Lead Perchlorate as a Neutrino Detection Medium

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Abstract

Lead can be an ideal medium for the detection and study of neutrinos. Such a detector may be realized through the use of a lead perchlorate (Pb(ClO$_4$)$_2$) solution as a Cerenkov radiator. The basic physical properties of lead perchlorate solution are given and preparation of the solution for use in a Cerenkov detector is described. Results from investigations of light transmission in lead perchlorate solutions are also presented.

Key words: neutrino detection, supernovas, lead perchlorate, cerenkov detector
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1 Introduction

In the energy regime of 10-30 MeV the neutrino interaction cross section [1,2] on lead is 2-3 orders of magnitude greater than that of carbon, a common detector medium. For this reason there has been interest in using lead to study neutrinos from supernovae [3–7] or in accelerator-based neutrino oscillation searches [8].

Neutrino interactions with lead may occur via either the charged current (CC) or neutral current (NC) mechanisms,

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Fig. 1. The level scheme of $^{208}\text{Pb} - ^{208}\text{Bi}$ system. The levels are labeled $GT$ to indicate the Gamow-Teller resonances, $IAS$ to indicate the isobaric analog state, and $1st$ to indicate the states populated by first forbidden transitions. The 1 and 2 neutronemmision thresholds are indicated by the labels 1n and 2n respectively.

\[
\begin{align*}
\nu_e + ^{208}\text{Pb} &\rightarrow ^{208}\text{Bi}^* + e^- & \text{(CC)} \\
\downarrow &\rightarrow ^{208-\gamma}\text{Bi} + X\gamma + Yn
\end{align*}
\]

\[
\begin{align*}
\nu_x + ^{208}\text{Pb} &\rightarrow ^{208}\text{Pb}^* + \nu'_x & \text{(NC)} \\
\downarrow &\rightarrow ^{208-\gamma}\text{Pb} + X\gamma + Yn
\end{align*}
\]

where $X$ and $Y$ are the number of $\gamma$ rays and neutrons emitted, respectively. $Y$ can be either 0, 1, or 2, depending on the incident neutrino energy and the resulting excited nuclear state. The energetics of these transitions are shown in Fig. 1.

Lead perchlorate ($\text{Pb(ClO}_4\text{)}_2$) has a very high solubility in water. A saturated solution consists of approximately five parts by weight of lead perchlorate to one part water (see Table 1) and is transparent to the eye. These properties led to its early consideration as a Cerenkov radiator [9] and for gamma ray detection [10] [11]. The presence of hydrogen in the solution results in efficient
thermalization of any neutrons associated with neutrino interactions. There is a high probability (>90%) that these neutrons will then capture on the $^{35}$Cl present in a saturated solution, with the subsequent emission of gamma rays totalling 8.6 MeV. As discussed by the Sudbury Neutrino Observatory collaboration [12], these gamma rays may then be detected via their Compton scattered electrons in a Cerenkov detector.

| Property                                      | Value                           |
|-----------------------------------------------|---------------------------------|
| $^{208}$Pb number density                     | $1.19 \times 10^{21}$ cm$^{-3}$ |
| H number density                              | $4.37 \times 10^{22}$ cm$^{-3}$ |
| $^{208}$Pb($\nu_e$, $e^-$) cross section at 30 MeV | $34 \times 10^{-40}$ cm$^2$    |
| $^{35}$Cl n capture cross-section             | 44.0 b                          |
| Density                                       | 2.1 gm cm$^{-3}$                |
| Refractive index                              | 1.45                            |
| Attenuation Length                            | $\approx 4$ m                  |

Table 1

Some properties of a 70% lead perchlorate solution prepared in the manner described in the text.

While both the CC and NC reactions result in neutron and gamma production, only the CC reaction produces a prompt electron. This is important since detection of the prompt electrons allows the separation of CC and NC events.

The CC reactions may further be divided into $\nu_e$ and $\bar{\nu}_e$ events. The $\nu_e$ events in lead can produce one or two neutrons. The $\bar{\nu}_e$ events result from interactions with hydrogen in the solution, and only produce a single neutron. Thus the two-neutron spectrum contains only $\nu_e$ events, while the one-neutron spectrum contains both $\nu_e$ and $\bar{\nu}_e$ events. By comparing the two spectra the $\nu_e$ and $\bar{\nu}_e$ reactions can be separated. The reaction $\bar{\nu}_e$-Pb is relatively insignificant due to its smaller cross-section [1,2].

