Measurements of liquid xenon's response to low-energy particle interactions

Payam Pakarha

Supervised by:

Prof. L. Baudis

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University of Zurich[UZH]

Outline

- There are evidences for the presence of dark matter in our universe consisting ∼25% of the total mass-energy of the universe.
- Among the possible DM candidates, we search for weakly interacting massive particles (WIMPs).
- There are 3 major categories of search strategies for DM:
  1. Collider searches
  2. Indirect searches
  3. Direct searches

LHC

AMS, ISS

XENON, LNGS

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Direct dark matter searches

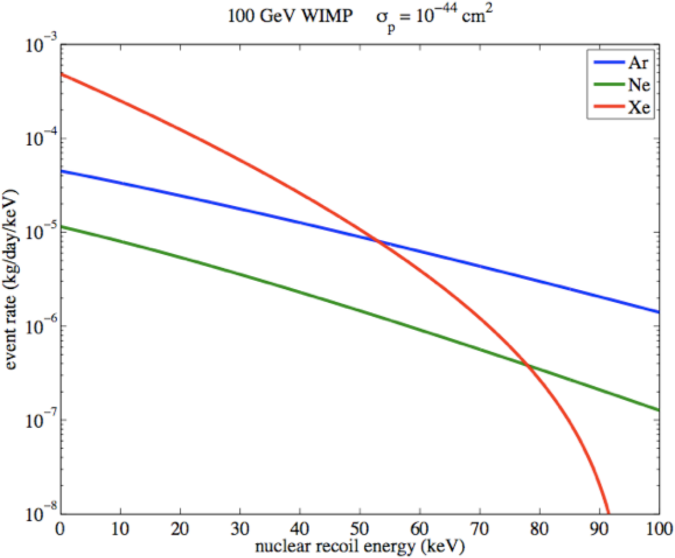
- The local dark matter distribution is determined based on many measurements (velocities of stars, rotation curve of the Milky Way and etc)[1].
  - $v_{rms} \simeq 270\,km/s$
  - $v_{esc} \simeq 650\,km/s$
  - $\rho \simeq 0.3\,GeV/c^2$
- So, how often a WIMP particle interact with a particular nucleus and what is the expected recoil energy imparted to the nucleus?

[1] **Anne M. Green; physics.Rev.Lett A; Vol.27 N.3; DOI:10.1142; (2012)**.

- Elastic scattering is (probably) the dominant interaction mechanism given the low velocity and subsequent momentum transfer.
- Spin-independent cross section is

$$\sigma_0 \propto A^2 \sigma_{\chi - p}$$

  where $\sigma_{\chi - p}$ is the WIMP-proton cross-section which is probed to be at below the limit of $\sim 10^{-44}\mathrm{cm}^2$ and A is the atomic mass.
- The expected signal rate is in the order of 1 events/kg/year for $m_\chi \simeq 100\,\mathrm{GeV}$.
- The main background in the energy of interest for WIMP detection are electromagnetic electron-recoils from gamma particles.



The differential nuclear recoil spectrum of a 100 GeV WIMP with 3 different nuclei.

Imagine if I tell you there are invisible people living in our planet just like us while not interacting with ordinary people in anyway! How would you try to find them?

Our suggestion: Construct a "pool" and wait whether they dive into it!

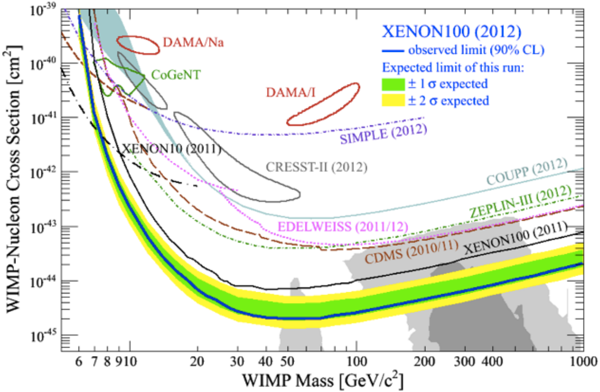
Which sets of characteristics does our “pool” require in order to detect “invisibles” (Dark Matter)?

