Snowmass2021 - Letter of Interest

Nuclear Recoil Calibration Techniques for Dark Matter and Neutrino Experiments

Topical Group(s): (check all that apply by copying/pasting ☐/☑)

Primary: Instrumentation Frontier

☑ (IF6) Calorimetry
☑ (IF8) Nobel
☑ (CF1) Dark Matter: Particle-Like
☑ (CF2) Dark Matter: Wave-Like
☑ (NF4) Neutrinos from Natural Sources
☑ (NF9) Artificial Neutrino Sources

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Abstract:

Neutron sources are needed that can deliver neutrons with kinetic energies in the range of 1 keV to 14 MeV, both for dedicated **nuclear recoil efficiency studies** and for ***in situ* calibrations** of larger experiments. This will permit studies of detector responses that are relevant to **CEvNS including solar neutrino, supernova, and atmospheric neutrino** detection, and a broad **range of particle dark matter candidate** searches. The target materials include **Xe, Ar, H_2O, C_3F_8, Ge, Si, CH_4, CF_4, and NaI**.

When evaluating the suitability of calibration sources, one must consider the accessible neutron fluxes vs other collateral backgrounds generated at the same time, the details of the neutron energy spectrum, including whether it is mono-energetic or has a well-defined maximum energy, and if it is possible to determine the recoil energy associated with individual recoil events.

We discuss the current source technologies including their pros and cons and highlight those experiments for which certain new techniques are optimal. Some techniques are best applied to individual target material studies in detectors dedicated to calibrations. Other techniques are best suited for *in situ* use directly on large detectors to cleanly determine their efficiencies to nuclear recoil events. We also discuss potential new initiatives for calibrations. There is clearly a significant benefit from cooperation within the dark matter and neutrino fields on nuclear recoil calibration techniques.

We are faced with significant challenges to calibrate and clearly determine the efficiencies with which we are able to detect nuclear recoils (NR) arising from dark matter and neutrino interactions in large detectors. All target materials show significant non-linearities in the yields of excitons, especially at low energies. High-statistics calibrations with low systematics need to be performed to render the errors in yields and energy-dependent efficiencies subdominant when ultimately reporting results for positive observations or placing limits on physics signals. This is well illustrated in Fig. 1 which shows the state of the art for Xe scintillation and ionization yields from 0.3 to 6 keVr. Xe is probably the best calibrated of all target materials at low energies for NR (and ER) events. The projected event rate of ^{8}B even when it reaches just 2 events is dominated by the remaining Xe yield uncertainties as the 1σ error spans over a factor 2. This would hinder the statistical separation of ^{8}B neutrinos and a low mass WIMP signal.

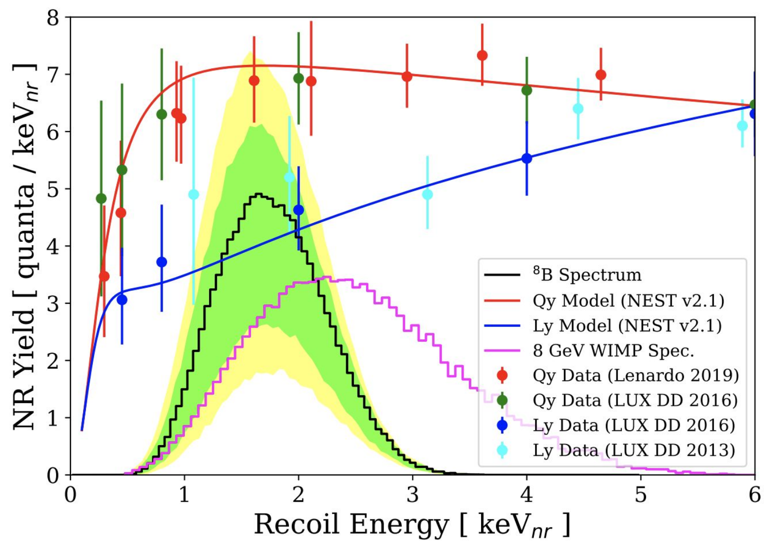

Figure 1: Scintillation light (Ly) and ionization (Qy) yields in liquid Xe at ~300 V/cm fields measured with neutron scattering experiments (keVnr) both in situ on LUX [Akerib:2016, Huang, 2019] and in a dedicated scattering experiment [Lenardo:2019] showing 68% CL errors. Fits using the NESTv2.1 [Szydagis:2020] framework are also shown. The effect of the yield uncertainties on the ^{8}B neutrino signal assuming 3 detected photon and 5 ionization electron signal threshold is shown as a median expectation (represents 1.0 event/6.8 tonnes fiducial/month) and at 68% (green) and 95% (yellow) CL regions. For comparison, the median signal spectrum (magenta) in arbitrary units for an 8 GeV WIMP is also shown. The event range due to yield uncertainty is not shown but is comparable to that of ^{8}B spectrum. The NR spectrum for a 6 GeV WIMP signal would be identical in shape to that of ^{8}B neutrino signal. [Analysis and figure from Xin Xiang, Brown University.] The ^{8}B flux is measured to +/-3% [Aharmim:2011, Agostini:2017].