Neutrino interactions in lead that occur through the NC process can produce, via a Gamow-Teller resonance, a single 7.6-MeV gamma ray and no neutron. Alternatively, the NC reaction may result in a single neutron, with little or no electromagnetic energy. Two-neutron production by the NC reaction has a lower cross section than for the CC reaction [1,2].

Thus, by careful measurement of the prompt energy and the number of neutrons produced, one may determine the neutrino flavor and, in the case of CC interactions, the energy of the interacting neutrino. Details of these analyses in Pb(ClO$_4$)$_2$ are discussed along with their applications to the study of supernovae in Ref. [3].
2 Applications of a lead perchlorate based neutrino detector

The interaction cross sections of neutrinos with complex nuclei are of great importance in supernova studies. They are central to the supernova explosion mechanism, the nucleosynthesis of heavy elements in supernovae, and the detection of supernovae neutrinos. Therefore accurate values for the cross sections are of both theoretical interest and an essential ingredient in the design and interpretation of a lead based supernova neutrino detector. Unfortunately, the theoretical predictions of the total inelastic neutral current and charged current cross sections for neutrino reactions on $^{208}$Pb given by [1] and [2] differ significantly and the cross sections for neutrino reactions on various isotopes of lead have not been measured. However because the neutrino energies are similar, a lead perchlorate based detector at a stopped-pion neutrino source would be a very effective way of measuring the $\nu$-Pb cross sections in the energy region of interest to supernova studies. For example, at the proposed ORLAND/SNS neutrino source [13], a 10 tonne Pb(ClO$_4$)$_2$ detector could measure the $\nu_e$-Pb cross section to an accuracy of 10% with approximately 100 days of detector livetime.

Lead offers promise as a supernova neutrino detection medium because the neutron production from neutrino interactions with lead is extremely sensitive to the energy spectrum of the supernova electron neutrinos. This sensitivity is due to the pronounced increase in the $\nu_e$-Pb cross section in the energy region significant to supernova neutrinos. In particular, the 2-neutron production cross section increases dramatically with energy. The measured one- and two-neutron spectra from a Pb-based detector and the 2 neutron/1 neutron event ratio provide data sensitive to any potential neutrino oscillation processes occurring in a supernova[3]. In the absence of oscillations, the expected energy hierarchy for neutrino production in supernovae is $E_{\nu_e} < E_{\bar{\nu}_e} < E_{\bar{\nu}_{\mu,\tau}}$. A Pb(ClO$_4$)$_2$ neutrino detector could exploit this hierarchy to discriminate between neutrino flavors. If higher-energy mu and tau neutrinos oscillate into electron neutrinos, both the average detected electron neutrino energy and the 2-neutron CC interaction rate would increase dramatically. Observing this increase would be strong evidence that neutrino oscillations are taking place. Fuller, et al. [2] predict that the definitive signal of tau to electron oscillations in a $^{208}$Pb detector is a dramatic enhancement (up to a factor of 40) in multiple neutron events.

3 Filtration and Attenuation Length Measurement

The attenuation length of light in a material may be defined as the length of material over which the intensity of light decreases by a factor of 1/e. For
In order to assess the feasibility of using lead perchlorate as a Cerenkov neutrino detection medium, we constructed an apparatus to measure the attenuation length of various lead perchlorate solutions (see Fig. 2). The apparatus consists of a 1.3-meter tall, 3-cm inner diameter, chlorinated polyvinyl chloride (CPVC) column. A 430 nm light emitting diode (LED), powered by a 1-kHz square-wave, is mounted at the top of the column. The light from the LED is focused onto a 1.9 cm diameter, flat-faced (Hamamatsu R1450) photomultiplier tube (PMT) mounted at the bottom of the column. The signals from the PMT, along with the LED pulse-generating waveform, are fed into a lock-in amplifier. To measure the attenuation length, the column is filled with the lead perchlorate solution, and as the liquid level is slowly lowered, the output of the PMT is recorded. Plotting the PMT output as a function of the liquid level $x$, yields an exponential curve $y = Ce^{-x/\lambda}$, where $\lambda$ is defined to be the attenuation length of the solution.

