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

B. Simpson[1]

**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

**Contents**

# 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 [1].

# 2. Science Case for a large Nuclear Recoil Observatory

[Section organizer: Katie Mack]

## *2.1. WIMP Scattering*

### *2.1.1. WIMP scattering review*

[KM]

- Detection overview

  The primary method of direct detection is nuclear recoil, in which the aim is the detection of the momentum transfer from a dark matter particle to a target nucleus. Experiments have been carried out using a wide range of targets, with recoil detection via charge, light, or heat (phonon) signals. Direct detection experiments have produced limits on the properties of WIMPs in the parameter space of mass and WIMP-nucleon cross section, with the tightest limits challenging favored supersymmetric WIMP models and reaching thermal production cross sections. However, several experiments have also reported detections that may be consistent with dark matter interpretations, while being inconsistent with existing limits. One notable example is the DAMA/LIBRA collaboration, which has reported a signal in annual modulation over 14 years and at a signal significance of $9.3\sigma$. As DAMA/LIBRA is unique in using a NaI crystal target, efforts are being made to reproduce the experiment in the Southern Hemisphere to rule out target-specific effects and to eliminate seasonal variations as an explanation for the effect.

  Meanwhile, directional detection presents a new opportunity for discovery in this space. With directional capability, detectors have a strongly enhanced ability to remove backgrounds, through the reliance on the expectation that the WIMP wind should originate primarily from roughly the direction of the constellation Cygnus, due to the direction of the motion of the Sun through the Galactic WIMP halo. Directional capability will make potential WIMP detection more reliable and robust through (1) confirmation of the connection between the events and the Galactic halo, and (2) elimination of backgrounds associated with solar neutrinos at low interaction cross sections (which come from the direction of the Sun) and with backgrounds from the detector's immediate surroundings (which will not correlate with the direction of Cygnus).

  Ongoing directional detection experiments such as DRIFT-II have provided a proof of concept and upper limits. Our proposed detection method will provide the opportunity to strongly improve these limits and potentially to detect the Galactic dark matter, and to study the structure of the halo. In addition, it will have the prospect to study unique phenomenology through sensitivity to coherent neutrino scattering, which presents a "wall" in detection space for non-directional experiments.

  We present below a brief summary of current limits on WIMP properties from non-directional and directional detectors, as well as prospects for unique discovery with directional detectors.

- Current limits

  Current limits on WIMP scattering from direct detection experiments are generally expressed in the parameter space of the WIMP-nucleon scattering cross section and the WIMP mass, where the detection threshold depends on the mass of the target nuclei and the energy threshold of the detector's sensitivity to nuclear recoils. In recent years, several experiments have produced signals consistent with WIMP recoil events, but the majority of detection efforts have produced lower limits, and there are presently no candidate detections that are consistent with the results of all experiments.

The event rate for nuclear recoils is given by:

$$\frac{\mathrm{d}R}{\mathrm{d}E}(E,t) = \frac{\rho_0}{m_\chi m_A} \int v f(\mathbf{v},t) \frac{\mathrm{d}\sigma}{\mathrm{d}E}(E,v) \mathrm{d}^3 v \tag{1}$$

where $\rho_0$ is the local dark matter mass density, $m_\chi$ is the dark matter particle mass, $m_A$ is the nucleus mass, $v$ is the dark matter velocity in the detector rest frame, $f(\mathbf{v},t)$ is the velocity distribution, and $\frac{\mathrm{d}\sigma}{\mathrm{d}E}(E,v)$ is the differential cross section, which can be written as:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E} = \frac{m_A}{2\mu^2 v^2} \left( \sigma_0^{SI} F_{SI}^2(E) + \sigma_0^{SD} F_{SD}^2(E) \right). \tag{2}$$

Here, the first term includes the spin-independent cross section and form factor and the second includes the spin-dependent cross section and form factor. The factor $\mu_A$ is the WIMP-nucleus reduced mass.

The strongest constraints available apply to the spin-independent cross section. Figure 1, from [2], shows a selection of constraints from direct detection experiments, along with the allowed detection regions due to results from the DAMA/LIBRA experiment and CDMS-Si.