The challenges have become greater in the last decade given that increasing large experiments [for example, Akerib:2016a :2016b, April:2010 :2011 :2012 :2018, Agnes:2014 :2015, :2018, Agnese:2013 :2017 :2018] have pushed their analyses to lower and lower NR energy events. Traditional searches for WIMPs (with mass range 10 GeV–10 TeV initially focused on nuclear recoil events in the range few keV to 100 keVr. Dark matter candidates with masses << 10 GeV are now routinely being pursued that require demonstration of sensitivity to sub-keV nuclear recoils. In addition, Migdal processes are now assumed [Ibe:2018] in event searches (pushing the sensitivity to low mass dark matter further) and need to be measured directly. Observation of ^{8}B solar, supernova and reactor neutrinos through CEvNS scattering also require calibration of keV nuclear recoils. Effective Field Theory-based analysis of dark matter couplings motivates the need to understand nuclear recoils in energy ranges above 100 keV to ~400 keV [Fitzpatrick:2013, Fan:2010]. Understanding the response accurately is crucial to realizing the detection potential of future experiments [Akerib:2018 :2019, Aprile:2018, Zhang:2018, Aalbers:2016, Aalseth:2015, Baxter:2017].

The primary characteristics that are relevant for the neutron sources include:

- Nuclear recoil energies relevant to given physics searches. As discussed earlier physics searches are being conducted in detectors where there is a need to calibrate the response in the range of nuclear recoil energies that could be somewhere from 0.1 keV to 400 keV. To span most target nuclear masses this requires neutron kinetic energies over the range 1 keV–14 MeV.

- Neutron source spectrum as a continuum versus mono-energetic. Sources able to deliver mono-energetic neutrons (or at least a well defined maximum energy) are effective. Creating scattering events where the neutron energy deposition can be inferred independently of the observed quanta is maximally effective since the yield at that energy is measured directly. For continuum distributions of event energies Monte Carlos must be used to model the detector response over a range of yield models to extract the best fits. There are systematics associated with such convolutions.
- The gamma background relative to the useful neutron flux can be an additional significant systematic. Accumulation of a large number of NR events (needed for accurate calibrations) can be slowed or even obscured by high associated event rates of electron recoils (ER). If there are significant gamma shielding requirements between the neutron source and final target this can introduce systematic alteration of the neutron energy spectrum that must be carefully modeled.
- The radioactivity induced during neutron calibrations has to be studied and well understood. Most induced isotopes are sufficiently short-lived to not pose a threat, but those that lead to longer-lived isolated gamma or beta decays can be particularly pernicious if allowed to accumulate to dominant levels. Again efficient use of the neutron flux is important.
- The suitability of certain calibration techniques to deployment underground *in situ* with large detectors during their operation is particularly effective since it can directly demonstrate the overall detector NR event detection efficiency if the neutron event spectrum has high statistics and the shape is well understood.

Neutron calibration techniques now being actively investigated and deployed include :

- (alpha,n) traditional sources such as AmBe and fission sources such as ^{252}Cf. They emit neutrons having a continuum in the range 0-8 MeV peaking between 1 and 2 MeV. The use of Am^{7}Li allows a reduction in peak neutron energy to 0.2 MeV with energies covering 0-1.5 MeV.
- Photo-neutron sources using a Be target excited directly by an intense monoenergetic gamma-ray source. This will give rise to monoenergetic neutrons at a kinetic energy of E_{γ}–1.666 MeV, which allows for great tunability of neutron energies. The yields can be < 1 neutron per 10^4 gammas so significant additional gamma shielding around a source is used, unless the detector being calibrated has no direct sensitivity to gammas. [Robinson:2016]
- High Energy Gamma-Rays can cause low energy nuclear recoils through coherent scattering. This process is significantly suppressed compared to the electron scattering, but can be used on detectors with no direct ER sensitivity. For instance, the coherent nuclear scattering of a 2.6 (1.4) MeV gamma would create a maximum 0.1 keVnr recoil in a Xe (Ar) nucleus.
- DD-portable neutron generator. Deuterium-deuterium exothermic reaction requiring an acceleration voltage of only ~100 kV that can generate pulsed or continuous mono-energetic neutrons at 2.45 MeV. The associated x-rays are low in energy and so are readily blocked. Similarly, a DT-portable generator can generate pulsed or continuous mono-energetic neutrons at 14 MeV.
- D-Reflector. A scintillating target containing deuterium-loaded xylene (D_8C_{10}) can be used to reflect 2.45 MeV neutrons down a collimated beam pipe. For instance, selecting an angle of scatter of 145 degrees for a kinetic energy of 350+/-10 keV. The neutrons can also be tagged to allow a time-of-flight energy analysis.
- H-Reflector. A scintillating target containing xylene (C_8H_{10}) can be used to reflect 2.45 MeV neutrons down a collimated beam pipe over a range of lab angles from 77-85 degrees. This generates a continuum of neutron energies primarily below 100 keV. Time of flight is used to identify each neutron's kinetic energy.
- Proton accelerator on ^{7}Li. Requires dedicated proton beamline accelerator voltages above ~2 MV and is capable of generating mono-energetic neutrons at reasonable yields with kinetic energies in the range 0.5–1.5 MeV [Cao:2015].
- Nuclear reactor neutrons with a filter material with strongly energy-dependent scattering cross sections. For instance, a combined Al and Fe filter can create 24 keV neutrons [Barbeau:2007].

It will be important to study and report on current optimal techniques, seek greater collaboration, and discover other new ideas for NR calibration during the SNOWMASS process.

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Apologies - Full author list is awaiting final approvals and will be re-submitted shortly.