

Feasibility of a Nuclear Recoil Observatory with Directional Sensitivity to WIMPs and Solar Neutrinos

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Abstract

Now that conventional WIMP dark matter searches are approaching the neutrino floor, there has been a resurgence of interest in the possibility of introducing recoil direction sensitivity into the field. Such directional sensitivity would offer the powerful prospect of reaching below this floor, introducing both the possibility of identifying a clear signature for dark matter particles in the galaxy below this level but also of exploiting observation of coherent neutrino scattering from the Sun and other sources with directional sensitivity. We survey the experimental status of all technologies proposed to date, and perform a cost-benefit analysis to identify the optimal choice in different WIMP and neutrino scenarios. Based on our findings, we propose a large-scale directional nuclear recoil observatory with directional WIMP sensitivity below the neutrino floor and capability to explore Solar neutrino coherent scattering with direction sensitivity

Keywords: keyword1, keyword2

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1. Introduction

[Section organizer: all]

The aim of this paper is to lay out the science case and goals for a large galactic recoil observatory, to show that the goals are achievable in principle, to compare the capability of different technologies to reach those goals. Here is a citation [?].

2. Science Case for a large Nuclear Recoil Observatory

[Section organizer: Katie Mack]

This section covers the science case and potential reach of a recoil observatory including comparison with non-directional detectors. This section may also introduce a new type of plot for comparing directional sensitivity of detectors. We should also make sure to include non-directional capabilities of a large directional detector, such as observing an annual modulation with a low, non-directional energy threshold.

2.1. WIMPs

2.2. Solar Neutrinos

2.3. Other Physics

3. Existing Directional Detection Technologies

[Section organizer: James Battat]

Contributors to this section:

- James Battat jbattat@wellesley.edu
- Elisabetta Baracchini baracch@gmail.com (esp. with “emerging tech.” such as columnar recombination, nanotubes, anisotropic scintillators, DNA, etc.)

3.1. Detectors that reconstruct the recoil track

3.1.1. Gas-based TPCs

- Negative ion drift vs. Electron drift
- amplification device may be integral to readout (micromegas, MWPC) or separate (GEM)
- MWPC
- MPGD (micromegas, mupic, pixel chip)
- Optical

3.1.2. Nuclear Emulsions

3.1.3. DNA detector (still going?)

3.1.4. 2D graphene? [arXiv:1606.08849](https://arxiv.org/abs/1606.08849)

3.2. Detectors that indirectly determine the recoil direction

3.2.1. Anisotropic scintillators

3.2.2. Carbon nanotubes

3.2.3. Columnar recombination

3.3. Summary table

- Energy resolution demonstrated.
- Axial reconstruction demonstrated? Down to what energy? With what angular resolution?

- Sense-recognition demonstrated? Down to what energy?
- Full-volume fiducialization demonstrated?
- Flexibility for different targets (mostly for gas-based TPCs – e.g. different gases, negative ion vs. electron drift)
- Technological readiness (including largest volume in operation, prospects for scaling up, some mention of cost per something (e.g. volume, or area, or))
- Background discrimination? This would potentially be a rather hard item to cover...

3.4. *The text below was the initial content by Sven*

This briefly reviews the current technologies on the table. Refers to our previous review papers for details. Should also include emerging technologies or more speculative approaches not covered in those papers, such as columnar recombination, carbon nanotubes, DNA, etc. . Useful additional information to tabulate, which may affect design of a future recoil observatory, may include:

- background level studies of material / components - perhaps already covered by Neil?
- background discrimination power of different TPC readouts and other technologies (e.g. gamma/recoil separation studies by Loomba et. al.)
- head tail capability
- fiducialization capability
- technological readiness of each approach

4. Quantitative Comparison of Directional WIMP and Solar Neutrino Sensitivity

[Section organizer: Sven Vahsen]

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This section compares the sensitivity of different simplified technologies to key science goals. This is done by developing a figure of merit that also considers cost, but assumes zero background is achievable. “Simplified technologies” means the comparison will be of idealized technologies; for instance wires versus strips versus 2D pixels (optical) versus 3D pixels, not a comparison of existing experiments. There will probably be a slight focus on TPC readouts in this section, as TPCs currently are the most studied in terms of performance, and furthest along in terms of technological readiness. This choice of focus means that the comparison becomes more realistic. That being said, comparing TPCs with the other approaches is also important, and should be included. We are still thinking about the how to do it in detail.