- Water surface not disturbed $\longrightarrow$ Low background $\longrightarrow$ underground
- “Invisibles” like it! $\longrightarrow$ high cross section $\longrightarrow$ high A material (for higher mass WIMPs)

Xenon as the subject material:

1. High A $\longrightarrow$ high cross section
2. High Z $\longrightarrow$ self-shielding $\longrightarrow$ low background
3. No long-lived radioactive isotopes.

- Different experiments have tried to follow the direct search strategy [2].

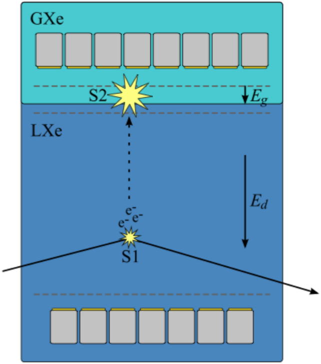


Spin-independent WIMP-nucleon scattering cross section versus WIMP mass covered by different experiments by June 2012.

[2] **E. Aprile et al; PRL 109; 181301; (2012)**.

How would we "see" the WIMPs?

- A WIMP-nucleus elastic scattering in the liquid xenon results a nuclear recoil.
- Exited atoms will de-excite producing scintillation photons (S1).
- Electrons from ionized atoms are drifted by a drift-voltage in the chamber through the gas phase where proportional scintillation signal (S2) is produced.



Schematics of a WIMP signal in a dual-phase Xenon TPC (time projection chamber).

E. Aprile, T. Doke ;Phys.Rev. 20532097; (2010)

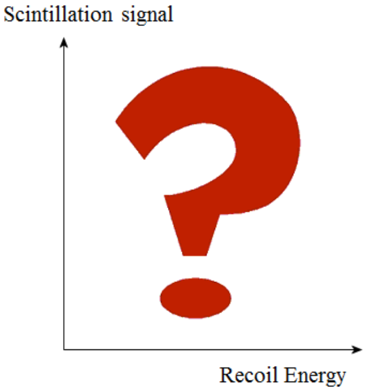
XENON100 experiment uses 62 kg of LXe in a dual phase TPC. A voltage is applied to allow drifting electrons and ions. A PMT array is used both on the top and the bottom of the TPC for signal readout of scintillation photons (178 nm).

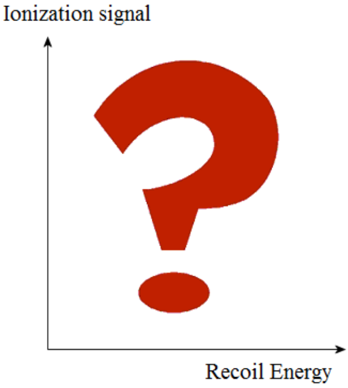
Image of the XENON100 TPC

In order to get prepared for observing WIMPs in our detector, the expected signal should be studied in advance.

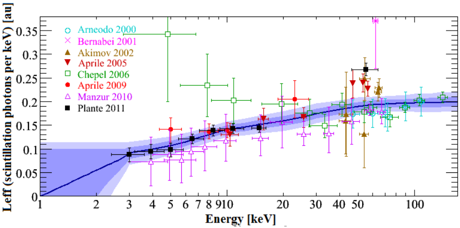
Same to say what would you see if the “subject” falls into your pool?

Particularly, we would like to have the following information about our signal.

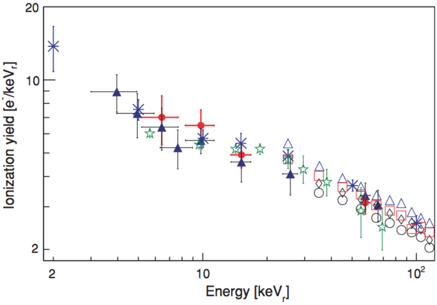




- $\mathcal{L}_{eff}$: Relative scintillation yield efficiency
- Q_y: Absolute ionization yield efficiency



Results of $\mathcal{L}_{eff}$ measurements.



