Response of liquid xenon to low energy nuclear recoils

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Zurich PhD seminar
12 September, 2014

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Dark-matter searches with liquid xenon

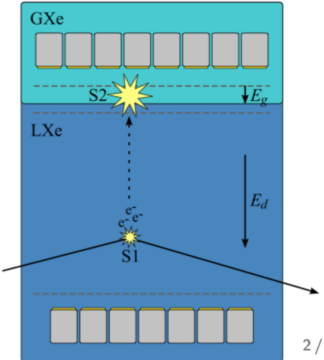
Liquid xenon (LXe) ⇒ ideal detection medium for WIMPs:

1. High A → high cross section ($\sigma \propto A^2$)
2. High Z → self-shielding
3. No long-lived radioactive isotope (only ^{136}Xe, $T_{1/2}^{2\nu\beta\beta} \simeq 2\times10^{21}$ years)

Detection strategy → Looking for WIMP scattering off xenon nuclei.

Signal → Prompt scintillation light (S1) & proportional scintillation generated by extracting and accelerating ionization electrons into the xenon gas (S2).

Background → Cosmic rays, intrinsic radioactivity in the liquid xenon and radioactivity from the detector materials and surroundings.

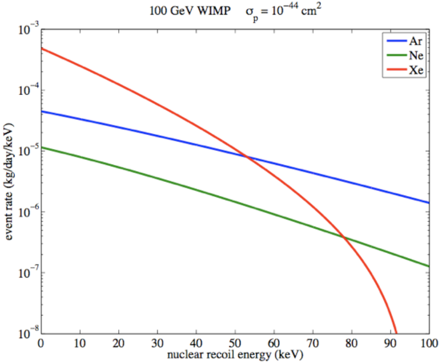


WIMP interaction with xenon: low energy nuclear recoils

For a given mass and cross section of WIMPs, the interaction rate with target atoms is higher at low energies. This effect is even more significant for more massive nuclei like xenon.

$$\frac{dR}{dQ} = \frac{\rho_0 \sigma_0}{\sqrt{\pi} v_0 m_\chi m_r^2} F^2(Q) T(Q)$$

$T(Q)$: kinematic form factor
$F^2(Q)$: nuclear from factor
Q: energy transfer
σ_0:zero energy transfer cross section
ρ_0:local WIMP density
v_0:characteristic WIMP velocity



Interactions with the nuclei (NR)

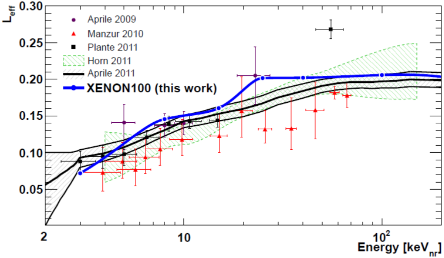
Not only the most promising, the low energy range is also the region with the largest uncertainties.

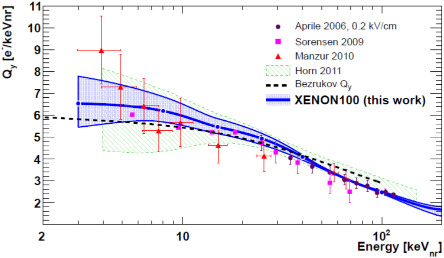
Relative scintillation efficiency

$$\mathcal{L}_{eff}(E_{nr}) = \frac{S1}{L_y} \times \frac{1}{E_{nr}}$$

Absolute ionization efficiency

$$Q_y(E_{nr}) = \frac{S2}{\epsilon_2} \times \frac{1}{E_{nr}}$$





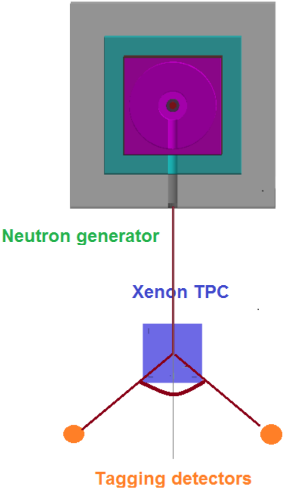
E. Aprile et al (XENON collaboration; Phys. Rev . D 88 0122006 ; (2013)

What we would like to do?

The goal of this work is to perform a direct measurement of the parameters Q_y and $\mathcal{L}_{eff}$ in a xenon TPC down to very low energies .

What do we need?

