -0.8 \text{ MeV} \quad \sigma \sim 10^{-43} \text{ cm}^2)
\]

\[
e^+ + e^- \rightarrow \gamma + \gamma \quad (Q = 1.02 \text{ MeV})
\]

coinc. of pulses from $e^+$ and 1 or 2 $\gamma$

2) **Delay of 1-2 $\mu$s while neutron thermalizes**

3) **Pulse #2 from neutron capture by Cd:**

\[
^{113}\text{Cd} + n_{th} \rightarrow ^{114}\text{Cd}^* \quad (Q \sim 8 \text{ MeV})
\]

\[
^{114}\text{Cd}^* \rightarrow ^{114}\text{Cd} + \gamma\text{-cascade} \quad (\Sigma E_\gamma \sim 9 \text{ MeV})
\]

coinc. of pulses from 2 or more $\gamma$
Reines, Cowan et al (1956): detector #2 (schematic)

2 slabs ■ of Cd solution between 3 slabs □ of liquid scintillator.

Inverse beta decay at 1 leads to 2 annihilation quanta detected at a.

γ’s from neutron capture by Cd at 2 are detected ~ 1 μs later, at b.

Delayed coincidence (1 followed by 2) is the signature of ν_e.

Note: The e^+ is not detected at 1. However, since events 1 and 2 are coincidences, discrimination against random coincidence backgrounds is improved.

2m x 1.5m x 7.5cm deep solution of CdCl_2 in water.

2m x 1.5m x 60cm deep liquid scintillator.

6 banks of 55 p.m. tubes

e^+  n  γ  e^−
Photographs of antineutrino detector #2 (Reines et al, 1956)

Used to detect $\bar{\nu}_e$ from the reactor at Savannah River.

CdCl$_2$-in-water solution

Liquid scintillator

Fig. 6: End view

Fig. 7: Light detector (55 p.m. tubes) at end of liquid scintillator.
A large antineutrino detector – KamLand (1980)

1 kiloton of liquid scintillator

Figure 27: The KamLAND detector for reactor antineutrinos. It has a fiducial mass in the 1,000 ton range and can measure the summed neutrino signal from multiple commercial power plants several hundred kilometers distant.
Super KamioKanda – 50 kilotons water (Cerenkov detector)
Super KamioKande (Japan)

Photographed in 2000 while being filled with water (50 kilotons). 11,200 PM tubes detect Cerenkov radiation from $\nu_e \to \nu_e$ (elastic scattering) and other interactions that release relativistic charged particles. Note the technicians on the raft, who are cleaning the PM tubes as the tank fills up.
The proposed $\nu_e$ detector is expected to have the following features:

1) The scintillator will be $^{10}$B-doped instead of Cd-doped or Gd-doped.
2) Pulse shape discrimination will be employed in the selection of double-pulse events.
3) A modular design that can be replicated easily and then assembled into a large detector will be used.
4) Each module will consist of 19 or more independent scintillators, in order to obtain a more selective antineutrino signature.
5) It is envisaged that semiconductor-based light sensors will soon become available, to be used instead of photomultipliers.
6) Data capture will be accomplished by electronics based on up-to-date techniques such as flash ADCs rather than NIM electronics.
7) Data reduction will be carried out by compact on-line computers.
8) Directional-sensing capability (FWHM ~ 15°).

Initial development and testing is now being undertaken at UCT/iTL, using neutrons to mimic the antineutrino signature. Further tests are planned at Koeberg nuclear power station, using antineutrinos.
**$\bar{\nu}_e$ signature in a $^{10}\text{B}$-doped scintillator**

1) **Pulse #1** from inverse beta decay of neutron:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (Q = -0.8 \text{ MeV} \quad \sigma \sim 10^{-43} \text{ cm}^2)$$

$$e^+ + e^- \rightarrow \gamma + \gamma \quad (Q = 1.02 \text{ MeV})$$

coinc. of pulses from $e^+$ and 2 $\gamma$

2) **Delay of $\sim 0.5 \mu s$** while neutron thermalizes

3) **Pulse #2** from neutron capture by $^{10}\text{B}$:

$$^{10}\text{B} + n_{\text{th}} \rightarrow ^7\text{Li}^* + \alpha \quad (Q \sim 2.3 \text{ MeV})$$

$$^7\text{Li}^* \rightarrow ^7\text{Li} + \gamma \quad (0.48 \text{ MeV})$$

coinc. of pulses from $^7\text{Li}$, $\alpha$ and $\gamma$
19-cell scintillator module (schematic)

single cell

35 cm

30-50 cm

6 cm

Al-foil

19 PMT

B-doped scintillator

“honeycomb”

