BDX-note-XXX
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BDX Response to TAC Report from PAC 46

BDX Collaboration

1 Theory

1.1 C12-16-001: Dark Matter Search in a Beam-Dump eXperiment (BDX) at Jefferson Laboratory

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This is an update to a proposal originally submitted to PAC44 seeking to place limits on a class of candidate dark-matter theories with a dark fermion or scalar mediated through either a *dark photo* that mixes with standard photon, or a separate (abelian) 5th force, coupling to SM currents as well as dark-matter currents. The original proposal was characterized by an extremely comprehensive theoretical review of the field. Since then there has been a *community white paper* on dark matter physics that they use to put this experiment in the context of other searches. In this update, the main effort has been in better understanding and modelling the backgrounds, most notably the neutrino backgrounds wherein the interaction of a neutrino with a nucleus can mimic the interaction of dark matter to produce and electron.

In Sec 4.2.2 they explain that $\nu_e\, N \to e\, X$ is the largest source of background for the experiment. They claim that this can be rejected by considering the kinematics of the process. In particular, they state that by considering the angular distribution of the scattered electron, one can distinguish this from $\chi\, e \to \chi\, e$, which is supported by Fig. 19. They normalize these two distributions and show that the latter is sharply peaked at large angles. **This seems to suggest that only at large angles one can hope to resolve the desired process. Is this correct? It would be good for them to expand on this. Furthermore, how does the resolution of these large angles and the relative size of the distributions relate to the expected exclusion regions shown in Fig. 1-3?**

Response The difference between the two distribution is due to the different kinematics of the two processes: in one case (background) an almost-mass-zero particle scatters off a heavy nucleus; in the other case (signal) a massive particle (how massive depends on the specific χ mass) hits elastically a light electron. Figure 19 (left) reports the scattered electron angle in the Lab system in the two cases. The signal peaks at low scattered electron angle, while the background has a much broader distribution, extending up to 180°. From this, one can conclude that scattered electron angle kinematic variable can be effectively used to discriminate the first from the second, by selecting events with **small electron scattering angle**. The scattered electron immediately interacts with the CsI(Tl) generating an electromagnetic shower that propagates differently in the two cases. BDX does not detect directly the scattered electron direction (angle), but it does measures the shower that the electron initiates, involving many crystals. A cut in the *Shower transverse dimension* R parameter, that is calculated weighting the crystal position in the calorimeter matrix by the deposited energy, allows one to separate the forward-going signal from the more transverse-shaped background. The optimisation procedure described in Sec. 4.3.2 uses the variable R as derived by the signal/background simulations fully accounting for any resolution effects. In the reach evaluation procedure this is fully accounted for.

Overall, they make a strong case for BDX. In particular, it does seem that BDX is uniquely able to produce and measure possible DM candidates and nicely compliment alternative constraints. Additionally it seems that BDX will be able explore presently unconstrained parameter-space regions.

2 Physics

2.1 Experiment parameters

Beam time request:

Days requested for approval	285 days w/ 11 GeV beam (or 0 if fully parasitic)
Time needed including energy changes	N/A
Tune up included in beam time request	N/A
Measurement as proposed is entirely parasitic	

Comment

Beam Characteristics:

Energy	11 GeV
Current	$> 60\mu$A
Polarization	No

Comment

Special requirements/requests:

1. New building and infrastructure behind Hall A (in line with Hall A dump). (JLab responsibility)

2. Custom detector
   (Collaboration responsibility)

3. DAQ for 1100+ channels
   (Responsibility unclear? $350k nominal cost)

   Respnse The DAQ is the responsibility of the collaboration.

2.2 Technical Comments

1. The total cost of this experiment ls likely to be in the range of "Major Research Equipment."

   Response Agree.

2. Days requested are assumed to be parallel to other running so that no dedicated accelerator time is needed.

   Response Yes.

3. $\sim$ 17m of iron/steel is requested to range out muons between the Hall A dump and the detector which will cost several million not including civil construction costs. This shielding would not address any issues about leakage of neutrons for example. Hall A would likely need to be off for 6-12 months.

   Response: The required thickness of iron along the beam is 7 m (see Figs. 4 and 16 and Section 4.1.3 of PAC46 Proposal Update). Indeed the total volume of iron required needs to be optimized for cost during a conceptual design of the facility. The PAC 44 cost estimate includes the cost to encase and bury iron shielding blocks, but assumes block availability. The total amount of shielding required still needs final optimization. Costs would be reduced by using existing steel and/or using a mixture of concrete and steel.

   The design and planning of the new infrastructure construction will be carefully studied and optimised to result in a minimal impact on Hall-A operations. In case of approval, the final design of the new facility and a plan to build it will be the first priority of the BDX Collaboration. JLab Facility, Hall-A management and the relevant Lab resources will be involved in the process. The envisaged $\tilde{2}0$ weeks of accelerator operation per year leave anyway a significant downtime available for construction.

