TF2: Liquid Detectors (draft)

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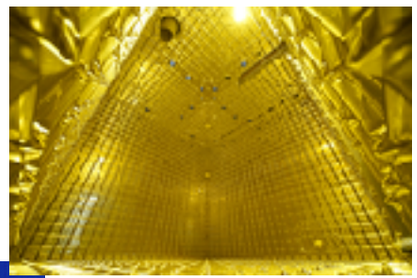
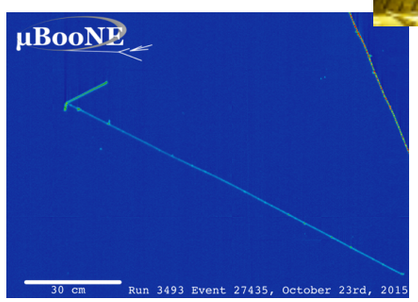
The Science covered

Neutrinos

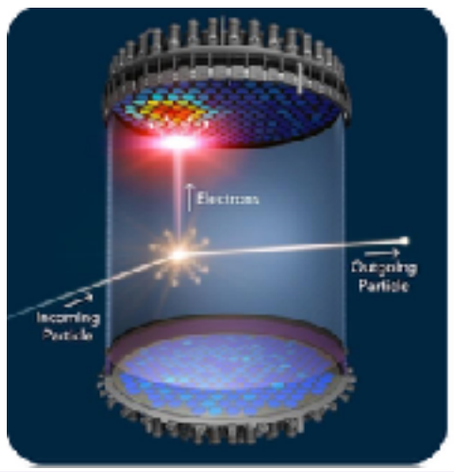
- Oscillation precision measurements (δ_{CP}, mass ordering, θ_{23} octant, sterile νs)
- Neutrino interactions (from CEvNS to DIS)
- Astro neutrinos





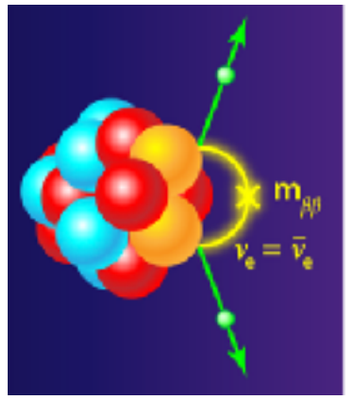
Dark Matter

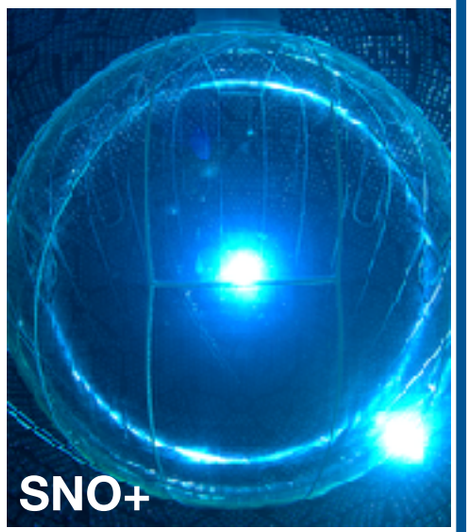
- Direct detection (WIMPs, …)

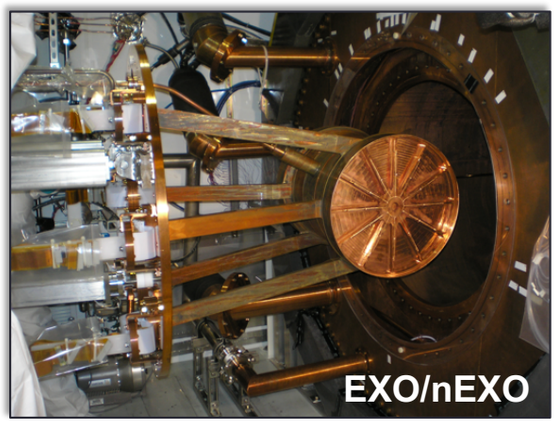


0νββ

- Search for Majorana neutrinos







The Experiments (not exhaustive)

Neutrinos

- Current generation:
  - ✓ MicroBooNE & SBN
  - ✓ LArIAT
  - ✓ protoDUNEs
  - ✓ CAPTAIN
  - ✓ COHERENT
  - ✓ Borexino
  - ✓ SK
  - ✓ Antares
  - ✓ KM3Net
- Future generation:
  - ✓ DUNE modules 1 & 2
  - ✓ DUNE near detectors
  - ✓ DUNE modules 3 & 4
  - ✓ HK
  - ✓ Future neutrino telescopes

