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Cryogenic design and operation of liquid helium in an electron bubble chamber towards low energy solar neutrino detectors

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Abstract

We are developing a new cryogenic neutrino detector: electron bubble chamber, using liquid helium as the detecting medium, for the detection of low energy p–p reaction neutrinos (<420 keV), from the Sun. The program focuses in particular on the interactions of neutrinos scattering off atomic electrons in the detecting medium of liquid helium, resulting in recoil electrons which can be measured. We designed and constructed a small test chamber with 1.5 L active volume to start the detector R&D, and performed experimental proofs of the operation principle. The test chamber is a stainless steel cylinder equipped with five optical windows and ten high voltage cables. To shield the liquid helium chamber against the external heat loads, the chamber is made of double-walled jacket cooled by a pumped helium bath and is built into a LN_2/LHe cryostat, equipped with 80 K and 4 K radiation shields. A needle valve for vapor helium cooling was used to provide a 1.7–4.5 K low temperature environments. The cryogenic test chamber has been successfully operated to test the performance of Gas Electron Multipliers (GEMs) in He and He + H_2 at temperatures in the range of 3–293 K. This paper will give an introduction on the cryogenic solar neutrino detector using electron bubbles in liquid helium, then present the cryogenic design and operation of liquid helium in the small test chamber. The general principles of a full-scale electron bubble detector for the detection of low energy solar neutrinos are also proposed.
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1. Introduction

We are currently engaged in a program on development of a novel cryogenic particle detector for future colliding-beam or fixed target facilities, to prepare for the next round of experimental needs in areas of high energy and particle physics [1]. The objective of this project is to study, design and develop a new electron bubble particle detector, using liquid helium as the detecting medium, for the detection of low energy particle tracks, such as neutrinos from the Sun and from accelerator beams and nuclear reactors, and interesting possibilities in deep underground particle astrophysics research. The program focuses in particular on the interactions of neutrinos scattering off atomic electrons in the detecting cryogenic liquid, resulting in recoil electrons, which can be measured experimentally. The program will allow the determination of the feasibility of constructing a modest-size tracking chamber that in turn would lead to a study for a large solar neutrino detector, which will provide a simultaneous and critical test of stellar evolution theory and of questions in neutrino oscillations. We anticipate that this technology may open up new possibilities for next-generation neutrino detectors, and may also have

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applications in detecting 'dark matter' particles. The challenge is to obtain the fundamental spatial and energy resolution, to supply a feasible detector structure and readout.

The electron bubble detector is a Time Projection Chamber-like (TPC) tracking detector and is currently envisioned as a two-phase detector. The expected signals from low energy solar neutrino interactions come the measurement of ionization of elastically scattered target electrons. The ionization signals are expected to be small and hence the signal needs to be amplified in the saturated vapor above the liquid phase. Gas Electron Multipliers (GEMs) can operate in noble gases at high gain [2,3] and therefore are naturally of interest. The use of a TPC based on GEMs as a central tracker is being studied by several groups [4,5]. Higher granularity and intrinsically suppressed ion feedback give a good spatial resolution and are the major advantages of this technology.

We have designed and built a relatively small size liquid helium e-Bubble test chamber, to make the fundamental measurements of physical properties of electron bubble transports in the liquid helium and at the interface of liquid/vapor under external electrical field. These measurements will allow us find a number of key physics and technical parameters that allow good spatial and energy resolution on low energy particle tracks. The test chamber is a double-walled cylindrical container equipped with five optical windows and 10 high voltage cables. A LN_2/LHe cryostat equipped with 80 K and 4 K radiation shields and a needle valve for vapor helium cooling was used to provide a 1.7–4.5 K low temperature environment. The cryogenic test chamber has been successfully operated to test the performance of GEMs in He and $He + H_2$ at temperatures in the range of 3–293 K [6,7].

One of the key issues to the cryogenic design and experimental sensitivity for electron bubble tracking is of keeping a thermally uniform liquid helium bath of the test chamber. Both the thermal radiation and conductive heat loads to the chamber will generate a temperature difference between the bulk liquid helium and its boundary, which will create inevitably a buoyancy-induced convection of liquid helium. Numerical simulations [8] have been conducted and showed that the potential velocity of natural convection is about 2 cm/s, comparable to the drift velocity of e-Bubbles in LHe, in a range of 1 cm/s–1 m/s, depending on the external electrical field. The natural convection within the LHe bath will inevitably carry the electron bubbles and accelerate or decelerate their transportation. Furthermore, the eventual formation of gas bubbles will collect the electrons and damp movement. The natural convection therefore must be reduced to the minimum, so that the slow motion of the electron bubbles will not be confused by this effect. In order to counteract the temperature gradient, vapor helium cooling was provided within the double-walled jacket and in the cooling circuit loops at top and bottom flanges of the chamber.

In this paper we will present, in Section 2, an introduction on the cryogenic solar neutrino detector using electron bubbles in liquid helium, and then present the detailed design of cryogenic facility as well as different cryogenic operations of the test chamber, in Sections 3–5. The general principles of a full-scale electron bubble detector for the detection of low energy solar neutrinos are also proposed in Section 6, followed by the concluding remarks.

2. Liquid helium solar neutrino detector

Neutrinos are the current physics interest and one of highest priorities in high energy and particle physics [9] that we have focused on in our initial studies, in particular of neutrinos from the Sun. Current experiments, relying on radiochemical techniques in gallium or chlorine, or on the production of Cerenkov radiation in water-based detectors, are mostly sensitive to the upper range of the solar neutrino energy spectrum, of order 1–10 MeV. However, this window encompasses only a small fraction of the total neutrino flux, about 98% of which is expected to have energies less than 1 MeV. Moreover, of the present experiments, only Cerenkov detectors provide information about the energies of the incoming neutrinos. The next major goal of solar neutrino astronomy is to measure neutrino fluxes in low energy region less than 1 MeV, and in particular to measure the flux from the dominant p–p reaction, which peaks in the range of 200–300 keV.

Charged signal of the low energy solar neutrinos interact mainly by scattering by atomic electrons, which carry about half the energy of the neutrino and follow its direction, allowing reconstruction of its direction. The task of such a neutrino detector is to detect the electrons scattered by neutrinos and measure their energy and direction and to distinguish them from any sort of background. The expected signals are expected to be small and hence the signal needs to be amplified in the saturated vapor above the liquid phase by GEMs, which can operate in noble gases at high gain [2,3] and therefore are naturally of interest. Multiple scattering of electrons of this energy constitutes another challenge. After a small fraction of a radiation length, the track deviates from the initial direction by radiation and is usually so curled up as to conceal its true range. Only materials of the longest radiation length combined with high spatial resolution can hope to cope with these effects. Liquid hydrogen and helium are by far the best in this respect, each having a radiation length of about 7 m.

Requirements of the detector for studying the details of neutrino oscillations in the presence of three or more neutrino species and CP violation have a large overlap with the requirements for deep underground particle astrophysics research. The common features needed are good spatial resolution and good performance at very low energies, in a very large volume with the lowest possible background rates. These considerations lead us to consider the

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