JINST Referee responses. 3-July-2020

We thank the referee for their careful reading of the paper and for their constructive comments and suggestions, which have improved the content and clarity of the paper. We have responded to each of the specific comments below.

* Using UAr in the fourth DUNE module is an idea that has been floating around the community for some time (see for example Kate Scholberg’s contribution to ["The Low-Radioactivity Underground Argon Workshop: A workshop synopsis", arXiv:1901.10108], which should be cited here). Nevertheless, to this reviewer’s knowledge this is the first time the possibility is explored formally with a detector design study.

We regret the oversight and have added the reference.

* The proposal presented in this manuscript is well-researched and well-written. Some design elements could be better supported by more detailed background estimate studies, although this could come later in a future Technical Design Report. In particular, it is unclear whether some of the chosen shielding thickness values are in fact optimal (3.5 m of UAr outside the fiducial region on all sides, 5 cm acrylic walls), so the 1 kT fiducial mass sounds arbitrary. Could it be made larger in the transverse dimension? Part of this answer is provided in Figure 3 on the dominant reducible neutron backgrounds: it would be best to show how, based on this simulation, the dark matter sensitivity (based on total background estimates at a given threshold) depends on the transverse dimension of the fiducial region.

We agree that 3 kT-years is a bit arbitrary. A fiducial 1kt was chosen in order to produce a result on a competitive timescale, given a preliminary look at the self-shielding of neutron backgrounds. Following the referee’s comment, we have explored transverse variations for three choices of fiducial length [in z] – 40m, as proposed in the text, and for 52 m and 56 m. These provide distances of 10m, 4m and 2m to nearest end wall in the beam-direction, respectively. To compare sensitivities we evaluated an approximate figure of merit (defined as (Number of Signal) /sqrt(Number of Background)) vs. transverse dimension. We consider an expected dark matter signal at a cross section choice of 1E-45 cm2 and dark matter mass of 0.2 TeV/c2. For the backgrounds we considered atmospheric neutrino, neutrons, and electron recoils with a threshold of 100 keVr. As shown in Figure 1 and Table 1 in this response, for a 40m length we find the transverse optimum half-size is at 2.64m --a little farther out than our chosen 2.1 m – giving a larger 1.56 kT fiducial volume. For a 52m length fiducial volume the optimum is also at 2.64m for a 2.03 kT fiducial volume. Both these rough figure of merits analyses give results slightly higher than our choice of 2.1m. At 56m the optimal figure of merit is significantly lower, with the preferred size at 4m transverse.

We have made more precise sensitivity plots for the first two optimized fiducial volumes (shown in Figure 2 in this report). In the end, the resulting 90% sensitivities are just outside the line width from the figure we have in the paper. We therefore add a line to the paper on page 15 that says the following (the tables/figures shown below are only for referee elucidation, not for publication):

“Lastly, we comment on optimizing the fiducial volume. Upon varying the transverse dimension for several choices of fiducial volume length, the geometry that maximizes signal to background uncertainty at the 100 keVr threshold was found to be roughly 5.3 m x 5.3 m x 52 m, for a total mass of 2.0 kt. The increase in sensitivity for this volume, with its attendant increase in background, compared to our 1 kt choice is quite small (~20%). We therefore use a conservative 1 kt fiducial volume of the dimensions described for all studies in this paper.”

A close up of a device

Description automatically generated

Figure : Variation of the sensitivity figure of merit with the transverse dimension (half-size) of the defined fiducial volume. The different colored curves represent different fiducial volume lengths.

|  |  |  |  |
| --- | --- | --- | --- |
| Fiducial Volume Length [m] | 40 | 52 | 56 |
| Buffer Size at Ends [m] | 10 | 4 | 2 |
| Optimal Transverse Size (half-length) [m] | 2.64 | 2.64 | 3.60 |
| Optimal Fiducial Mass [kT] | 1.56 | 2.03 | 4.06 |
| Expected Signal | 17.3 | 22.5 | 45.1 |
| Neutron Background | 8.3 | 13.1 | 1229 |
| Atmospheric Neutrinos | 16.0 | 20.8 | 41.6 |
| Electron Recoil PSD Leakage | 1.0 | 1.3 | 2.6 |



Figure 2: This sensitivity plot (for referee only, not paper) includes green and blue lines superposed, labeled “100 keV thresh opt1” and “100keV thresh opt2”. “opt1” is the 1.56 kT volume and “opt2” is the 2.03 kT volume that correspond to the orange and blue curves in the previous optimization plot of this report.