Lead perchlorate solutions were obtained from GFS Chemicals [14] in 50% and 82.4% (saturated) solutions by mass. The saturated Pb(ClO$_4$)$_2$ solution contained visible precipitates and had an initial attenuation length of approximately 20 cm. The saturated solution was diluted to 70% concentration by first mixing it with deionized water and heating it to 42°C while stirring.
overnight. This procedure removed the visible precipitates and increased the attenuation length to 54 cm. In order to determine whether any lead salts still present in the solution were affecting the attenuation length, a means of filtering the solution was developed. The filtration system consisted of a positive-displacement, compressed-air-driven Warren Rupp Marathon Pump (model MP01P) constructed from polyvinylidenedifloride (PVDF) and compatible with lead perchlorate solutions. This pump was used to transfer solutions from one reservoir to another via a 47-mm diameter polypropylene filter holder (Advantec MFS, Model 501200). The primary consideration for filtering lead perchlorate is the compatibility of the filter material with the lead perchlorate solution. Polytetrafluoroethylene (PTFE) filters were found to be the most compatible, but have the disadvantage of being hydrophobic. The recommended procedure for using PTFE filters is to wet them with alcohol before filtrations. Unfortunately, alcohol and lead perchlorate are incompatible, so wetting was impossible. Thus, the usable pore size of unwetted PTFE filters was limited to 1.0 micron; smaller pore sizes did not allow even pure water to pass through without puncturing the filters. PVDF filters were also quite compatible as long as the pH of the lead perchlorate solution was > 4. It is necessary to maintain the acidity of the solution to minimize the formation of salts, but allowing the solution to become too acidic resulted in the disintegration of the PVDF filters. PVDF has the distinct advantage over PTFE of being hydrophilic, which allowed the use of smaller pore sizes.

While \( \text{Pb(ClO}_4\text{)}_2 \)-induced deterioration of the CPVC column was negligible, PVC filters suffered deterioration. Glass-fiber filters and ceramic (alumina) filters were also found to be highly unsatisfactory, as both media seemed to introduce contaminants into the solution, even though the ceramic did not visibly deteriorate.

After each filtration, the attenuation length of the filtered solution was measured. The curve for a measurement was fit to an exponential and the best fit value for \( \lambda \) was taken as the attenuation length for that measurement. For some solutions this attenuation length measurement was repeated two or three times and the reported attenuation length and uncertainty is the average and spread of these measurements. For other solutions the uncertainty was estimated based on the characteristic uncertainties of the repeated measurements.

For each solution the refractive index was measured using a standard refractometer. Each measurement was repeated a number of times and the spread in the measurements was very small (\( \pm 0.0001 \)). However a measurement of water and Isopropanol found a difference of \( \approx 0.003 \) with respect to the known values. We represent the uncertainty with this latter larger value. The density was measured using a 10-ml glass gravity pycnometer to an accuracy of \( \pm 0.3\% \). The index of refraction and the density both scale linearly with the molarity of the solution.
The most successful sequence of filtrations started with a 70% lead perchlorate solution, which was filtered through a progressively finer series of filters, with a single pass through each filter. The pore sizes and material were: 5.0 micron PTFE, 2.0 micron PTFE, 1.0 micron PTFE, 0.2 micron PVDF. This filtration sequence resulted in an attenuation length of 422.5 ± 14.5 cm. The attenuation curve from one measurement of this filtered solution is shown in Fig. 3.

The improvement in the attenuation length with each stage of the filtration sequence is shown in Table 2. Also shown are the measured values of the liquid density and refractive index after each filtering step. The transmission spectrum for a 60% Pb(ClO$_4$)$_2$ solution which has undergone an identical filtering sequence is shown in Fig. 4.

| Filter type | Attenuation (cm) | Density (g cm$^{-3}$) | Refractive Index |
|-------------|------------------|-----------------------|------------------|
| unfiltered  | 9.5 ± 1.5        | 2.164(6)              | 1.455(3)         |
| 5.0 μm PTFE | 14.5 ± 2.5       | 2.119(6)              | 1.450(3)         |
| 2.0 μm PTFE | 49.0 ± 5.9       | 2.122(6)              | 1.450(3)         |
| 1.0 μm PTFE | 322.7 ± 14.9     | 2.114(6)              | 1.449(3)         |
| 0.2 μm PVDF | 422.5 ± 14.5     | 2.098(6)              | 1.448(3)         |

Table 2
The filtration results for 70% solution of lead perchlorate. The attenuation length was measured using 430 nm light.
4 Conclusions

The neutrino continues to offer unique insights into both the standard model of particle physics and the nature of extreme physical phenomena such as supernovae. A Cerenkov detector using a solution of lead perchlorate has the ability to both measure neutrino energy as well as discriminate between neutrino flavors, features which make it an ideal detector to study neutrinos in the regime of 10-30 MeV. Simple filtration techniques have yielded light attenuations lengths suitable for accelerator neutrino studies and astrophysical neutrino detectors.

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