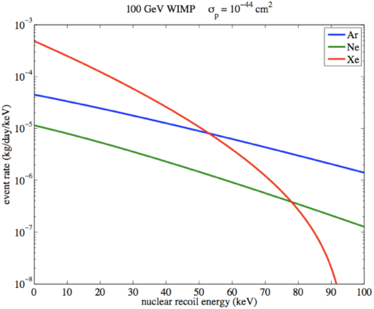
Results of Q_y measurements.

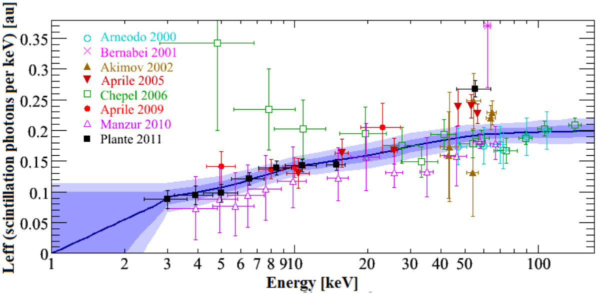
E. Aprile et al; Phys. Rev. Lett.107,131302; (2011)
A. Manzur et al; Phys. Rev. C 81 025808; (2010)

Neutrons playing the roll of WIMPs

- WIMPs will produce nuclear recoils in the target
- UZH has no WIMP generator facility!
- Neutrons will also produce nuclear recoils.
- $\Longrightarrow$ We can use neutrons to study the expected signal from WIMPs.

- The low energy section: The most promising and the least studied!!





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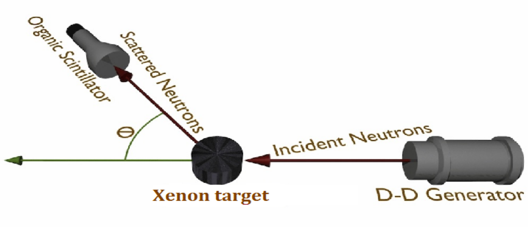
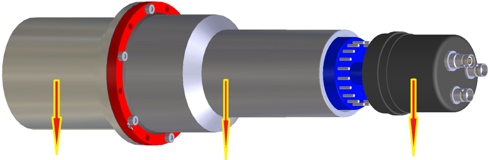
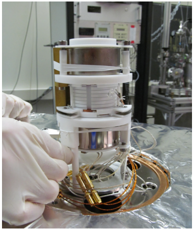
Schematics of our setup.

$$E_r \simeq \frac{2E_n A}{(1+A)^2}(1 - cos\theta)$$



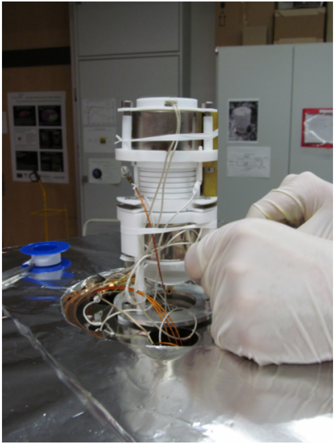




D.N. McKinsey et al; Phys.Rev. C78 035801; (2008)

Xurich-2: A small LXe TPC

- The detector is designed as a small dual-phase TPC. It is thoroughly optimized for charge readout and will be sensitive to ionization signals as small as single electrons. It is also designed to minimize the amount of non-active detector components (i.e. PTFE, non-active LXe).
- The detector is under construction and will be ready soon.



Xurich-2 detector image.