72 4.1. Simulation of nuclear recoils

73 This section describes the part of the simulation that takes a recoil momentum vector as input, and creates an
74 ionization distribution in the detector. By default we use SRIM to create the ionization distribution, and create a
75 uniform spatial distribution. Sven has code that builds PDFs based on SRIM, but his code ignores straggling. Cosmin
76 has similar code that also includes straggling, and is willing to contribute. Kentaro also has code.

77 The detector target (low-pressure gas mixture, noble liquid, or emulsions) is part of the the SRIM simulation, so
78 it should also be discussed here. I imagine that for each target chosen, we show plots of:

- 79 • SRIM range vs energy
- 80 • SRIM quenching factor vs energy
- 81 • SRIM stragling vs energy

82 A starting point for gas mixtures to simulate could be: CF₄, SF₆, CF₄+SF₂, SF₆+He

83 4.2. Simulation of detectors and readouts

84 This section describes simulation of the charge propagation and readout. Charge propagation can be described
85 by Gaussian smearing for diffusion and ion attachment (?). Readout simulations will be simplified. Both Sven and
86 Kentaro have existing code for this. We will consult the relevant experts for each readout type, as listed in parentheses
87 below, and fill in the specs.

- 88 • TPC w/ MWPCs wires [D. Snowden-Ifft],
- 89 • TPC w/ strip readout [James]
- 90 • TPC w/ optical readout [James/Cosmin]
- 91 • TPC w/ mu-pic readout [Kentaro],
- 92 • TPC w/ GEMs and pixels [Sven, Elizabetta]. Proposed specs to use: 50 x 50 micron pixels. 50 micron equiva-
93 lent time-binning for TOA. 100 electron noise. 2000 electron threshold. Dynamic range: ?
- 94 • emulsions
- 95 • TPC w/ noble liquid target

96 4.3. Algorithms to extract directional signals

97 Because the above detectors measure very different quantities, different algorithms are needed to reconstruct a
98 directional signal. (For instance, wires don't reconstruct tracks.) How can we ensure that the comparison is done
99 fairly, i.e. that we are optimally exploiting the directionality of each detector? Let proponents of detector propose
100 method? It would be nice to keep this part as simple as possible. We can probably adopt what has been done in the
101 papers of Green, O'hare, Billard et al. This could be a good place to get Billard and O'hare to help.

102 4.4. Directional power of detectors versus recoil energy

103 The final detector comparison is sensitive to astrophysics, gas optimization, detector performance, and cost. To
104 decouple these effects, we here start out by quantifying directional performance versus recoil energy. This is done by
105 estimating how many recoils each detector needs to observe, to discriminate a delta function (all recoils go in the same
106 3D direction) at 5-sigma from a flat recoil distribution, versus recoil energy. This goal here is to provide an intuitive
107 results that clearly shows the recoil energy range where each technology is effective, and how directional it is.

4.5. Directional WIMP and Solar Neutrino Sensitivity

Compared to the previous section, in this section, and the next, we now also fold in the recoil distributions for a realistic physics scenarios, target interaction probability, and cost. We explain how we compare the sensitivity of directional technologies, including how we optimize for nuisance parameters such as gas pressure. The procedure for one physics goal is explained in detail, culminating in a final publicity plot where directional detector technologies are compared against each other and against non-directional ones. Such a publicity plot is one key goal for the paper. A candidate example plot could be “# sigma that a galactic-coordinate dipole pointing back to CYGNUS, and a flat recoil distribution can be separated, per million dollars, for a 100 GeV WIMP” [with a specified cross-section]. Non-directional detectors probably score zero on this performance metric. If cost proves too hard to pin down, then we can instead show #sigma per cubic meter for each technology, chose a TPC with wires as the default, and tabulate the required cost for other technologies to become competitive.

Ciaran has agreed to provide the recoil distributions, probably as 3-vectors + time. These will then be interfaced with Sven’s/Cosmin’s/Kentaro’s code.

(We also have to discuss here or elsewhere any form factor or angular distribution assumptions we make for WIMP and neutrino scattering.)

4.6. Figure of Merit for Specific Science Goals

The same procedure as in the previous section is now repeated for a number of physics goals. Again, we’ll ask Ciaran to generate the 3-vectors for nuclear recoils from WIMPs and neutrons. This time, only the final result (the publicity plot) is given for each physics goal.

