LAr Energy Response to Nuclear Recoils

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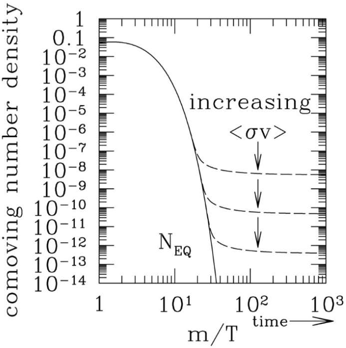
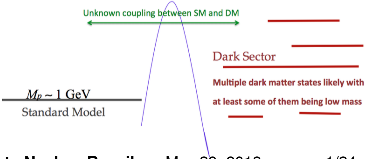
WIMPs

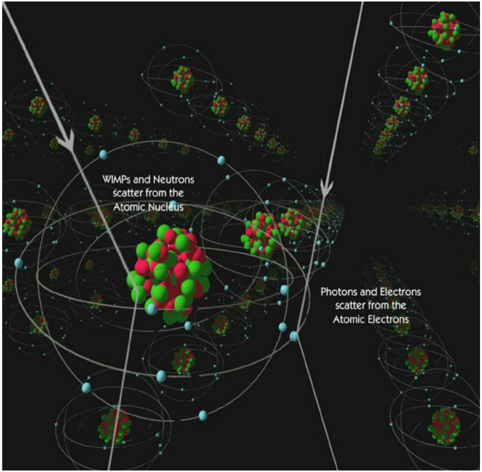
- Most discussed candidate: **Weakly interacting Massive Particle**
- Produced during Big Bang, in thermal equilibrium in the early Universe
- Decouples from ordinary matter as the Universe expands and cools
- Still around today with densities about a few per liter



Dark sector could be as complicated as the SM. Searches not limited by expectations from SUSY models

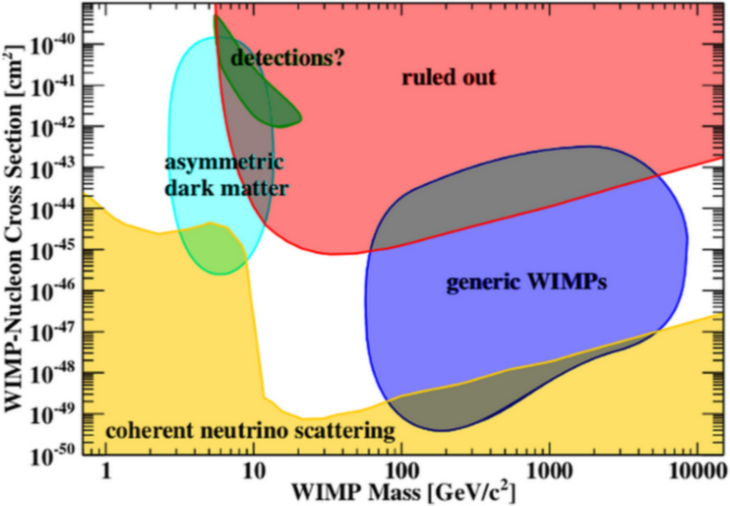


Direct Detection



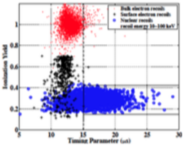
WIMPs can scatter elastically with nuclei and the recoil can be detected.

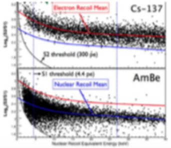
Where are the WIMPs?

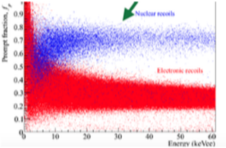


The recipe for direct detection of dark matter

- Detect tiny energy deposits, energy of recoils is tens of keV
- Background suppression:
  - Deep sites to reduce cosmic ray flux
  - Passive/active shielding
  - Careful choice and preparation of material
- Background discrimination (electronics recoils vs nuclear recoils)







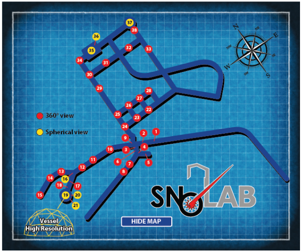
- Large target mass, scalability to ton-scale targets

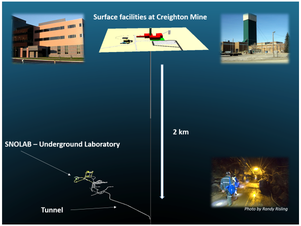
Sudbury Neutrino Observatory Laboratory

Deepest and cleanest large-space international facility in the world (UNAM is collaborating with SNOLAB in several experiments since 2015)

- 2 km underground near Sudbury, Ontario
- ultra-low radioactivity background environment Class 2000
- Physics programme focused on neutrino physics and direct dark matter searches

