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# A liquid argon scintillating bubble chamber for CE$\nu$NS reactor neutrino detection and dark matter search

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**Summary.** — The Scintillating Bubble Chamber is a novel detector based on 10 kg of LAr that is currently under construction at Fermilab (Chicago, USA). This detector is projected to reach a threshold of 100 eV and will take advantage of the excellent electromagnetic background discrimination characteristic of bubble chambers to measure neutrinos from nuclear reactors via coherent elastic neutrino-nucleus scattering (CE$\nu$NS). The physics reach of the bubble chamber is studied for the cases of non-standard interactions through a new gauge boson $Z'$, the weak mixing angle and the neutrino magnetic moment. A second bubble chamber will be placed in SNOLAB to search for dark matter in the form of weakly interacting massive particles (WIMPs), for that reason an extensive background program is being developed to keep all backgrounds to less than 1 event per year.

## 1. – Introduction

A Scintillating Bubble Chamber is currently under construction at Fermilab (Chicago, USA) [1]. This detector is composed of 10 kg of liquid argon (LAr), contained between two quartz jars with the goal to archive 100 eV of energy threshold. The LAr is doped with $\sim$ 100 ppm of Xe in order to change the scintillation wavelength from 128 nm to 175 nm (VUV). Both quartz jars are located inside a stainless steel pressure vessel and are surrounded by $CF_4$ which serves as a thermal bath and as hydraulic fluid (fig. 1). It also has an array of piezoelectric sensors, SiPMs (Hamamatsu VUV4 Quads), and three cameras that record the acoustic and scintillating signals, and bubble images, respectively. The detector [2-4] requires very low backgrounds for neutrino detection and in the search for dark matter (DM).

Neutrons represent the main source of background, they generate single and multiple interactions (bubbles), where the singles are indistinguishable from those expected to be induced by WIMPs (Weakly Interacting Massive Particles) or neutrinos through coherent elastic neutrino-nucleus scattering (CE$\nu$NS). Reducing background neutron sources constitutes the main challenge in this detector.

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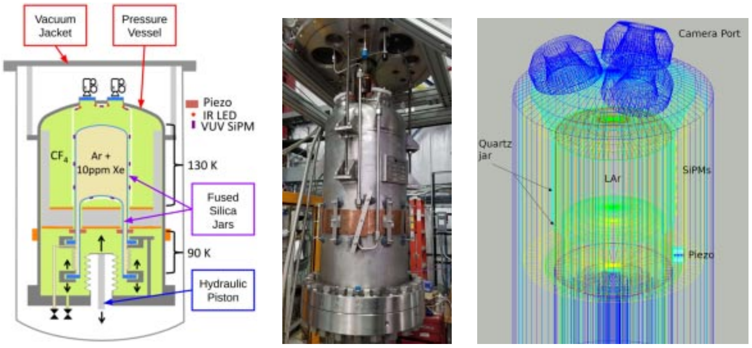


(a) (b) (c)

Fig. 1. – (a) Schematic representation of the scintillating bubble chamber [1]. (b) Bubble chamber assembly process .The detector will have an approximate height of 2.7 m. (c) Optical and scintillation systems models from GEANT4.

The SBC collaboration is building two similar chambers: a scintillating bubble chamber dedicated to studying the nuclear and electron recoil (NR, ER) response; this detector will be repurposed and calibrated for studies of CE$\nu$NS in Ar and a second chamber for a low-mass WIMP search to be located at SNOLAB is under construction in Canada.

## 2. – GEANT4 model

Monte Carlo simulations are a valuable tool in the choice and location of the different components of the detector and in the process of design and subsequent construction of the scintillating bubble chamber. The detector model is constantly being developed and updated, as part of the detector construction process. Figure 1(c) shows the GEANT4 [5-7] model developed in this work, that provides important information about the internal backgrounds generated by its different components.

## 3. – Backgrounds produced by neutrons in the search for DM

The scintillating bubble chamber located at SNOLAB has the main goal of searching for dark matter in the form of WIMPs with masses between 0.7 and 7 GeV. The internal backgrounds of the detector have a target of less than 1 event/year and the components are currently being assayed for the construction of the detector. This process is under development and the simulations in GEANT4 are a valuable tool to achieve it.

A screening programme to assay materials is underway to select components with high radio-purity to produce acceptable backgrounds. Fabrication and construction of the majority of the components is either complete or nearing completion. The collaboration expects to cool down the detector for the first time by the end of summer 2021 as part of the quality assurance and expect to start operating the detector at Fermilab on the time scale of approximately a year.