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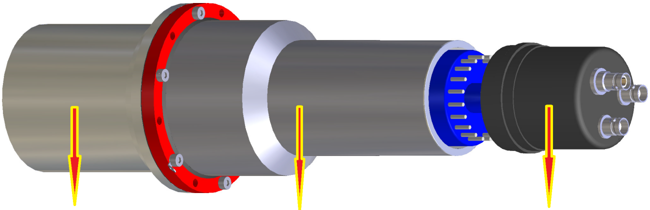
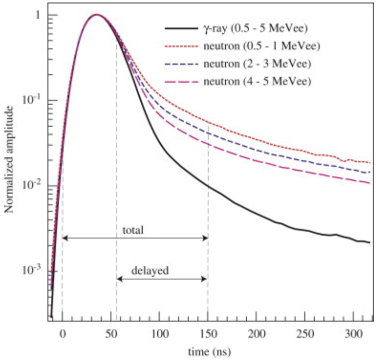
EJ301 liquid scintillator



- Scintillation material: $C_6H_4(CH_3)_2$ called commercially NE213, BC501-A, and EJ301.
- Capable (and optimized) to distinguish neutrons from gammas using pulse shape discrimination (PSD).

How to distinguish neutrons (signal) from gammas (BG).

$\Longrightarrow$ The pulse shape differs from nuclear to electron recoils allowing for a pulse shape discrimination (PSD).



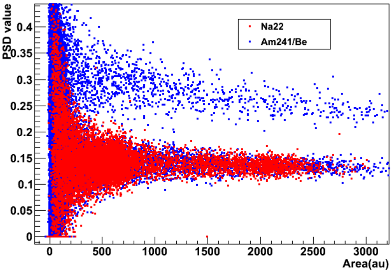
Example of a signal shape for nuclear and electron recoils.

Another discrimination method.

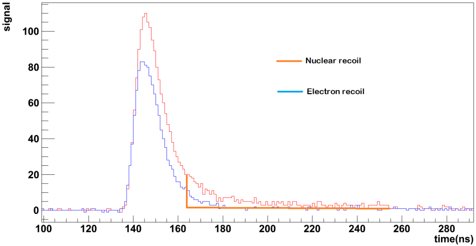
C.Guerrero et al; DOI:10,1016; (2008)

- The excited molecules are produced in both singlet and triplet states.
- Singlet states decay in ns scales while triplet states in the order of microseconds.
- Bi-molecular interactions convert triplet states into singlet states (causing a tail in the signal shape).
- The rate of these reactions depends on the density of triplet states.
- Nuclear recoils caused by heavy particles produce a different density of triplet states compared to electron recoils caused by gamma and X-ray photons.

- Example of PSD with EJ301 using tail over total area of the pulse as the discrimination parameter.



PSD versus area plot of AmBe (blue) and Na22 (red) sources. The nuclear recoils from neutrons from AmBe produce signals with higher PSD values.



Example raw waveform of a nuclear and a electron recoil (AmBe waveform).

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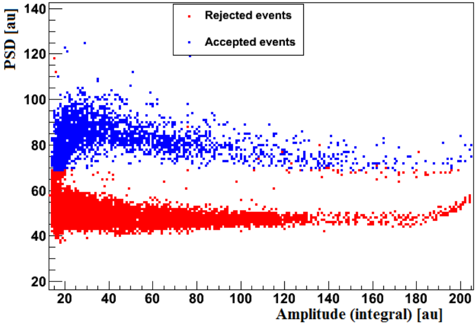
A useful device! MPD-4 PSD module

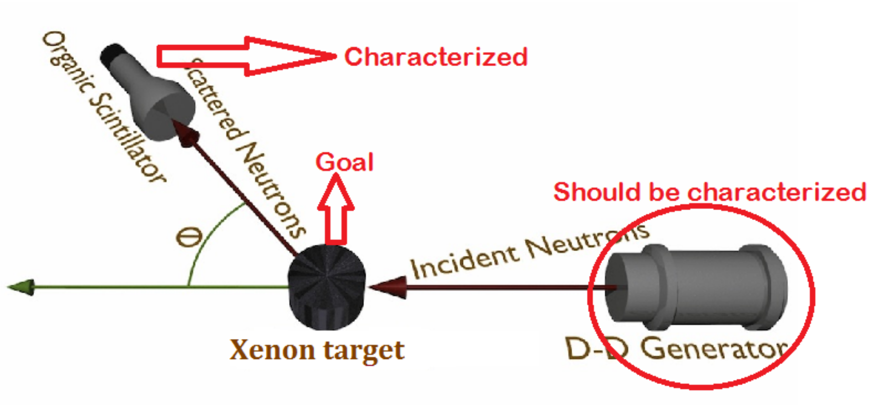
- Example of PSD plot using MPD-4 module.