As can be seen, they sit almost on top of the black “100 keV thresh” line in the original plot in our paper for the 1 kTon fiducial volume.

* The photon counting study seems sound to first order, given the assumptions stated. Attenuation in argon is explicitly neglected on page 9, however for a detector of this size the effect may actually be significant: for example [Neumeier, A. et al. EPJC 72, 2190 (2012)] measured an effective attenuation length on the order of 1.6 m. It would be worth quantifying the impact of this effect on the ability to reach the required PE yield at the photodetectors.

The attenuation of the scintillation light in liquid argon has been found to be highly dependent on the level of impurities. The Neumeier reference mentioned above has limited consideration of the effects of oxygen and nitrogen on the attenuation. We use as the basis of our estimates a paper by Jones et al. (full reference below) which measures extremely long attenuation lengths that justify our assumption to neglecting attenuation. With the 1790m attenuation length measured by Jones et al. for 37 ppb nitrogen, the number of photons is reduced by 0.5% in our simulation. Added clarifying text and reference to page 9/10:

“Attenuation was assumed to be negligible in this study. Measurements of attenuation length are highly dependent on argon purity, and attenuation lengths of 30-60 m have been achieved with parts-per-million levels of nitrogen and kilometer-scale attenuation lengths with parts-per-billion (ppb) levels [26]. Since the presence of impurities can strongly suppress the scintillation light from the long-lived triplet state required for pulse shape discrimination, ppb levels of impurities will be required for this module. This corresponds to less than 0.5% reduction in collected light..“

[26] BJ P Jones, C S Chiu, J M Conrad, C M Ignarra, T Katori, M ToupsA measurement of theabsorption of liquid argon scintillation light by dissolved nitrogen at the part-per-million level,Journal of Instrumentation8(2013) 07.

* Expected background studies are thorough for some sources, namely radiogenic neutrons, as well as beta and gamma rays, and the irreducible neutrino background. They are however incomplete or absent for other sources, e.g. - Cherenkov backgrounds are very briefly mentioned on page 11 as neglected. They could be a very significant source of high-f90, low-PE background for a detector with this technology and size, and deserve further study. - Alpha decays with unusual topologies, either with limited path length in LAr leading to smaller energy depositions, or with light-shadowing effects, can provide significant backgrounds that are not considered here. Without necessarily going into much detail, they would be important to mention too

1.) Added clarification of management of Cherenkov backgrounds (pg 11):

“The most significant potential source of Cherenkov light, from the acrylic walls used to mount the reflectors, is managed in our design by ensuring the reflective foils are opaque and mounted on the inner surface.”

Added clarification of management of alpha backgrounds in a dual-phase TPC (page 6):

“We do not consider direct $\alpha$ backgrounds in this study, relying on the difference in energy and scintillation time profile to remove these events. It is possible that geometrical features near the inner detector surfaces may cause effects that shift these events into the region of interest, however position reconstruction and fiducialization will remove this contribution.”

2.) Upon re-running our gamma simulations through cross-checking, we realize we significantly underestimated our pre-PSD background coming from the acrylic. These numbers are now about 85000 per 3 kt-years, up 3 orders of magnitude from the original paper. This was due to a units problem, and we regret the error! The number is still 0 after PSD, so no conclusions are changed. The G10 gamma result is changed also but remains tiny. No other backgrounds were affected. The background table summaries are thus now fixed, and we change the two relevant paragraphs in the Gamma Background section to read as follows.

“We find that for acrylic with a few parts-per-trillion $^{232}$Th content (as achieved by SNO~\cite{acrylic} and DEAP-3600 \cite{deapacrylic}), a 5-cm thick box bordering our inner fiducial volume contributes about 85,000 events for 3 kt-years in our fiducial volume, almost flat across our choice of thresholds, before applying any pulse shape discrimination.