- A xenon TPC.
- A mono-energetic neutron source.
- Tagging detectors which are able to discriminate neutrons (signal) from gammas (background).



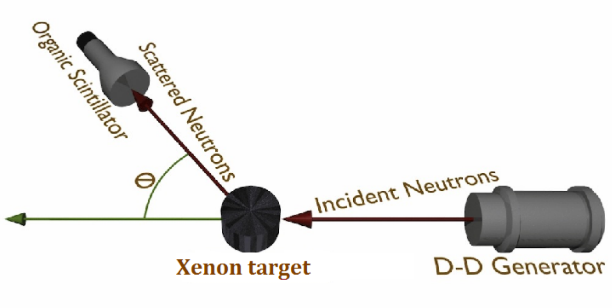
Setup for neutron measurements

The recoil energy for elastic scattering of neutrons with nucleus is given by:

$$E_r = \frac{2E_n}{(1+A)^2}\left[1 + A - \cos^2\theta - cos\theta\sqrt{A^2 + \cos^2\theta - 1}\right] \qquad (1)$$

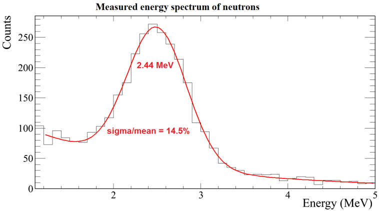
$$E_f = E_n - E_r = \frac{1}{2}m_n\left(\frac{v}{c}\right)^2 \qquad (2)$$

Where E_r is the energy of the recoiling xenon nucleus, E_n initial energy of neutron and E_f the final energy of neutrons after scattering off xenon nucleus.

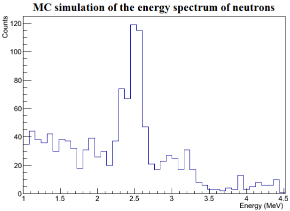


Characterization of the neutron generator

- D-D neutron generator at University of Zurich is used for the measurements.
- Energy distribution of the neutrons at the exit of the neutron generator plays a major role in the nuclear recoil studies.
- The neutron energy spectrum was measured via time-of-flight with two liquid scintillators.
- Also, we simulated the whole setup in GEANT4 to determine the distribution due to angular discrepancies.



Measured energy spectrum of neutrons



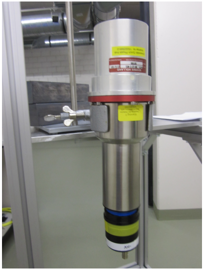
MC simulation of the energy spectrum of neutrons

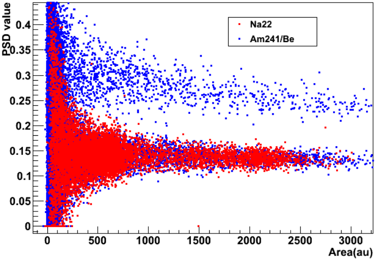
Neutron tagging & particle discrimination

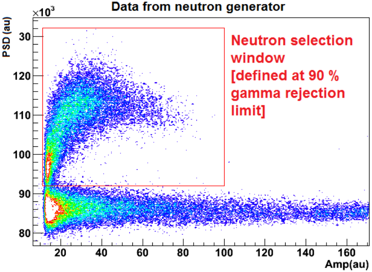
→ EJ301 liquid scintillator will be used for tagging neutrons after scattering off LXe.

→ MPD-4 pulse shape discrimination module (from mesytec Co.) is used to distinguish neutrons (signal) from gammas (background).

→ Measurements have been performed to characterize the particle discrimination capability of the setup.

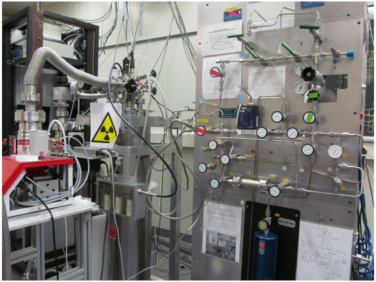


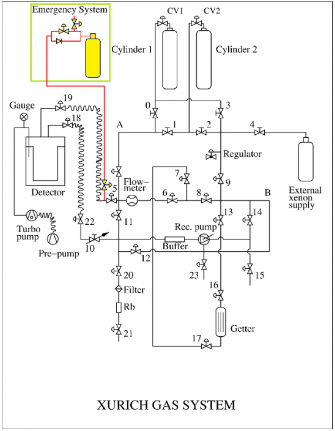




The Xurich detector

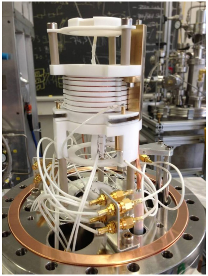
- A small dual-phase TPC optimized for charge readout.
- It will be sensitive to ionization signals as small as single electrons and it has minimized amount of non-active detector components (i.e. PTFE and non-active LXe).