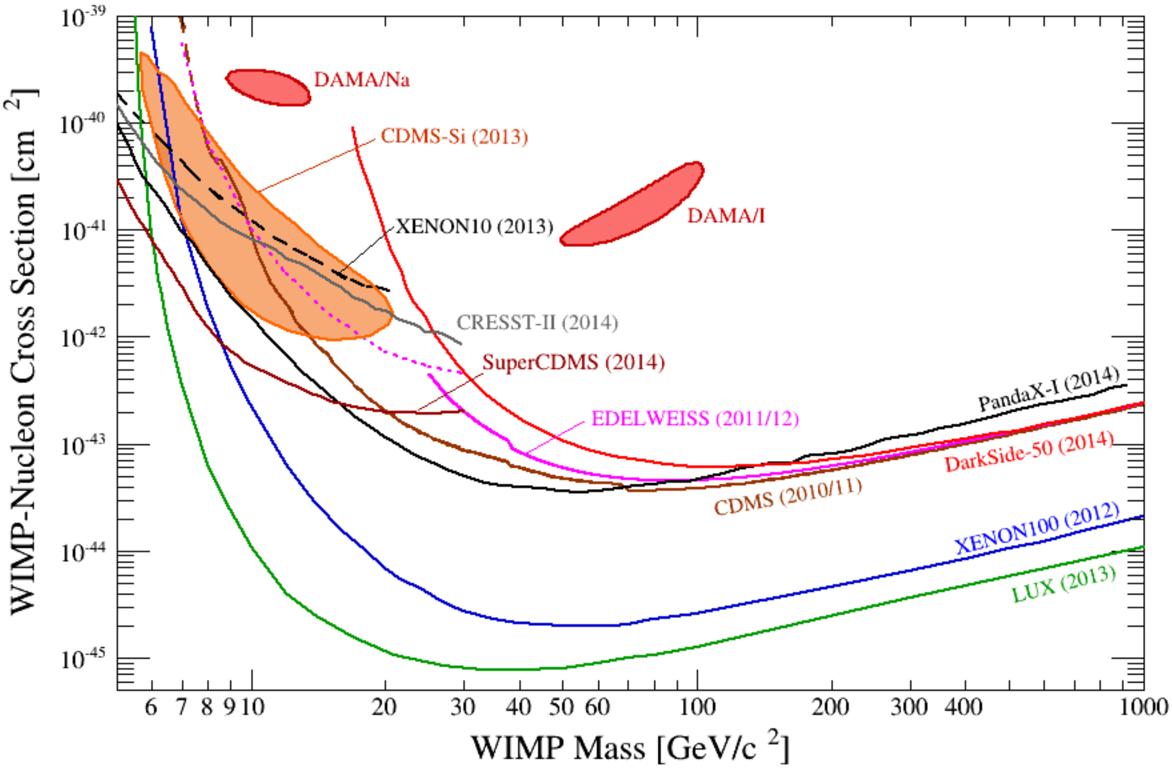


Figure 1: Constraints on the spin-independent cross section, from [2]

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### *2.1.2. Galactic signal detection below the neutrino floor*

[JM, JB]

### *2.1.3. WIMP astrophysics*

[KM, JB?]

- Halo parameters
- Substructure and streams

#### *2.1.4. Particle models and directionality*

[Fredric Mayet?, KM]

- Advantages of directionality for distinguishing models
- Classes of models to explore

### *2.2. Solar Neutrino Coherent Scattering*

[JM, PB]

The coherent scattering of neutrinos off nuclei was predicted over 40 years ago with the realization of the neutral weak currents [3]. This standard model process remains unobserved due to daunting detection requirements: ~keV nuclear recoil thresholds, kilogram to ton-scale target masses, and low backgrounds. Due to the small weak charge of the proton, the coherence results in an enhanced neutrino-nucleon cross-section that is approximately proportional to the square of the number of neutrons in the nucleus. A few years after the coherent neutrino scattering prediction, and, ironically, before the conception of the first dark matter direct detection experiments, the possibility of using this enhanced process to develop a "neutrino observatory" was put forward [4]. A cornucopia of physics searches were envisioned using neutrinos from stopped-pion beams, reactor neutrinos, supernova, solar neutrinos and even neutrinos of a geological origin.

Shortly thereafter, the first generation of dark matter experiments began to search for the scattering of WIMPs of their detectors, where the signature was a low-energy nuclear recoil. These experiments have dramatically improved their sensitivities over the last three decades by simultaneously increasing the target masses, as well as reducing background nuclear recoils. Today the irony lies with the fact that the unshieldable recoils that result from coherent neutrino scattering will soon be a source of background for the next generation of dark matter direct detection experiments [5][6][7][8]. Without the ability to separate the neutrino recoils, the progress in WIMP detection sensitivity will be halted. On the other hand, an experiment that can successfully separate and identify these neutrino events can not only proceed past the so-called "neutrino floor", but can also realize the long-awaited vision of a "neutrino observatory". A detector with directional sensitivity has the potential to do just that.

#### *2.2.1. Solar neutrino scattering review*

In the coherent neutrino scattering process, coherence is only satisfied when the initial and final states of the nucleus are identical, limiting this enhancement to neutral current scattering. The coherence condition, where the neutrino scatters off all nucleons in a nucleus in phase, is also only maintained when the wavelength of the momentum transfer is larger than that size of the target nucleus. Full coherence for all scatters is only guaranteed for low energy neutrinos – less than 10's MeV, depending on the target size. The standard model total cross section for the process can be approximate (neglecting neglecting axial vector terms that arise from unpaired nucleons):

$$\sigma = \frac{G_F^2}{4\pi}\left[Z(4\sin^2\theta_W - 1) + N^2\right]E_\nu^2|F(q)|^2 \tag{3}$$

Where $G_F$ is the Fermi constant, Z is the number of protons, N is the number of neutrons, $\theta_W$ is the Weinberg angle, q is the momentum transfer, $E_\nu$ is the energy of the nucleus and $\theta$ is the scattering in the lab frame. It is evident that the cross section also increases with the square of the energy of the neutrinos; however, while the form-factor condition–which comes in as $|F(q)|^2$–is easily satisfied for Solar neutrinos, the total cross section begins to suffer from decoherence with supernova neutrinos, and neutrinos from stopped pion beams. A detector with an energy threshold of zero can expect to see several hundred to a few thousand recoils from solar neutrinos per ton-year of exposure, depending on the target mass [4].