Example of a discrimination plot using MPD-4 module's PSD and Ampl outputs.

Neutron generator

The energy distribution of the incident neutron beam plays a very important role in the results.



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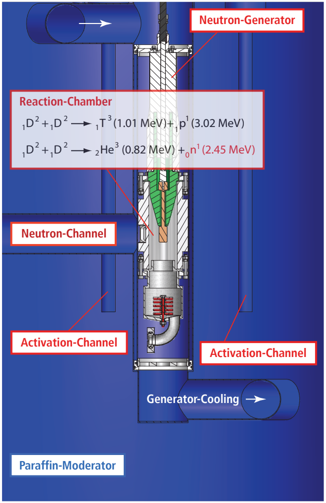
- D-D neutron generator at University of Zurich is used for the measurements.
- Uses a high electric field to hit deuterium gas atoms with deuterium.
- Shielded in 3 layers

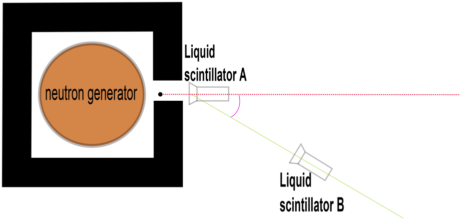
  Paraffin $\longrightarrow$ Slows down high-energetic neutrons.
  Boron doped polyethylene $\longrightarrow$ Captures neutrons.
  Concrete $\longrightarrow$ Absorbs gammas (and slows neutrons).



- We used the following setup to measure the time of flight (TOF) of neutrons between two EJ301 scintillators and reconstruct the initial energy of the neutrons from kinematics.

How we reconstruct the neutron energy :

1. Use the MPD-4 module plus liquid scintillators to tag neutrons.
2. Measure the TOF of neutrons using TOF module (needs calibration).
3. Use the kinematics to convert the TOF into energy.



Schematics of neutron measurements technical setup.

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

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

where A is the atomic mass, M_N and m_n nucleus and neutron mass respectively, θ the angle of second detector with respect to the beam line, E_r and E_n energy of the recoil and the incoming particle respectively. And finally,

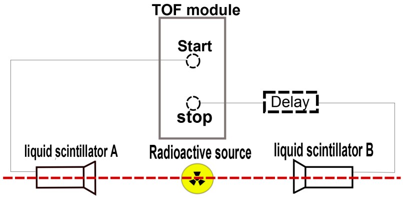
$$E_f[eV] = E_n - E_r = \frac{1}{2}m_n[eV]\left(\frac{v}{c}\right)^2 \qquad (2)$$

where E_f is the energy of the neutrons after scattering and v is their speed.

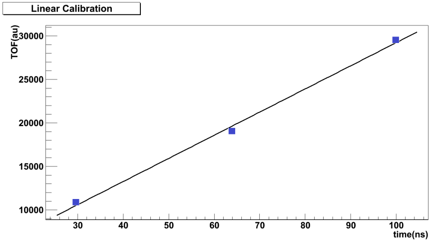
- The (raw) TOF signal output from the module needs to be calibrated into appropriate units.
- We used the second interaction with a $^{22}\mathrm{Na}$ source to produce coincidences in two detectors. An artificial offset delay is applied with a few values in the range of interest.

$$^{22}\mathrm{Na} \longrightarrow {}^{22}\mathrm{Ne}^{*}\,(1275\ \mathrm{keV}) + \mathrm{e}^{+} + \nu \tag{3}$$

$$\mathrm{e}^{+} + \mathrm{e}^{-} \longrightarrow 2\,\gamma\,(511\ \mathrm{keV}) \tag{4}$$



Schematics setup for TOF calibration.