4. The BDX Experiment is a proposal to search for terrestrial evidence of Dark Matter due to BSM physics. Looking for evidence of Dark Matter is a hot topic,

particularly as the window for BSM is decreasing. For example, as of late the astrophysics community has been making steady progress towards the possibility that the missing Dark Matter in the universe is explainable by unaccounted for Black Holes with properties and sizes previously excluded.

Response The window for BSM is not decreasing; the window for WIMPs at higher mass is decreasing, which is an argument in favor of BDX, not against it. Forming a population of "unaccounted Black Holes" in the early universe before the CMB (when we know that DM is already present) absolutely require a great deal of new physics. Also, even if primordial black holes were the dark matter, there are strong bounds on their fractional abundance in the Galaxy and there are almost no values for their mass which can accommodate the total DM abundance without running into nontrivial constraints - see Figure 3 of https://arxiv.org/pdf/1607.06077.pdf. The controversy over properties and sizes previously excluded has to do with relaxing (not eliminating) a tiny window around 30 solar masses.

5. It is unclear what are the CL associated with the contours shown in Figures 2 and 3.

   Response The exclusion limits are at 90% CL.

6. The proposal presents results from "hole in the ground" detector measurements behind the Hall A dump recently taken over approximately 2 months of beam on which appears to confirm their Monte-Carlo's ability to predict anticipated muon leakage from the Hall A complex with its present (not enhanced for BDX) shielding configuration. It is a big leap to conclude that the neutron background in the actual experimental vault will be acceptable. Therefore, it is still unclear if the experiment will truly be free from low neutron backgrounds after integrating over a year of production running. These muon measurements of course do provide information with respect to potential neutrino induced backgrounds - which in the case of ν_e generated backgrounds might be consequential. The measurement proposes to employ energy and forward angle cuts to suppress all these backgrounds. However, neutrinos generated in the wide decay "dump" tunnel can strike the detector at much larger angles than those from the beam dump proper. It is unclear if this is accounted for in their simulations of events at the detector.

   Response (a) In this update to PAC 46 (Appendix A), we have developed a process to evaluate the impact of the combined effect of changes to the geometry (e.g. shielding) and analysis selection cuts. Each of these may affect the efficiency for detecting the signal as well as ability to reject background. In the final analysis, what matters is not how a single cut affects signal or background, but rather how all changes taken together affect the reach of the experiment. The specific analysis and optimization as described in the proposal update should not be taken as final for the experiment. They serve only as a guide to realistic analysis cuts and demonstrate that the reach of the experiment as presented in the original proposal is still valid. Trade-offs between various veto and detector configurations and corresponding analysis cuts are still possible and the success of the experiment does not depend on any one in particular.

(b) High-energy neutrons could be, in principle, a background from the experiment: from simulations (with eq. statistics $\sim 10^{17}$), there are no neutrons with energy greater than 100 MeV that are hitting the detector.

(c) Low-energy neutrons can't interact in the detector resulting in a background source, since our thresholds will be much higher. However, they could represent, in principle, an issue, if the rate of low-energy events was so high that pile-up or other effects could prevent the measurement (in other words, they could represent an issue to the measurement itself). We find no neutron beam excess with the BDX-Hodo, which uses the technology as the final detector, and in a non-optimized shielding configuration ranging all muons (4.3 GeV).

(d) The full geometry is captured in the simulations, including neutrinos generated at all locations and angles in the dirt.

7. For neutrino calculations they employ several codes that calculate detector event rate and energy spectra of neutrinos (flux and species) that have been used at proton facilities to model neutrino beamlines. This may be the first application of these codes to calculate neutrinos generated from the decay of electro-produced secondaries. The simulated neutrino spectra presented are difficult to evaluate in part because they are on log-log plots and show no systematic errors (due to uncertainties on the input double differential cross-sections and the overall geometry assumptions). These codes have generally been used to simulate neutrino in-flight decays channels but are not particularly good at absolute flux rates. The input double differential cross-sections often end up being "tuned" so the rates match measured peg points for experiments that also often rely on the neutrino/anti-neutrino ratios to be fully interpretable.

Response (a) The log-log plot seems the best way to present observables that span over 3 orders of magnitude in X and 10 orders of magnitude in Y, see fig. 18. To generate the neutrino spectrum, we used only one tool, FLUKA.

(b) BDX relies on calculations to estimate ultimate backgrounds. However, the effort required to conduct a realistic experimental test of backgrounds is of the scale as the experiment itself and it is unrealistic to require this before the experiment has been approved. The main question to ask is, are we using the best tools available? Is something specific missing from these calculations? The simulations in the original proposal to PAC 44 were based on GEANT and a substantial effort was mounted to work with experts in the JLab Radiation Control group to simulate the experiment with FLUKA and make detailed comparisons between the results of these two simulation tools. The results were completed a year ago and reported to PAC 45. We determined that they agree in the kinematic regions where they are both expected to be valid. For lower energies in particular, FLUKA is a more reliable tool and is therefore used as a basis for hadronic interactions, although GEANT is still used to simulate the detector response. In addition, the FLUKA interaction package with a tuned set of biasing weights, is naturally able to generate reliable particle distributions with very small probabilities. A final check to the modeling of the signal is provided by comparisons of neutrino interactions using FLUKA and GENIE (PAC 46 Update, Appendix B). Results show a good agreement between the two codes, thus confirming the robustness of background calculations we performed.