19 PMT
19-cell unit
15-30 cm long cells
2 PM tubes per cell

Container filled with $^{10}$B-doped liquid scintillator NE311

0.2 mm Al foil to separate cells.
$\bar{\nu}_e$ event ($1^{st}$ pulse)

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

$e^+ + e^- \rightarrow \gamma + \gamma$

$E_e = E_\nu - 1.8$ MeV

neutron goes forward

$E_n \leq 100$ keV

Vertex position is determined from cell position $(x,y)$ and pulse height division $(z)$.
$\bar{\nu}_e$ event ($2^{nd}$ pulse)

$^{10}\text{B} + \text{n} \rightarrow \alpha + ^7\text{Li}^*$

$^7\text{Li}^* \rightarrow ^7\text{Li} + \gamma$

Vector from vertex 1 to vertex 2 gives direction of $\bar{\nu}_e$
n-event ($1^{st}$ pulse)

n + p → p + n
\textbf{\textit{n-event}} (2\textsuperscript{nd} pulse)

\[ ^{10}\text{B} + \text{n} \rightarrow \alpha + ^{7}\text{Li}^* \]

\[ ^{7}\text{Li}^* \rightarrow ^{7}\text{Li} + \gamma \]

\textit{same as for} $\bar{\nu}_e$ \textit{event}
Experiments with neutrons and two small scintillators

- **Det A**: A → Discrim & Coinc → Digital Scope → Laptop
- **Det B**: B

B (NE213)  A (boron-doped)

Am-Be or $^{252}$Cf neutron source

Iron

- **Event 1**
  - Pulse #: 1
  - 2500 ns
- **Event 2**
  - Pulse #: 1
  - 530 ns
Double-pulse events from a $^{252}$Cf source (Inverted pulses from Detector A).

$L_f =$ fast component (0-30 ns)

$L =$ total light (0-240 ns)

$S =$ “Shape” = $100L_f / L$

$T =$ time difference

(1) hadron

$T =$ 776 ns

(2) lepton

$T =$ 520 ns after pulse

$\gamma_e$
**PSD from pulse 1**

$L_1$ vs $S_1$

2240 events in 2 hr

$L_1$ vs $T$

( $T = \text{time difference}$)

After-pulses

$S_1$ window

leptons

hadrons
$L_2$ vs $T$

After-pulses

PSD from pulse 2
$L_2$ vs $S_2$

After-pulses

$L_2$-$S_2$ cut

$S_2$ window
$L_2$ vs $T$ after imposing: window $S_1$; window $S_2$; and the $L_2$-$S_2$ cut.

204 events selected from 2240
Tests using reactor antineutrinos at Koeberg? (proposed)

Two reactors of 950 M\(\text{w}_e\) (2700 M\(\text{w}_{\text{th}}\)). At full power each reactor produces \(\sim 10^{20}\) antineutrinos per second into \(4\pi\).

The test position is directly below reactor 2, 17 m from the centre of the core, with 6 m of concrete in between. The estimated antineutrino fluence at this point is \(9 \times 10^{12}\) per cm\(^2\) s. This should produce about 5 inverse beta decays per day in a detector of volume 1 litre. Thus for a module of volume 30 litres \(\sim 150\) events/day is estimated.
A single voxel

ZnS(Ag) scintillator with $^6$Li loading

Liquid organic scintillator with pulse shape discrimination

~10 cm
SUMMARY

These tests show that the $^{10}$B-doped detector:

should select the antineutrino signature efficiently; and

should reject neutron-induced backgrounds efficiently.

Other tests have shown that the detector should have sufficient position resolution to achieve a direction-sensing capability.

The next step will be to carry out further tests using larger detectors with antineutrinos from the Koeberg nuclear reactors.
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