For gammas emitted from the top of the detector we explore $^{40}$K and $^{208}$Tl decays, respectively, in our fiducial volume. Given reasonable material radioactivities of 1 Bq/kg $^{40}$K and 10 mBq/kg of $^{232}$Th and a mass density of 0.5 gm/cm$^2$ (e.g. 3-mm thick G-10) we place upper limits of 30 and 4.3 events/3 kt-years from these two sources, respectively, in the inner 1-kt fiducial volume -- again before application of PSD. For $^{232}$Th decays this follows from non-observation of a single event in the fiducial volume at any of our thresholds for a reasonable simulation job length (a 30$^{\text{th}}$ of 3 kt-years). For $^{40}$K, where our simulations also give zero events, we scale from the $^{232}$Th result with a ratio of the above activities multiplied by the ratios of attenuation through 3.6m of argon for the two different gamma energies.”

* page 16  
  The clarity of Table 1 would be greatly improved with three distinct columns for the three threshold scenarios (100 keVr, 75 keVr, 50 keVr). A row with "total" background estimates would be nice to have as well. "bPSD" and "aPSD" acronyms are unnecessary, please spell out "before PSD" and "after PSD". If necessary, making the table orientation landscape would give more space to implement these suggestions.

We have changed the format of the table for clarity, according to the referee’s suggestion. We have kept the abbreviated ‘bPSD’ and ‘aPSD’ designations for the gamma backgrounds before and after PSD to keep the table in the standard portrait orientation (we believe it’s important to show that while the backgrounds are negligible for all these sources after PSD, except 39Ar, we did study them to get a sense for their size).

* References  
  For consistency, please cite as collaboration names where appropriate, i.e. Ref 4: DarkSide-50 Collaboration  
  Ref 15: DarkSide-50 Collaboration  
  Ref 16: DEAP Collaboration

Done

* Throughout "Darkside" –>"DarkSide" including on Figure 6 page 2   
  "DP phase" –>"DP" as P stands for phase

Done

* page 4 "The motivation of the size of the inner volume is largely cost-based": this may be true for directions along the photodetector plane, but not perpendicular to it?

We intended to make a distinction between the fiducial volume (where this statement by the reviewer applies) and the inner volume (where the photodetection coverage is enhanced). To clarify we have rewritten the sentence:

“The motivation for the size of the densely-instrumented inner volume (independent of the size of the fiducial volume) is largely cost-based; increasing the size of the inner volume and adding additional photodetection would increase the sensitivity to low energy interactions.”

* page 5 "Darkside50" –>"DarkSide-50" with dash

Done.

* page 6 7.3\*10ˆ-4 Bq/kg \* 4.3\*10ˆ6 kg = 3.1 kBq, suggesting to write this number explicitly

Done

* "12 events" pileup over which period of time?

These sentences now read as follows for clarity:

“The maximum drift time in the current design of the DUNE DP module is roughly 7.5 ms at a drift field of 500 V/cm and (for the assumed \artn~activity of \SI{7.3E-4}{\becquerel\per\kgar} in the underground argon) the rate within the 4.3 kton acrylic box is expected to be 3.1 kBq. The average number of pileup events for interactions at the center of the fiducial volume (drift time $\sim$ 3.8 ms) is therefore 12 events.”

* page 8 Figure 2 x-axis quantity missing "neutron energy [MeV]"

Done

* page 14 Footnote: please write km/sec unit after each speed value

Done

* page 15 Figure 6: DEAP-3600 curve does seem to reflect their latest results, although the correct reference is [DEAP Collaboration, Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB. Physical Review D, 100 (2019) 022004]: please add in caption and References section. Reference missing in Figure 6 caption for XENONnT expected sensitivity. Figure 6 title and caption: after "90%" add "C.L." Figure 6 y-axis would be clearer as "Spin-independent WIMP nucleon cross section [cmˆ2]" Figure 6 x-axis unit should be [TeV/cˆ2]

Done