Calibration results.

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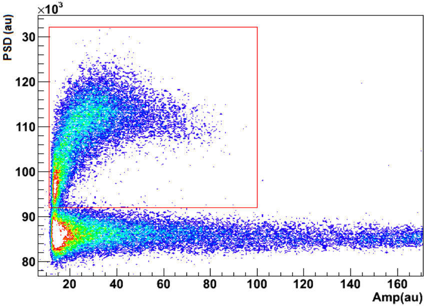
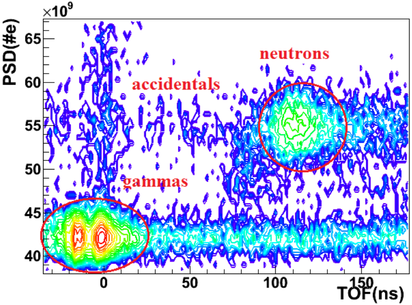
- PSD plots are used to select neutrons from background gammas.



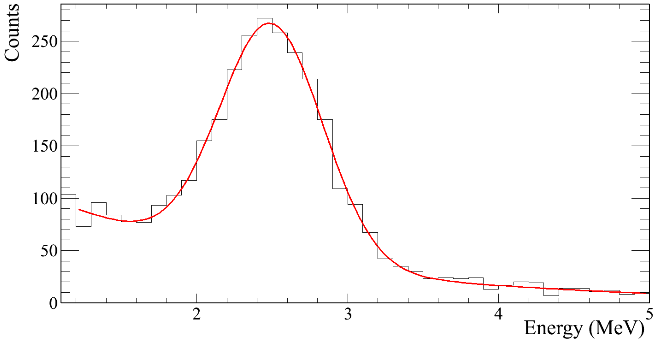
PSD versus Amp of events. Neutrons (high PSD values) are selected in the box.



PSD versus TOF plot of events.

That moment when you reach what you were looking for after a while!

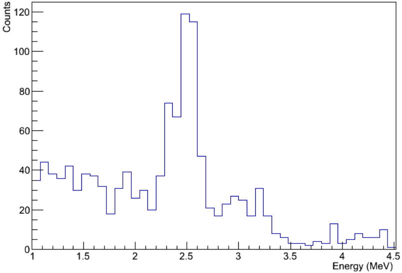
Finally, one can determine the TOF spectrum for neutrons and convert it to the spectrum of their initial energy.



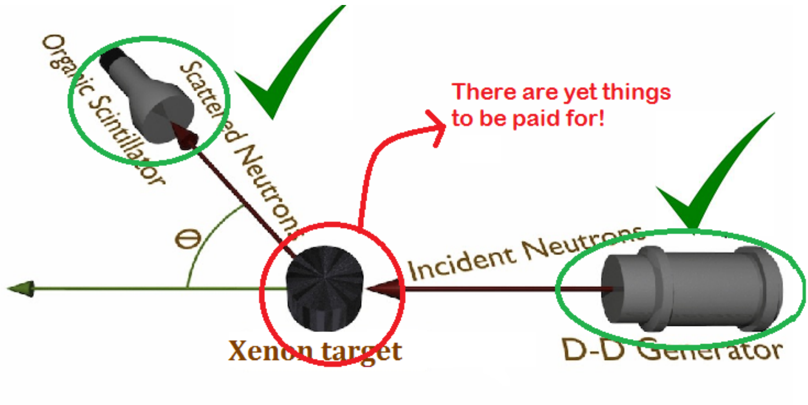
Reconstructed energy distribution of incident neutrons generated by the NG from their TOF.

What to do right after the conference?

- In order to enhance the analysis, we are working on GEANT4 simulations of the setup.
- For example, generating and ideally mono-energetic beam of neutrons results in a spread in the energy caused by geometrical uncertainties.
- Also the energy spread due to other factors like energy loss of neutrons inside the generator is still to be done.



Energy distribution of simulated neutrons.