Dark Matter

- Current generation:
  - ✓ LUX / LZ
  - ✓ XENON 10/100/1T/nT
  - ✓ Dark Side 50/20k
  - ✓ DEAP-3600
  - ✓ Panda-X
- Future generation:
  - ✓ DARWIN / G3 LXe
  - ✓ GADMC/Argo
  - ✓ HeRALD
  - ✓ SBC

$0\nu\beta\beta$

- Current generation:
  - ✓ EXO-200
  - ✓ KamLand-Zen
  - ✓ SNO+
- Future generation:
  - ✓ nEXO
  - ✓ KL-Z+
  - ✓ Upgrades to SNO+

The Physics Needs (high level overview)

Neutrinos

- **Push Energy thresholds down** to ~1MeV to enhance oscillation physics, supernovae νs study, to enable solar νs …
- **Unambiguous readout**
- **Scalability**

Dark Matter

- **Push Energy thresholds down** to 1 meV/10 eV/1 keV to enable low mass DM/1 GeV DM/ WIMPs.
- **Reduce background rates**
- **Scalability**

0νββ

- **Improve Energy Resolution** to sub-% FWHM
- **Reduce background rates**
- **Scalability**

TF2 Process

- Input Session:

08:00 → 08:30 **Detector R&D requirements for future short and long baseline neutrino experiments**
Speaker: Marzio Nessi (CERN)
21-02-22-ECFA-Neutr... 21-02-22-ECFA-Neutr...

08:30 → 09:00 **Detector R&D requirements for future astro-particle neutrino experiments**
Speaker: Maarten De Jong (Nikhef National Institute for subatomic physics (NL))
ECFA - Maarten de J... ECFA - Maarten de J...

09:00 → 09:30 **Detector R&D requirements for future dark matter experiments**
Speaker: Laura Baudis (University of Zurich)
baudis_ecfa_feb21.p...

09:30 → 09:40 **Coffee-Tea Break**

09:40 → 10:10 **Detector R&D requirements for future rare decay processes experiments**
Speakers: Cristina Lazzeroni (University of Birmingham (GB)) , Cristina Lazzeroni (University of Birmingham (GB))
ECFA_Lazzeroni.pdf

10:10 → 10:40 **Detector R&D requirements for future low energy experiments**
Speaker: Dr Alexandre Obertelli (TU Darmstadt)
ECFA_LowEnergyFoc...

- Community Input: 38 form submissions + many national contacts emails

- TF2 Symposium: 6 expert talks, + ~20 breakout room discussion led by “young” 11 experts, ~125 attendees (> 80% in discussions)

Introduction

- Technologies:
  - ✓ Noble liquids
  - ✓ Water Cherenkov
  - ✓ Liquid Scintillators
  - ✓ Other related technologies
- Physics topics:
  - ✓ Neutrinos
  - ✓ Dark Matter
  - ✓ Neutrinoless double-beta decay
  - ✓ Calorimeters (mostly TF 6)
  - ✓ nEDM (just mentioned, some quantum sensing…)
- Broad summary:
  - ✓ Executive summary style…

Main Drivers (from facilities)

- TF2 is not directly tied to facilities, but more to physics/ experiment generations

- **Neutrinos (accelerator-based)**: FNAL nu-beam, JPARC nu-beam, CERN test beams (Neutrino Platform) (DUNE & HK detectors)

- **Neutrinos (non-accelerator)**: Neutrino Telescopes (KM3Net), DUNE and HK detectors

- **Dark Matter**: Current (ton scale) and next generation of large scale experiments

- **$0\nu\beta\beta$**: Current (100s-kg scale) and next generations (ton to multi-ton scale)

Conveying the “Main drivers” (examples…)

Facilities	Neutrino	Dark Matter	$0\nu\beta\beta$
Fermilab accelerator complex	x	(x)	
JPARC accelerator complex	x	(x)	
CERN Neutrino platform	x		
Next Generation of dark matter detectors	(x)	x	(x)
Next Generation of $0\nu\beta\beta$ detectors	(x)		x
...			

Table 1: Main facilities and their associated physics programs. The (x) indicates secondary physics programs.

General Requirement	Neutrino	Dark Matter	Double beta decay
Lower Energy threshold	x	x	
Better Energy resolution	x	x	x
Increased Imaging resolution	x	x	
Increased Light collection	x	x	x
Better radiopurity	(x)	x	x
Large scale infrastructure	x	x	x
...			

Table 2: Key requirements for liquid detectors.

Exploring other ways…

Key technologies

Liquid Properties of Noble liquids

HV, calibration, doping...