Candidate list of physics scenarios (will be revised based on physics case chapter):

- discover DAMA/LIBRA WIMP
- discover 100 GeV WIMP above neutrino floor
- discover 1TeV WIMP above neutrino floor
- discover WIMPS below neutrino floor (1, 10, 100, 1000 GeV)
- discover WIMP streams

4.7. Conclusion on Technology Choices

Follow this with discussion of optimal technology choices: Is there a general winner that emerges? Or one winner for high, and one for low energy recoil scenarios? Is the conclusion biased by the zero background assumption? How would it change if discrimination power is included? (Can we think of an easy way to do that?)

5. Zero Background Feasibility

[Section organizer: Neil Spooner]

Generally direct search dark matter experiments strive to control backgrounds sufficiently so as to achieve an expected rate of less than 1 background event recorded in the anticipated exposure time and target mass, essentially that we have zero background within the fiducial volume. An assumption that this is achievable for all the directional technologies compared here was an important caveat made in the previous section of this work. This next section now addresses the realities of this assumption. Specifically we seek to answer the question firstly whether or not directional low pressure gas TPCs can in principle achieve such low backgrounds at the experiment scale required to reach the proposed scientific goals, but further, whether particular TPC readout technologies, with their individual associated intrinsic backgrounds and discrimination capabilities, are more or less able to reach these goals. The latter aspect depends in part on assumptions about the radio-purity of internal detector materials likely involved, most notable for instance because this affects the total internal neutron background. So an alternative tack, adopted here also, is to estimate and compare the specification on material radio-purity required for success, for instance the ^{238}U content in each case, then to comment on the achievability of these requirements.

As shown in [ref x] the additional particle identification properties of directional detectors mean that in principle they may in actuality be able to tolerate a non-zero level of isotropic nuclear recoil background, yet still be able to identify the signal of interest here for dark matter, a non-isotropic distribution of recoil directions. However, the level of tolerance will depend strongly on the capabilities of the technology and anyway will clearly reduce sensitivity overall. A maximum signal to background ratio of order $\times 10$ might be a reasonable upper limit in certain circumstances [ref]. Nevertheless, a good starting point for comparison purposes, adopted for this work, is to assume an aim of zero background.

The following sections present results and conclusions on these issues based on new GEANT4 detector Monte Carlos and other simulations of the various key background contributions. Although not necessarily mandatory, experience from many dark matter experiments demonstrates that full fiducialisation of the active detector volume is likely necessary to achieve the background goals. This aspect is addressed in Sec 5.1. The fundamental issue of neutron backgrounds, that result in nuclear recoil events likely indistinguishable from WIMP induced events, is addressed in Sec 5.2, considering separately contributions from cosmic ray muon neutrons, and rock and detector neutrons. The subsequent parts, Sec 5.3, 5.4 and 5.5, cover respectively simulations of gamma, radon related backgrounds and other possible surface backgrounds. For the majority of the technologies some generic conclusions can be drawn based on the commonality of the basic infrastructure needed for any TPC dark matter experiment, such as a deep site, passive shielding and containment vessel. The majority of any variance from this comes from details of the internal TPC structures, notably the readout planes. These aspects are together summarized in Sec 5.6.

5.1. Fiducialization

5.2. Neutron Backgrounds

Neutrons are a major concern for all direct search experiments because they can produce nuclear recoils just like WIMPs. However, there are various issues that make the requirements for mitigating against neutron backgrounds in a low pressure gas TPC significantly different from those cases involving conventional solid or liquid based detector technologies. Firstly, the potentially low sensitivity to light charged particles, muons, muon-induced secondary particles and electrons, means that these may not be recorded. Secondly, the low density of the target means neutrons are less likely to undergo double or multiple scatters. Both these factors potentially reduce options for vetoing neutron induced nuclear recoils, depending on the readout technology chosen. The former does depend critically on the degree of position segmentation of the readout and the energy threshold achievable in those individual readout channels, essentially the sensitivity to dE/dx . The issue of vetoing by recording multiple neutron scatters then depends on the contiguous size of the detector array. For instance, at 200 torr SF6 the mean free path of a typical background neutron is 60m. This would be the sort of scale required to have any benefit from detection of multiple neutron scatters.