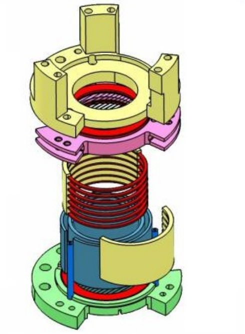


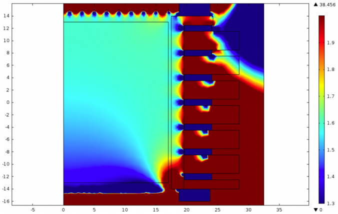


The Xurich TPC

- Small (Z=3 cm, D=3.5 cm) cylindrical chamber to reduce geometrical uncertainties.
- Anode, cathode, gate and field shaping rings to provide homogeneous electric field inside the TPC based on field simulations performed by Hrvoje Dujmovic.
- 3 plate capacitors placed symmetrically around the TPC to be used for determining the liquid level.

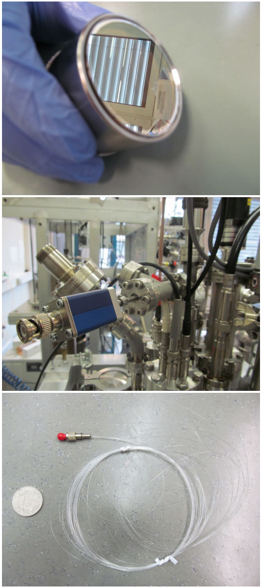






Xurich PMTs

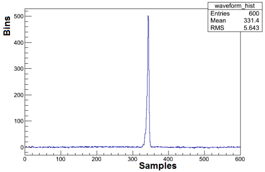
- Two PMTs (2 inch Hamamatsu model R9869) are used at the top and the bottom of the Xurich TPC.
- The gain value of each PMT plays an important role in the data analysis$\Longrightarrow$ it needs to be monitored regularly, due to fluctuations that can be caused by pressure and temperature.
- Gain of a PMT is defined as the number of electrons produced as a response to a single photo-electron.
- A light emitting diode (LED) is placed outside the chamber and PMMA fibers plus an optical feed-through are used to guide the LED light to the PMTs.

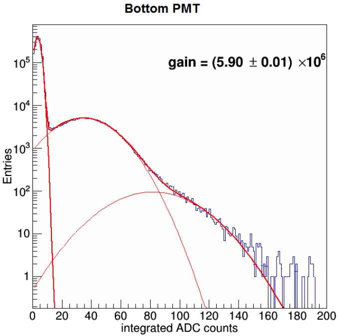


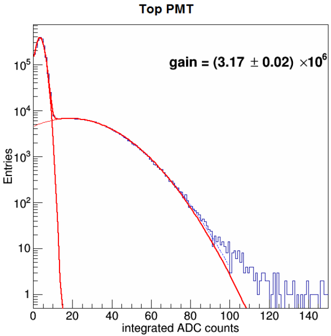
PMT calibration analysis software

Tasks of the program:

- Search for pulses and process them
- Plot the spectrum and fit the single PE peak
- Evaluate the gain value from the position of the single PE peak for both top and bottom PMTs



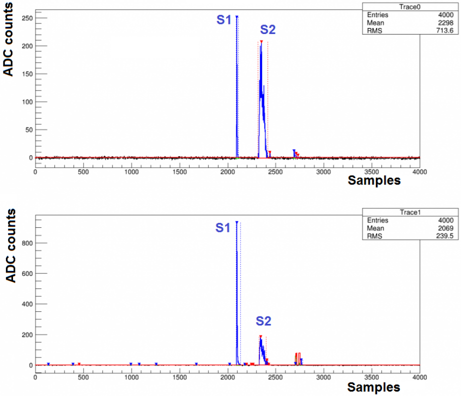

Bottom PMT


Top PMT

Xurich data analysis

S1: Prompt scintillation signal
  - Short (10-50 ns)
  - Should be observed in coincidence in both PMTs