Speaker: k Mavrokoridis (University of Liverpool (GB))

NobleLiquids_Mavro...

Charge collection in Noble liquids

Charge production, propagation, extraction and readout

Speaker: Igor Kreslo (Universitaet Bern (CH))

ChargeReadout_Kres...

Purification, Cryogenics, infrastructure and integration for Noble liquids → (cross-cutting with TF8: Integration)

In context of scalability

Speaker: Christian Philipp Weinheimer (Westfaalische Wilhelms-Universitaet Muenster (DE))

ecfa_tf2_weinheimer...

Light collection in noble and other liquids → (cross-cutting with TF4: Photon Det.)

Light production and propagation, properties and readout (focus on nobles, but address some liquid scintillators, water)

Speaker: Giuliana Fiorillo (Universita e sezione INFN di Napoli (IT))

Fiorillo090421.pdf

Challenges related to Liquid Scintillator and Water detectors

Presentation of the challenges associated in future liquid scintillator and water based detectors, including liquid properties and doping, specific light propagation challenges, purification...

Speaker: Michael Wurm (Johannes Gutenberg Universitaet Mainz (DE))

wurm_wls_ecfa_ap...

Readout challenges → (cross-cutting with TF7: Electronics)

Processing, trigger and DAQ electronics (nobles, liquid scintillators, water)

Speaker: Giovanna Lehmann Miotto (CERN)

2021 ECFA TF2 DA... 2021 ECFA TF2 DA...

Observations: (mostly from input sessions)

4.1 Neutrino Detectors

Community: the community is growing, costs are increasing and most funding agencies will be involved in both programmes (LHC/Neutrino). Global planning and coordination is required. R&D efforts are already playing a role in this. There is significant emphasis on photon detectors, PCB-type readout technologies and related front-end microelectronics to increase detector resolution, for both near and far detectors (e.g. pixels, fine grained detectors, magnetized trackers, high angle TPCs, high pressure TPCs) as the field moves from statistical to systematic uncertainty dominated measurements.

Cross-cutting issues: very complex detector integration and installation plans represent a step-change for the field, with 5 years of components manufacturing across ~30 countries and almost 1 decade of construction. In both LAr and water Cherenkov programmes the complexity of the detectors in increasing by an order of magnitude, with much bigger far detectors, more diversified near detectors, and more dependencies from industrial projects / initiatives. Proper engineering approaches, both structural and electrical, are becoming more important, in particular as concerns integration and installation underground.

The community has adopted the concept of test beams to test and qualify the performance of what has been built, e.g. the detector characterisation of ProtoDUNE at CERN and planned Hyper-Kamiokande intermediate water cherenkov detector beam test.

Interactions: with industry include membrane cryostat technology. This technology from the liquified natural gas shipping industry has been adopted for very large cryostat vessels (~13,000 m^3). It has been deployed in ProtoDUNE, and in the near term is being deployed in SBND, DarkSide-20k, and DUNE far detector modules.

Observations: (mostly from input sessions)

4.2 Astroparticle Neutrino Experiments

Community: a global neutrino network (GNN) is envisioned by the community, in which (European) astroparticle neutrino experiments benefit from interaction with particle physics centres, in particular CERN, for collaboration, reviews, knowledge exchange.

There is aspiration to make a long baseline neutrino experiment for δ_{CP} measurement with tagged neutrino beam from Protvino to KM3Net.

Cross-cutting issues: there are overlaps with earth and sea sciences, with measurements from astroparticle neutrino experiments potentially relevant for studies of climate change, marine life (e.g. noise pollution), and tsunami warnings.

Drivers for making the technology for 10^{12} kg neutrino detectors affordable include photosensor price, maximizing quantum efficiency and minimizing dark count rate. Other cross-cutting R&D for the future is exploring more pixellization of photon detectors for increased resolution, as well as new technologies exploiting radio and acoustic detection of neutrinos.

Interactions: with industry include moving towards commercial cabling solutions, and civil engineering of O(km^3) detectors, which is a major challenge, e.g. in deployment of photosensor arrays from ice surface, or surface vessels (at sea). Potential involvement with offshore industry was identified in a future cosmic-ray detector on the bottom of the sea.

Observations: (mostly from input sessions)

4.3 Dark Matter Experiments

Community: next-generation dark matter detectors aim to reach the sizes, detector configurations and background levels to probe the available parameter space for particle dark matter above the neutrino floor, which requires background levels below the neutrino floor and masses at the 10-100s kg (for ¡1 GeV dark matter masses) and 10s-100s tonnes (¿10 GeV). Simple extrapolations of existing technologies to larger scales not sufficient to meet this ambition. Much of this community is in transition from small scale experiments towards large HEP size experiments, like DARWIN, DUNE, ARGO.