Factors such as these, the uniqueness of the low pressure TPC technique and potentially powerful particle identification, mean that estimating neutron backgrounds by extrapolation from existing background simulations such as have been performed for massive xenon or bolometric detectors[], is not appropriate. The work presented here is thus based on a set of dedicated TPC Monte Carlos. Some relevant initial work on neutron backgrounds was previously undertaken by some of the authors here but focused on smaller TPC target masses of order 1-10kg []. The new work presented here makes use of the latest updated GEANT4 and SOURCES packages and specifically targets the more complex situation of neutron background mitigation in the much larger experiments required to reach the goals of CYGNUS. As noted the procedure adopted is to start by examining aspects that are independent of the internal readout technology. This includes firstly the laboratory location, determined by the depth, rock composition and cavern geometry. Secondly, the outer passive shielding and any active veto system, and finally the containment vessel, modeling both its geometry and composition. The remit here is to investigate muon-induced neutrons resulting from cosmic-rays penetrating from the Earth's surface and also neutrons produced by spontaneous fission and alpha-n reactions in the rock and shielding/vessel materials. The procedure thus requires simulation of the geometry, particle production, tracking and detection, the goal being to find the rate of neutron-induced nuclear recoils anticipated in different situations. From this can be determined requirements for such issues as the amount of passive shielding, the efficiency and form of any external veto and the form and purity of the vessel materials, such as required to achieve the goal of zero background. The issue of neutrons from internal detector components, that depends on details of the readout technology, is addressed last.

5.2.1. Laboratory and TPC Geometry

In order to explore some range of possible scenarios for potential experiments we adopt here two broad geometries and underground site characteristics used for the GEANT4 simulations. Details of these scenarios are given in Table 1. The first, Option 1, assumes a laboratory akin to that of the Italian Gran Sasso facility in depth and rock composition. The second one is designed to be broadly compatible with the Boulby Underground Laboratory in the UK or the WIPP site in the US, located in salt rock. The two geometries are illustrated in Fig. 1.

In both cases the rock was simulated to a depth of 3 m outwards from the cavern walls, with the appropriate rock composition. It was assumed that the cavern volume around the detector contained 1 atmosphere of an 80:20 nitrogen to oxygen mixture and that there were no other materials or objects present in the caverns. Regarding the detector vessel dimensions, the choice obviously depends on the pressure and gas composition adopted for the experiment of which there are many possibilities. For the purposes of making broad comparisons here, bearing in mind the science goals of CYGNUS, it was decided to assume use of SF₆ gas at 50 Torr with volume sufficient to produce around 0.5 tons of target nuclei, in this case of fluorine. For a facility in salt rock there are usually restrictions on the height and width feasible but not the length. So for this option an elongated vessel of 5 x 5 x 40m was chosen. Other sites in hard rock, such as Gran Sasso, do not necessarily have such a height restriction. In this case a generic size of 10 x 10 x 10m was selected. Based on these dimensions engineering studies were made to determine a minimum total mass of vessel material required in each case. For instance for Option 1 a mass of 200 tons was found necessary. Real vacuum vessels of such size will require strengthening supports both inside and outside. However, for simplicity in simulations the mass of these was taken into account by applying an appropriate average increase in thickness to the vessel walls.

As stated, the background from internal TPC components will be affected by details of the readout design, covered later. Nevertheless, some generic assumptions can be made about other TPC structures required inside the detector which are likely common to any design. Most notable here is the central cathode and field cage. However, we note that the total area required for the former will also depend on the gas mixture adopted, since this influences the diffusion and hence determines the maximum drift distance that can be tolerated. For the comparisons here we assume a compromise drift distance of 50 cm, which yields a total cathode area of 2000 m² in both options. The design of this is assumed here to comprise ultrathin cathode sheets supported on acrylic frames, of design similar to that demonstrated previously [ref]. The field cage itself can also be made of light acrylic components, with copper strips to act as the field rings. In these components the acrylic provides by far the dominant mass, conservatively estimated to be xx tons. These components are again approximated as sheets of appropriate thickness distributed in the TPC volume (see Fig. 1). An additional important potential source of internal background is the resistor chain required to feed voltages to the field cages since these are generally composed of ceramic materials. These are modeled as a mass of xxkg of ceramic composition containing x ppb U and y ppb Th, as typically measured [ref], distributed in rectangular strips along the sides of the field cages.