## 4. – Physics reach for studying reactor neutrinos via CE$\nu$NS

Another bubble chamber will be placed near a reactor to study neutrinos interacting via CE$\nu$NS. Detection of reactor neutrinos by means of CE$\nu$NS presents a challenge due to the very low NR energy (sub keV range) [8]. This signal is typically eclipsed by environmental backgrounds generated by neutrons, $\gamma$-rays and muons. The COHERENT collaboration [9] achieved the experimental sensitivity to measure this process with a CsI

TABLE I. – *Relevant parameters assumed for the setups considered.*

| Setup | LAr mass (kg) | Power ($MW_{th}$) | Distance (m) | $\bar{\nu}_e$ flux uncertainty (%) | Threshold uncertainty (%) |
|---|---|---|---|---|---|
| A | 10 | 1 | 3 | 2.4 | 5 |
| B | 100 | 2000 | 30 | 2.4 | 5 |
| B(1.5) | 100 | 2000 | 30 | 1.5 | 2 |

crystal [10] and using a liquid argon detector [11] in the Spallation Neutron Source at Oak Ridge National Laboratory (Tennessee, USA). Reactor neutrinos provide an exclusive opportunity to study CE$\nu$NS and their observation is still an experimental competition within several detector technologies.

The analysis presented in [8] considers two experimental configurations (table I): a scintillating bubble chamber based on 10 kg of LAr with energy threshold of 100 eV that is located 3 m from a 1 $MW_{th}$ reactor (Configuration A), where $\sim$ 8 events/day are estimated due to neutrinos above threshold; and another similar detector based on 100 kg of LAr operated at the same threshold and located 30 m from a 2000 $MW_{th}$ reactor (Configuration B), where $\sim$ 1570 events/day due to neutrinos above threshold are expected (fig. 2). Two sites are explored, a 1 $MW_{th}$ research reactor near Mexico city and a 2000 $MW_{th}$ power reactor in the east coast of Mexico.

Simulations were performed in GEANT4 in order to characterize the backgrounds in the detector for both configurations. The neutron sources that were considered were the following: neutrons generated in the reactor, ($\gamma$,n) reactions, ($\mu$,n) reactions, and cosmogenic neutrons. The results are summarized in table II.

The physics reach of the setups described above is analysed for a one-year exposure. The SM cross section for CE$\nu$NS, after neglecting the axial contribution, is:

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right) F^2(q^2) \tag{1}$$

where $Q_w = Zg_p^V + Ng_n^V$ and $m_N$, $Z$, $N$ are the nuclear mass, proton, and neutron number of the detector material.

First, the value of the weak mixing angle at low energies is extracted with its corresponding uncertainty (fig. 3(a)). Assuming that the experiment measures only the SM signal, a fit is performed using a $\chi^2$ function.

TABLE II. – *Reactor and cosmogenic backgrounds for the configurations A, B and B(1.5). In the case of the ($\gamma$,n) reactions, the isotopes $^2H$, $^{207}Pb$ y $^{208}Pb$ where considered in water and lead, respectively. The muon-induced neutrons were calculated assuming that the interactions take place in the shielding of water and concrete. For configurations B and B (1.5), the backgrounds generated by the reactor are not included because the detector is at a sufficient distance (30 m) to be considered negligible.*

| Configuration | Reactor backgrounds (events/day) | | | Cosmic backgrounds (events/day) | |
|---|---|---|---|---|---|
| | Neutrons | ($\gamma$,n) | Thomson Scattering | Neutrons | ($\mu$,n) |
| A | 0.003 | 0.22 | 0.0002 | 0.38 | 0.47 |
| B & B(1.5) | – | – | – | 125 | 55 |