There is a proliferation of creativity in detection schemes (new sensors, new detector ideas combining heat and ionization partitions, integration with quantum technologies for readout etc.) in this community, with time scales that can be shorter than most areas of HEP. Both incremental and transformative R&D efforts are essential to make progress in dark matter, because the physics parameter space is so large.

Shared facilities, for example for low-background screening and cryogenics facilities to test large scale equipment (e.g. high voltage feedthroughs), are needed.

Cross-cutting issues: the main technological challenges across different technologies is upscaling whilst reaching ultra-low backgrounds. Material science is increasingly important (e.g. surface treatment to reduce backgrounds on surfaces, cryogenic distillation on huge scale, new insulator or semiconductor target materials for bolometer development) reaching across fields (chemistry, materials science, etc.)

Many new R&D efforts aim towards measuring recoil energies down to meV scales, to extend the sensitivity to MeV dark matter masses and below. Technological innovations benefit other fields (e.g. cryogenic distillation and medical isotopes for MRI). The need to keep the engineering/technical expertise at universities for efficient R&D progress is high.

Interactions: with industry include photosensor development for lower radioactivity (PMTs) and dark count rate (SiPMs); vibration-isolated, cryogen-free dilution refrigerators, large cryogenic systems and cryogenic distillation

Key Findings (draft)

Summary of key findings including comments from the symposium
(from the experts of our symposium)

- We need more measurements of the properties of liquid nobles: understanding from direct measurements the increase of light from Xe doping and the scattering lengths in Xe-doped and Xe and Ar detectors.
- Challenges related to Ar-37: storage and transportation.
- Radon: how to combine in a large detector radon purity with the needed high flux. Material screening.
- Pay attention to chemical cleanliness: this would imply less recirculation introducing less radon
- High-voltage: light emission around breakdown voltage. Strategy to understand where does it come from and to mitigate it.
- Calibration: gammas, electrons good strategy. Nuclear recoil calibration is challenging for large detectors. Important to find isotopes with spontaneous neutron emission to calibrate.
- Study possibilities to dope Xe and improve the performance of the detector
- Production of ASICs: Diversification and mass production. Combine the effort of the existing groups.
- LAr doping: look for other dopants and the impact in the Ar properties. Importance of calibration.
- Important to identify which liquid properties need to be measured and at which level, specially for very large detectors.
- Pixels versus wires: noise sensitivity, diffusion
- Xe doping: ProtoDUNE results encourage this strategy. Cost is not an issue. Perhaps infrastructure is an issue. More systematic studies are needed on HV breakdown voltage in Xe doped detectors.

Key Findings (draft)

- Advantages of combining light and charge
- Limitations for HV supplies. Possibility to amplify the supplied voltage inside the cryostat (as in Neutron EDM experiment). Some industry solutions combining several power supplies.
- Xe doping: more R&D is needed to understand the impact of Xe doping in the t0 information from light signals and how much the doping affects the pulse shape discrimination power. Gradiant: possible non-uniformities or accumulation near the bottom or at the liquid-gas interphase in dual-phase detectors.
- Exploration of other wavelenghts (like IR) to improve the event reconstruction
- Important to know the liquid noble properties and not just rely on simulations
- Problems related to the scale up of detectors: limit of photosensor coverage in large detectors. For Xe detectors, dark rate is the main concern. Possible solutions: pixelation and digitization of signals in a very low level. R&D is needed on the reduction of the power consumption for large detectors.
- Collaboration with industry in SiPMs is crucial for future developments. Concern: for VUV applications we are small customers.
- Collaboration through projects as AIDA
- Reach higher quantum efficiency of SiPMs together with industry
- Increase of light collection: for large experiments with beams, not the most important parameter. For LXe, the threshold and energy resolution depend on light collection.
- Potential of LS: loading. Minimize the material and backgrounds. Good time resolution in photosensors is needed for LS. Separation of Cerenkov vs scintillation.
- Need for collaboration in the LS community: liquid and MC scintillation model developments. Possibility for a symposium to exchange improvements.
- Quantum dots: possibilities for loading and the scale of production needed for large experiments
- Limit of LS maximum transparencies (around 30m). How to go beyond that?
- Potential of loaded scintillators for neutrinoless double beta decay: better energy resolution

Plan for the week…

- We have a good first draft (~15 pages)
- Need to formulate recommendations,
- Organise with cross-cutting topics with other TFs (TF4, TF6, TF7, TF8)
- Decide on tables/figures to convey our messages and to address timescales etc…