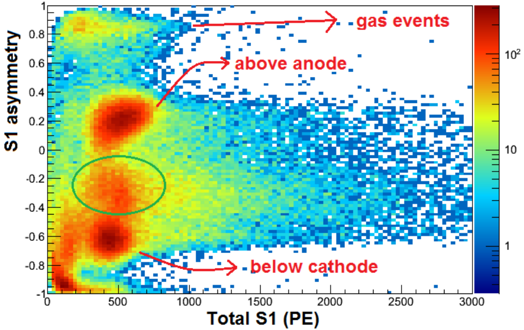
S2: Secondary scintillation due to the drift of ionization electrons into xenon gas
  - Long (0.5-1.5 μs)
  - Larger in the top PMT



An analysis software is developed to find S1/S2 pulses in the traces and process them into meaningful physical parameters such as S1/S2 integral, width, drift time and etc.

Calibration with ^{57}Co source

122 keV gammas from ^{57}Co are used both for energy calibration and determining the thickness of the gas gap.



$$^{57}\mathrm{Co} + e^- \longrightarrow {}^{57}\mathrm{Fe}^* + \nu_e$$

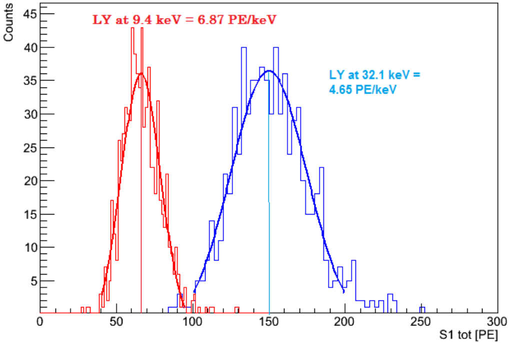
$$^{57}\mathrm{Fe}^* \longrightarrow {}^{57}\mathrm{Fe} + \gamma(122\,\mathrm{keV})$$

Calibration with ^{83}Kr source

The light yield of the detector was measured at two low energy gamma lines from ^{83}Kr source at zero field.

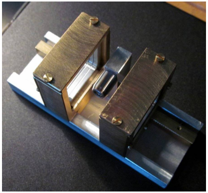
$$^{83}\mathrm{Rb} + e^{-} \longrightarrow {}^{83}\mathrm{Kr}^{*} + \nu_e$$

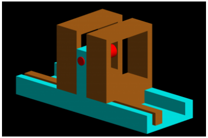
$$^{83}\mathrm{Kr}^{*} \longrightarrow {}^{83}\mathrm{Kr} + \gamma(9.4\,\mathrm{keV}) + \gamma(32.1\,\mathrm{keV})$$

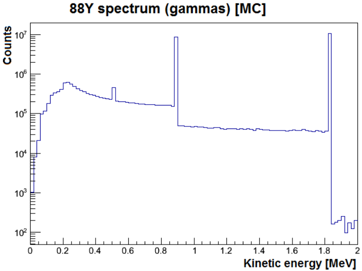


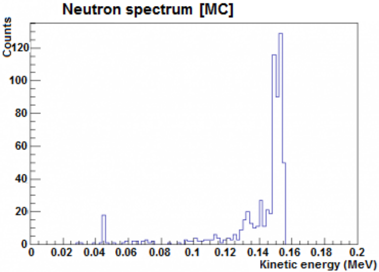
Using ^{88}Y^{9}Be to produce mono-energetic neutrons

- One can use (γ,n) reactions to produce low-energy mono-energetic neutrons.
- ^{9}Be has the lowest threshold (1.666 MeV) for these reactions.
- ^{88}Y has a gamma line at 1.836 MeV.
- 152 keV neutrons after scattering off xenon, will produce 10 keV nuclear recoils!









Conclusions and outlook

- Understanding of the low energy response of liquid xenon to nuclear recoils is crucial for xenon dark matter searches.
- Xurich TPC was designed and constructed to be used for nuclear recoil studies.
- Setup for measurements of the response of xenon to low energy nuclear recoils is proposed and individual sections of the setup including neutron generator, tagging detectors and pulse shape discriminator are characterized.
- The whole setup including the TPC, tagging detectors and neutron generator was modeled in GEANT4.
- Commissioning of the Xurich detector is ongoing and measurements will start soon.

THANKS FOR YOUR ATTENTION!