Home of the SNO experiment 2015 Noble prize in Physics



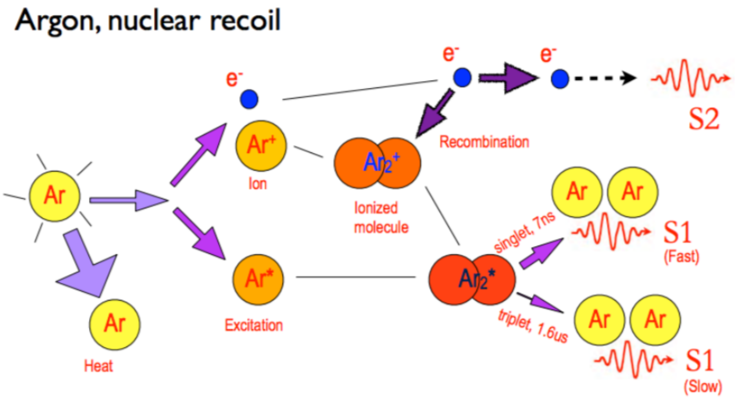


DEAP

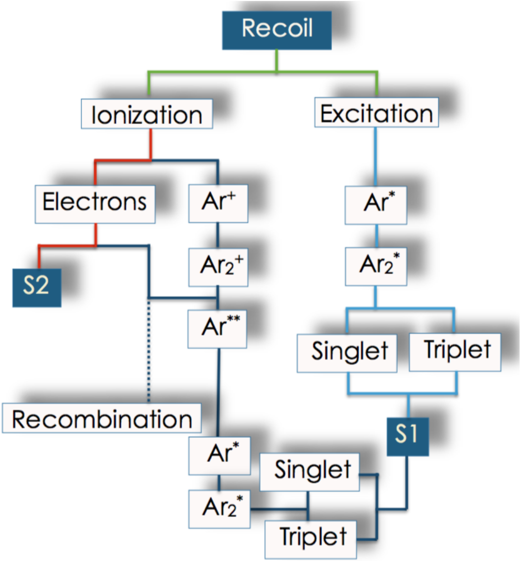
Dark Matter Experiment with Argon and Pulse-shape Discrimination:

- Scattered nucleus detected via scintillation
- Pulse shape discrimination for suppression of β/γ events
- LAr advantages
  - is easily purified and high light yield
  - is well understood (ha!)
  - has an easily accessible temperature (85 K)
  - allos a very large detector mass with uniform response
- Detectors:
  - DEAP-1: prototype, 7 kg LAr, 2 PMTs
  - DEAP-3600: 3600 kg LAr, 255 8" PMTs

Liquid Argon Scintillation

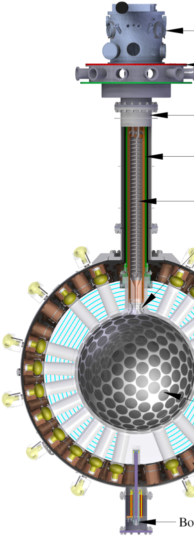


Liquid Argon Scintillation

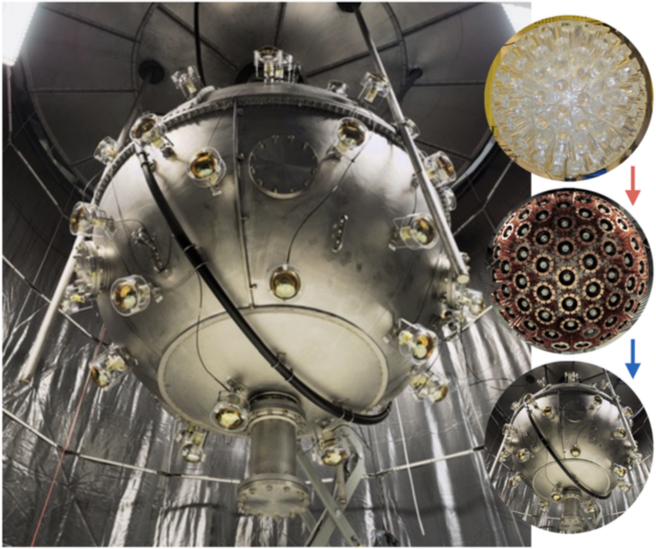


DEAP-3600

- Single phase liquid argon: simple, scalable, inexpensive
- 3600 kg argon (1000 kg fiducial) in ultra-clean AV
- Vessel is "resurfaced" in-situ to remove Rn daughters
- TPB wavelength shifter deposition: in-situ vacuum evaporation
- 255 Hamamatsu R5912 HQE 8@ PMTs (32% QE, 75% coverage)
- 50 cm light guides and PE shielding for neutron moderation
- Detector immersed in 8 m water shield tank in Cube Hall



This is DEAP-3600



Neutron Interaction in Liquid Argon

The three types of interaction that neutrons may undergo in LAr are the following:

- **Elastic scattering** producing nuclear recoils
- **Inelastic collision** leading to γ emission and nuclear recoils
- **Neutron capture** with subsequent emission of a γ and Auger electrons.