(c) The comparison between FLUKA and GENIE was done regarding neutrino-detector interactions to verify that we are consistent with the most up-to-date neutrino experiments. This was the most critical part, in particular for neutral current interactions, where we require a proper description of the nuclear part of the reaction, resulting in final state hadrons that may release energy in the detector. Neutrino produced in the dump and in the diffuser/target mainly come from decays of pions/muons/kaons. FLUKA is the best code in this energy range to properly manage the production of these particles, both in terms of kinematics and absolute yield. FLUKA has been benchmarked extensively for neutrino production generated by protons in the CNGS facilities (Nuclear Physics B - Proceedings Supplements 188 (2009)188 and Eur. Phys. J. C 73 (2013) 2345). At Jefferson Lab, the FLUKA program has been checked against Pavel Degtiarenko's private version of GEANT3, which is the best model we have for radiation estimates at the lab. The decay mechanisms for pions, muons and kaons that produce neutrinos are the same in all facilities.

8. Inspecting these simulations is made more difficult as figures presented do not fully separate the neutrino spectra generated by the three major sources. Specifically, those generated in the Hall A (water/Al) dump and those generated by in-flight decays along the beam dump tunnel of Hall A -which are associated with the upstream LH2 target and/or beam diffuser. The details of the individual contributions are not shown, only additive results in the figures and rate summaries. However, they do note (which can be seen in the figures) the higher average neutrino energies of the long decay tunnel for target/diffuser associated

events -which is qualitatively correct. In "proton beam" neutrino facilities, the high energy neutrino spectrum is dominated by neutrinos from in-flight decay compared to neutrinos from decay in the matter of the beam dump, whereas in the simulations presented here, neutrinos from the dump and those generated in the target/diffuser/in-flight tunnel both have similar magnitude and energy fall offs. It would be worth checking the simulations by assuming a proton beam to assure that the simulations give qualitative results as expected at proton facilities.

Response (a) The three neutrino sources (Hall A target, diffuser, and beam dump) all have the same shape because they are indeed generated by in-flight decays of muons, pions and kaons. The relative proportions depend on the number of mesons produced in each location times the decay probability relative to its interaction probability following production. For the target and diffuser, fewer particles are produced, but each has a relatively larger decay probability in the space following production. The detailed geometry of each of these has been used to generate the spectra shown in Appendix C.

(b) Our estimates on ν-background for the experiment were done considering the beam-dump only (and the following elements, like the concrete), i.e. no diffuser, and no target were present. Then, we checked (appendix C) what is the effect of this simplification, by comparing the fluxes at the detector position for the different configurations: "simplified," "Moller target," "diffuser." Note that we did not include both target and diffuser at the same time, since from previous discussion (Keith Welch) we understood that the Moller target alone is sufficient to spread the beam on the dump enough so that power limits are respected. When the final BDX configuration (or configurations, in case of multiple runs, at different energies and/or beamline configurations) will be identified, we will run neutrino simulations in that configuration to identify final numbers.

(c) From this check, it results that at low energy the flux is the same for the 3 configurations, while at higher energy there is a slightly larger flux for the "Moller" and "diffuser" configurations. The total background contribution for the different configurations is summarized in table 6. We note that our thresholds will be around 350 MeV: hence, neutrinos starting from $\sim$ 500 MeV will contribute to the background Even considering the linear behavior with energy of the interaction cross-section, the sharp drop in the neutrino flux results in neutrinos with energy $\sim$0.5-1 GeV being the largest contribution to our background. For the "diffuser" configuration, as stated in the text, the neutrino background will be about twice the "simplified configuration." However, the result on the reach is $\sim$20% due to the way this scales with respect to the number of background counts.

(d) It is unclear how to model a proton beams at Jefferson Lab to validate simulations with the nominal electron beam.

9. This experiment needs to isolate a signal that is only a few events over a long running period when using a CW beam. It is highly possible that some dirt effect background or accidentals may set a floor well above the measurement goals. Extrapolation from limited background studies and simulations are risky at best. For example: In older neutrino measurements (BNL 1970's) using $\sim$30 GeV proton initiated in-flight produced neutrino beams there was a π^0 background floor that would mimic neutrino interactions. Although the proposers take note of this -it is tricky background to estimate precisely as its suppression depends in part upon the position resolution of the detector.

   Response (a) We cannot rule out unexpected backgrounds even though all checks of our simulations to date have been confirmed. However, we have two strategies that can be used in case irreducible backgrounds are larger than expected: The first is to measure the muon neutrino flux via charged current interactions in the detector and using this measured rate to normalize the predicted the number of neutral current and electron neutrino interactions. This will check the absolute flux prediction of the simulations for the ultimate backgrounds in the experiment.The second is to adjust the threshold, which affects backgrounds more strongly than the signal efficiency.