Organic Scintillator
Scattered Neutrons
There are yet things
to be paid for!
Θ
Incident Neutrons
Xenon target
D-D Generator

Summary

- The setup for studying low energy response of liquid xenon is motivated and explained.
- The work done for preparations of these measurement at UZH is described including characterization of individual devices.
- Preliminary results of the neutron energy distribution measurements is shown together with early results of simulations.
- The status of the work plus the plans to continue are presented.

interactions inside LXe

The following sets of interactions will be possible as the response to a projectile.

$$\mathrm{Xe}^{+} + \mathrm{Xe} \longrightarrow \mathrm{Xe}_2^{+} \quad (\textit{dimer formation}) \tag{5}$$

$$\mathrm{Xe}_2^{+} + \mathrm{e}^{-} \longrightarrow \mathrm{Xe}^{**} + \mathrm{Xe} \quad (\textit{electron recombination}) \tag{6}$$

$$\mathrm{Xe}^{**} \longrightarrow \mathrm{Xe}^{*} + \mathrm{heat} \tag{7}$$

$$ceXe^{*} + Xe \longrightarrow \mathrm{Xe}_2^{*} \tag{8}$$

$$\mathrm{Xe}_2^{*} \longrightarrow 2\,\mathrm{Xe} + \mathrm{scintillation} \tag{9}$$

$$\mathrm{Xe}^{*} + \mathrm{Xe}^{*} \longrightarrow \mathrm{Xe} + \mathrm{Xe}^{+} = \mathrm{e}^{-} \quad (\textit{quenching}) \tag{10}$$

Where the last process is common for the regions of high excitation density.

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processes of the mentioned radioactive sources in the presentation

AmBe:

$$ {}^{241}_{95}\mathrm{Am} \longrightarrow {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\alpha + \gamma \tag{11} $$

$$ {}^{4}_{2}\alpha + {}^{4}_{9}\mathrm{Be} \longrightarrow \mathrm{n} + {}^{6}_{12}\mathrm{C} + \gamma \tag{12} $$

Na22:

$$ {}^{22}\mathrm{Na} \longrightarrow {}^{22}\mathrm{Ne}^{*}\,(1\ \cdot 275\ \mathrm{MeV}) + \mathrm{e}^{+} + \nu \tag{13} $$

$$ {}^{22}\mathrm{Ne}^{*} \longrightarrow {}^{22}\mathrm{Ne}_{\mathrm{g.s}} + \gamma \tag{14} $$

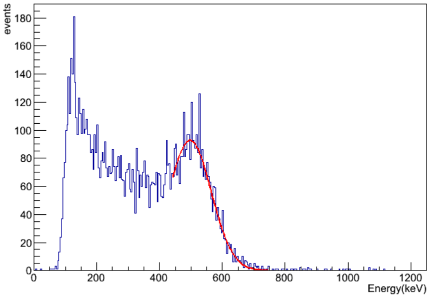
$$ \mathrm{e}^{+} + \mathrm{e}^{-} \longrightarrow 2\,\gamma \tag{15} $$

- Example of recoil energy calibration with a radioactive source.

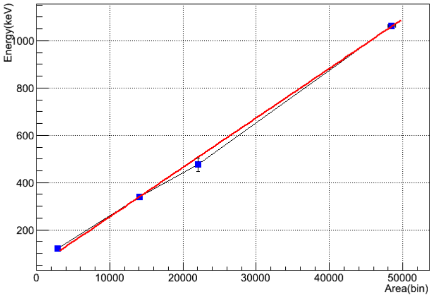
$$^{137}\mathrm{Cs} \longrightarrow {}^{137}\mathrm{Ba}^{*}\,(662\ \mathrm{keV}) + \mathrm{e}^{-}$$

$$^{137}\mathrm{Ba}^{*} \longrightarrow {}^{137}\mathrm{Ba} + \gamma$$

$$E_{edge} = \frac{2E^2}{m_e c^2 + 2E}$$



Fitted Compton edge of a Cs137 source



Calibration result points.