Since its event topology is similar as WIMPs, neutron elastic scattering might be an issue because both particles produce a recoiling argon nucleus.

Neutron Interaction in Liquid Argon

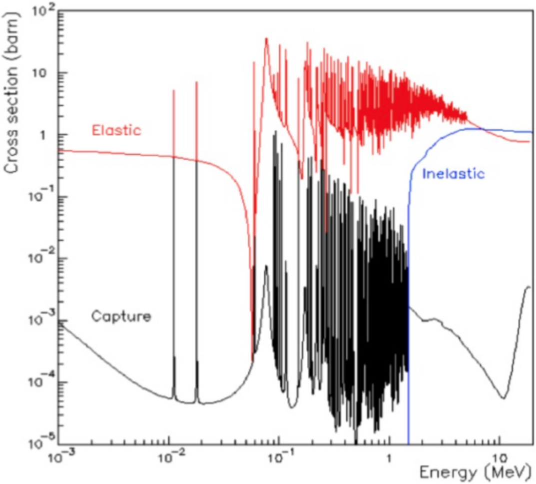


Figure 2.1: Neutron elastic scattering (red), inelastic scattering (blue) and capture (black) cross section on LAr. PhysRevC.85.065811

Energy Dependent Light Yield in LAr

- It is well known that for nuclear recoils in liquid noble gas, only a fraction of the energy deposit leads to ionization and scintillation.
- The rest of the energy is transferred to atomic motion and lost in heat without electrically exciting or ionizing argon target.
- This effect is called **nuclear quenching** and is described by the Lindhard theory[1].

[1] *Mat. Fys. Medd. Dn. Vid. Selks.* 33(1963), no. 10, 1-42.

Energy Dependent Light Yield in LAr

The luminescence quenching depends upon other processes:

- A.Hitachi and T.Doke[2]:

$$\text{Ar}^* + \text{Ar}^* \rightarrow \text{Ar} + \text{Ar}^+ + e^-. \tag{3.1}$$

- The penning process:

$$\text{Ar}_2^* + \text{Ar}_2^* \rightarrow 2\text{Ar} + \text{Ar}_2^+ + e^-. \tag{3.2}$$

- Superelastic collisions quenching the singlet states to the triplet states[3].
- Purity effects.

[2] PhysRevB.27.5279

[3] doi:10:1016/0009-2614(76)80566-0

Lindhard Theory

In general

$$(\frac{dE}{dx})_{total} = (\frac{dE}{dx})_{elec} + (\frac{dE}{dx})_{nucl}. \tag{3.3}$$

Lindhard suggested:

$$E_R = \eta(E_R) + \nu(E_R). \tag{3.4}$$

Then:

$$f_n(E_R) \equiv \frac{\eta(E_R)}{E_R} = \frac{\eta(E_R)}{\eta(E_R) + \nu(E_R)} = \frac{\int_0^{E_R} (dE/dx)_{elec} dE}{\int_0^{E_R} (dE/dx)_{tot} dE}. \tag{3.5}$$

Lindhard Theory

The last expression needs to be evaluated for any possible recoil energies and can be approximated by

$$f_n = \frac{k \cdot g(\varepsilon)}{1 + k \cdot g(\varepsilon)} \tag{3.6}$$

where $k \approx 0.133 Z^{2/3} A^{-1/2}$ and

$$g(\varepsilon) \approx 3\varepsilon^{0.15} + 0.7\varepsilon^{0.6} + \varepsilon. \tag{3.7}$$

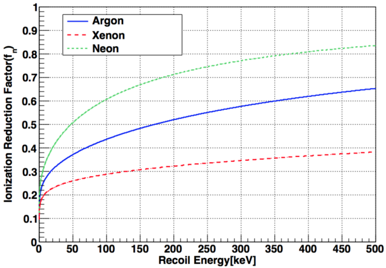


Figure 3.1: Ionization energy reduction factor (f_n) as a function of the recoil energy for argon.

Model for reduced scintillation light at high ionization density

In the presence of the luminescence quenching, the scintillation light response is described by the Birk's law saturation:

$$\frac{dS}{dx} = \frac{A(\frac{dE}{dx})_{elec}}{1 + kB(\frac{dE}{dx})_{elec}} \tag{3.8}$$

$\Longrightarrow$

$$f_l := \frac{1}{1 + kB(\frac{dE}{dx})_{elec}} \tag{3.9}$$

For LAr[4] $kB = 7.4 \times 10^{-4}\mathrm{MeV}^{-1}$gcm^{-2}.