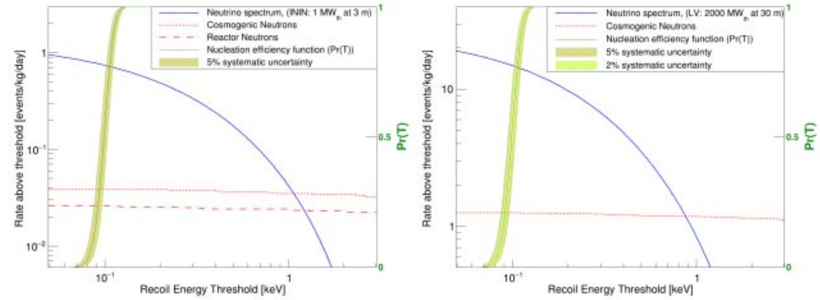
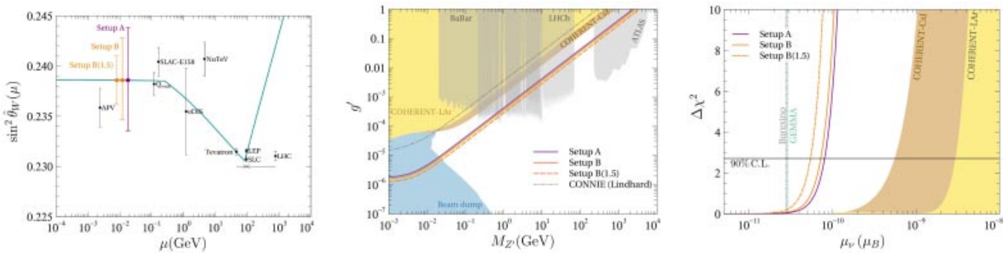


Fig. 2. – Signal and neutron background rates above threshold for setups A (left) and B (right). Backgrounds in setup A come from reactor and cosmogenic neutrons while only cosmogenic neutrons are shown in setup B since at 30 m (usually outside of the reactor building) the backgrounds produced from the core are negligible. A cumulative distribution function (CDF) was assumed for the threshold efficiency.



(a) (b) (c)

Fig. 3. – (a) RGE running of the weak mixing angle in the $\overline{\text{MS}}$ renormalization scheme, as a function of the energy scale $\mu$. (b) Exclusion limits at 95% C.L. in the $g'$-$M_{Z'}$ plane. (c) Limits for the neutrino magnetic moment [8].

Next, a gauged $B-L$ symmetry is studied, namely that the extra gauge boson couples to quarks and leptons. This will induce the following BSM interaction between neutrinos and quarks. Extra $U(1)'$ gauge symmetries are very popular within the extensions of the Standard Model, motivated by GUT's in the case of heavy $Z'$ or sometimes for the searches of dark photons, namely, very light $Z'$. Many phenomenological analysis on both limits have been done combining direct searches in colliders and beam dump experiments.

$$Q_w = Z(g_p^V + 2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV}) + N(g_n^V + \epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{dV}) \rightarrow \epsilon_{\alpha\alpha}^{qV} = \frac{g' x_\alpha x_q}{\sqrt{2} G_F (q^2 + M_{Z'}^2)} \tag{2}$$

In fig. 3(b), the expected sensitivities from the scintillating bubble chamber are shown in the configurations A, B and B(1.5) in the $g' - M_{Z'}$ plane.

Finally, neutrino magnetic moments can arise from their interaction with the electromagnetic field, either for Majorana or Dirac neutrinos. This new interaction contributes to the CE$\nu$NS cross section without interference, with the following expression:

$$\frac{d\sigma}{dT} = \pi \frac{\alpha_{\text{EM}}^2 Z^2 \mu_\nu^2}{m_e^2} \left( \frac{1}{T} - \frac{1}{E_\nu} + \frac{T}{4E_\nu^2} \right) F^2(q^2), \tag{3}$$

where $\alpha_{\text{EM}}$ is the electromagnetic coupling and $m_e$ is the electron mass. The neutrino magnetic moment is normalized by the Bohr magneton $\mu_B$. The resulting limits from the $\chi^2$ analysis for the three setups are presented in fig. 3(c), along the current limits set by the COHERENT collaboration, Borexino [12] and GEMMA [13].

## 5. – Conclusions

The study of backgrounds using simulations in GEANT4 is essential for the design and construction of the LAr scintillating bubble chamber. This novel bubble chamber technique has excellent discrimination for backgrounds generated by electromagnetic radiation. The SBC collaboration is building two similar detectors: a scintillating bubble chamber to study the NR and ER response (the goal is to reach a minimum threshold of 100 eV) and a second chamber for low-mass WIMP search at SNOLAB. The sensitivity of this detector for different physics cases such as electroweak precision test, new scalar mediators and the neutrino magnetic moment, when deployed near a nuclear reactor, can be very competitive by controlling the systematic uncertainties in the anti-neutrino flux from the reactor. The energy threshold will be calibrated using photo-nuclear, $\gamma$-rays and thermal-neutron sources to demonstrate that the detector reaches and maintains the target value of 100 eV.

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