5.2.2. Rock Neutrons and Passive Shielding

The first simulations were performed to determine what thickness of passive neutron shielding is required around the CYGNUS detector to ensure an induced recoil rate from this source that is below 1 per year for each of the two detector options. It is recognized that an active veto shield is also likely needed to assist with rejection of muon related neutrons (see sec 5.2.3) and that this in practice could be fully, or partially, integrated with the passive shield. To allow for this the passive shield was modeled in two forms, namely a generic hydrocarbon, able to represent either passive material or a plastic or liquid scintillator, and water, also useable in passive form as part of a veto using Cherenkov radiation. In both cases it is assumed here that any containment structure or internal components, such as photomultipliers, are of sufficiently low background and low mass to be ignored. We note also that account needs to be taken of the energy threshold chosen, as determined in part by the science priorities. To allow for this we consider cases for 1 keV and 10 keV threshold. For this work the SOURCES code was used to generate neutrons from the decay chains of U and Th in the rock. The Watt spectrum was used to generate events from spontaneous fission whilst for alpha-n reaction events were obtained by using the relevant isotope lifetimes, energy spectra of alphas, reaction cross sections, alpha stopping powers etc. [continue description as in the Carson paper]

The results from these simulations are outlined in Table 2 and plotted in Fig. x. It can be seen from these that at least 1.5m of passive neutron shielding is required in all scenarios, though for the hard rock case of Option 1 this rises

to around 1.7 m [these are guesses] due to the higher U content of that rock. For option 1 this amounts to a total mass of passive shielding of xx tons.

5.2.3. Vessel and TPC Neutrons

As seen in Sec 5.2.2 the external rock neutron flux can be controlled by passive shielding, as expected. Neutrons from internal detector radioactivity is known to be a harder challenge since control of this likely relies on selecting radio-pure materials, use of tricky internal shielding or innovative analysis techniques. The vacuum vessel, being the component with by far the largest mass, has the potential to dominate this aspect, followed by the outer passive shield, TPC field cage and resistors. Rather than assume values for the U and Th content of the vessel materials the approach taken here is to determine from the simulations what amount of U, Th contamination can be tolerated in each of these major components without compromising the criteria of ≤ 1 event recorded per year, at each energy threshold. Given the potential difficulty of obtaining steel with low U, Th content simulations were also performed assuming an acrylic vessel. [describe any details of the simulations, see Carson etc]

The form of the neutron energy spectrum for each of the components, normalized to x ppb U and y ppb Th, is shown in Fig. x. Table x summarizes the results in terms of specifications on the maximum U, Th levels that can be tolerated in each scenario.

Some initial conclusions can be extracted from these results. Firstly, well selected steel has been measured to have U and Th content as low as typically x and y ppb respectively. This is a factor x10 and x10 higher than would be tolerable according to the results obtained. To our knowledge no serious efforts to develop or pre-select steel for ultra-low background have been made so it is conceivable that steel with this level of contamination can be obtained. The alternative of acrylic looks more favourable since there has been extensive work on developing low U, Th material. For instance, levels as low as x and y PPB U and Th have been reported [ref]. However, there are clearly significant mechanical challenges with this option. An alternative could be to mount non-structural acrylic shielding within a steel vessel, to shield off steel related neutrons. To explore this, further simulations were run using the Option 1 steel vessel design but with internal acrylic added. Results for this are shown in Table x. It can be seen that at of order 20cm (??) of internal acrylic would be needed to gain a factor x10 in neutron rate.

Regarding the internal TPC components, including resistor chain but excluding the readout planes, the specification on U and Th content appear achievable based on known levels as measured [probably not true?], for instance...

5.2.4. Muon-induced neutrons and active vetoing

The main question here I think is to determine what veto efficiency is needed and to make comments on how that would be achieved in practice. This could include an assumption on the sensitivity for vetoing muon neutrons by recording coincident EM in the TPC, which in turn depends on the readout.

The nuclear option is to go deeper underground.

Include some comment on double scatter vetoing both internal to the detector (hard) and external using the muon veto.

5.2.5. Neutron Conclusion

Summary of the design specs needed

5.3. Gamma Backgrounds

5.4. Radon and Radon Progeny Backgrounds

5.5. Surface and other Backgrounds

5.6. Comparison of Technologies for low background

6. Underground Sites and Engineering

[Section organizer: Neil Spooner]

This covers the requirements for and feasibility of achieving the necessary engineering and underground site infrastructure including the scientific argument for multiple sites? E.g., for a 1D detector, is there an advantage to distributing the same total target mass over multiple sites? Or do you get the same benefit from multiple orientations at the same site?

296 **7. Conceptual Design Strategy**

297 [Section organizer: all]

298 This summarizes the above technology discussions and briefly outlines possible scenarios and a straw man design for
299 a Galactic Recoil Observatory

300 **8. Conclusion**

301 [Section organizer: all]

302 This section restates the science case in light of the technology discussion and provides comment on the likely
303 feasibility, cost and design of a future large scale galactic recoil observatory.