The differential cross-section with recoil energy can be approximated as:

$$\frac{d\sigma}{dE_{rec}} = \frac{G_F^2}{8\pi}\left[Z(4\sin^2\theta_W - 1) + N^2\right]M\left(2 - \frac{E_{rec}M}{E_\nu^2}\right) \tag{4}$$

Where $E_{rec}$ is the recoil energy of the target nucleus, and M is the mass of the target nucleus.

A more realistic scenario for estimating count rates can be made assuming a $^{19}$F target, for example, and a 5 (10) keV threshold for observing nuclear recoils. This results in an expectation of ~90 (15) background recoils per ton-year, from solar neutrinos alone [6].

#### *2.2.2. Advantages of directional detection*

It is possible to alleviate the constraints that these solar neutrino recoils place on any dark matter search by taking advantage of the expected directional response recoils due to both the putative WIMPs, as well as those from solar neutrinos. The coherent neutrino scattering differential cross section with respect to the recoil angle can be written as:

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi}\left[Z(4\sin^2\theta_W - 1) + N^2\right]E_\nu^2(1+\cos\theta) \tag{5}$$

The resulting recoils are thus biased to the forward direction, away from the location of the Sun. As the solar position changes diurnally with respect to the expected direction of the WIMP wind, an analysis of the recoil direction of events in the detector should reduce the impact of this background. A similar separation could be imagined for terrestrial, atmospheric and diffuse galactic supernova neutrino backgrounds–each with their own characteristic directionality and energy scale.

#### *2.2.3. Science with source and detector*

### *2.3. Other Physics*

[JB, KM, JM, KS]

#### *2.3.1. Non-solar neutrinos*

[KS] Neutrinos with energies less than a few tens of MeV [anything else besides supernova and solar? Low-energy atmospheric... a section on stopped-pion nus?]

- Supernova neutrinos: A core-collapse supernova will emit an enormous fluence of neutrinos over a few tens of seconds time scale. The neutrinos in the burst will have a few to a few tens of MeV of energy, and will include all flavors of neutrinos and antineutrinos with roughly equal luminosity [**?** ].

  Dark-matter detectors with very low recoil energy thresholds are sensitive to a supernova neutrino burst via coherent elastic neutrino-nucleus scattering. The order of magnitude is a few events per ton of detector material for a supernova at ~10 kpc (near the most likely distance to the supernova [**?** ]), and statistics will scale linearly with detector mass and as the inverse square of distance to the supernova. Such a detection would be valuable due to its sensivity to the entire flux, given that most other detectors online are sensitive primarily to the $\bar{\nu}_e$ (in water, scintillator detectors) and $\nu_e$ (in argon, lead detectors) components of the flux [9]. Furthermore, some neutrino spectral information can be reconstructed from the measured nuclear recoil spectrum.

  The advantages of directionality for the detection of supernova burst neutrinos via CEvNS are several: first, obviously, directional information about the source will be of value to observers in electromagnetic wavelengths and in gravitational waves who want to make prompt observations of the supernova event in real time. Currently, only detectors able to make directional measurements of elastic scattering on electrons have good pointing ability (and Super-K is the only current instance). Even if there is no obviously bright supernova event (as may be the case for a failed supernova), directional information will be able to narrow down the possible progenitors. Finally, the direction information can be used on an event-by-event basis to reconstruct an more precise neutrino energy.

#### *2.3.2. Axions*

[KM]

#### *2.3.3. Exotic models*

[JB, PB, KM]

## 3. Existing Directional Detection Technologies

[Section organizer: James Battat]

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]

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 (for instance) of idealized technologies; e.g. wires versus strips versus 2D pixels (optical) versus 3D pixels, not a comparison of spefific 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. Were still thinking about the how to do it in detail.

### *4.1. Quantifying Directional WIMP and Solar Neutrino Sensitivity*

This subsection explains how we compare the sensitivity/suitability of directional technologies to different physics goals, and how we optimize nuisance parameters such as gas pressure. The procedure for one physics goal is explained in this section, culminating in a final publicity plot where directional detector technologies are compared against each other and non-directional ones. Such a publicity plot is one key goal for the paper.

The same procedure is then followed for other physics goals, but for those only the final result (the publicity plot) is given in section 4.2.

### *4.2. Figure of Merit for Specific Science Goals*

Present the sensitivity per cost (publicity) plots for the most interesting physics goals.

### *4.3. 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 238U 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 x10 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 Earths 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 composted 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 know 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 obtain 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 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 The 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?

## 7. Conceptual Design Strategy

[Section organizer: all]

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

## 8. Conclusion

[Section organizer: all]

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


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