[4] PhysRevB.54.15724

Relative scintillation efficiency $\mathcal{L}_{eff}$ from Lindhard and Hitachi models

In order to fully describe the luminescence quenching for noble liquid, Mei *et al.* arXiv:0712.2470, combined Lindhard theory f_n and Birk's saturation law f_l.

$$q_n = f_n \times f_l \qquad (4.1)$$

where q_n is called the quenching factor or the total scintillation efficiency.

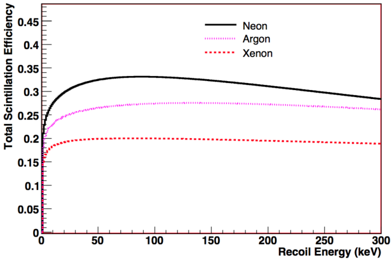


Figure 4.1: Ionization energy reduction factor (f_n) as a function of the recoil energy for argon. arXiv:0712.2470

Relative scintillation efficiency $\mathcal{L}_{eff}$ from Lindhard and Hitachi models

The relative scintillation efficiency is usually denoted by $\mathcal{L}_{eff}$ and is definded as the ratio of the scintillation yield of nuclear recoil to the scintillation yield of electron recoil from a photoabsorbed γ-source.

$$\mathcal{L}_{eff} = \frac{L_{y,nr}(E_{nr})}{Ly,er(E_{er})} \tag{4.2}$$

where the subscripts "nr" and "er" are used for nuclear and electron recoil.

Relative scintillation efficiency $\mathcal{L}_{eff}$ from Lindhard and Hitachi models

Two techniques have been employed to measure $\mathcal{L}_{eff}$:

- **Indirect measurement**: Comparison between a continuum-energy source of neutrons with a simulated spectrum. $\mathcal{L}_{eff}$ is obtained by applying iteratively a fit procedure until the best fit with the measured spectrum is achieved.[5]
- **Direct measurement**: Study of the measured response by recording at fixed angle the single elastic scattered from a monochromatic neutron source.[6]

[5] arXiv:1007.3746

[6] PhysRevC.84.045805 & PhysRevC.85.065811

Experimental results

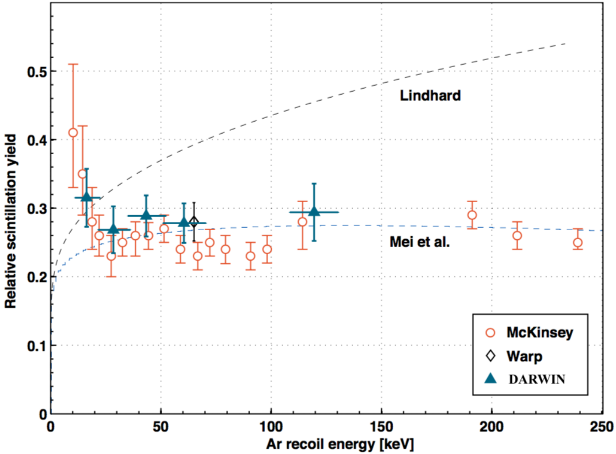


Figure 5.1: Measurements of the relative scintillation efficiency in LAr $\mathcal{L}_{eff}$ as a function of recoil energy. arXiv:1203.0849v1 [astro-ph.IM]

Experimental results

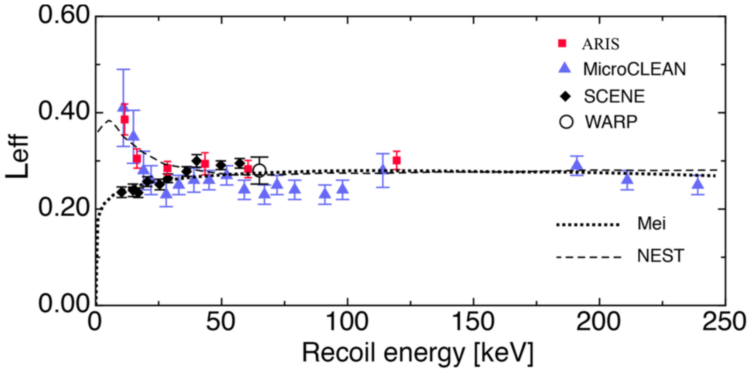


Figure 5.2: Measurements of the relative scintillation efficiency in LAr $\mathcal{L}_{eff}$ as a function of recoil energy. ARIS, P.Agnes.

Conclusions

- It is necessary to measure the scintillation efficiency down to the energy threshold so as to quantify the WIMP detection sensitivity.
- Plan to measure the LAr response at different NR energies from an AmBe source in the DEAP-3600 experiment (largest operating dark matter detector).

Thank You.

A. Míchell Martínez Mendoza