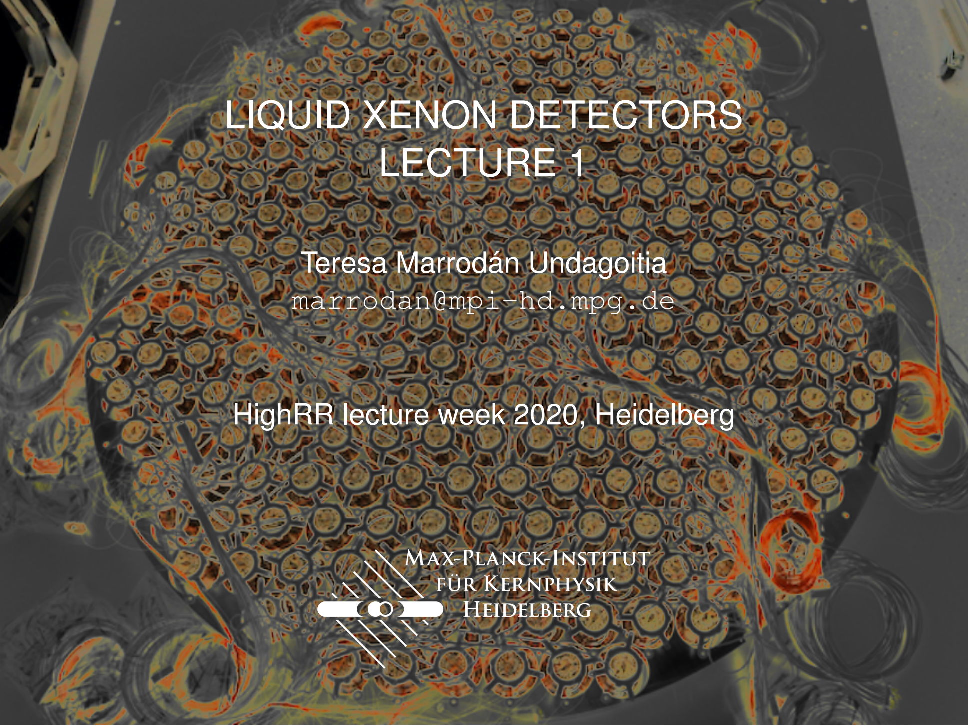

LIQUID XENON DETECTORS
LECTURE 1

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HighRR lecture week 2020, Heidelberg

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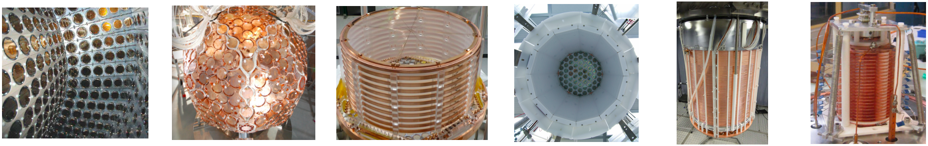
Heidelberg

Physics questions

- Direct search for dark matter via elastic scattering
- Measurement of coherent neutrino-nucleus scattering
- Measurement of supernova and solar neutrinos
- Solar axion searches
- Search for neutrinoless double-beta decay
- Particle physics calorimeter
- Applications in medical physics



Lecture structure

- LECTURE 1:
  - General xenon characteristics
  - Scintillation & ionization processes

- LECTURE 2:
  - Xenon purity & radiopurity
  - Signal yields, resolution and calibration strategies
  - Photon detection

- LECTURE 3:
  - Low energy searches: dark matter & CEνNS
  - Search for neutrinoless double-beta decay
  - Xenon calorimeters and medical applications

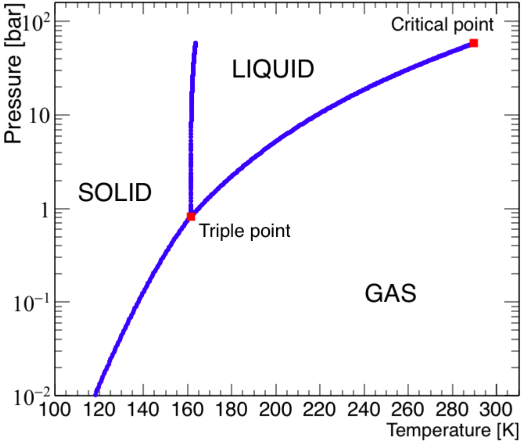
Image from *'Xenon, xenon everywhere'*, Symmetry magazine

Main xenon isotopes

Isotope	Abundance	Decay mode and half-life
^{124}Xe	0.09 %	double-electron capture, 1.8×10^{22} y
^{125}Xe	synthetic	electron capture, 16.9 h
^{126}Xe	0.09 %	stable *
^{127}Xe	synthetic	electron capture, 36.35 d
^{128}Xe	1.92 %	stable
^{129}Xe	26.44 %	stable
^{130}Xe	4.08 %	stable
^{131}Xe	21.18 %	stable
^{132}Xe	26.89 %	stable
^{133}Xe	synthetic	beta decay β^-, 5.25 h
^{134}Xe	10.44 %	stable *
^{135}Xe	synthetic	beta decay β^-, 9.14 h
^{136}Xe	8.86 %	double-beta decay, 2.23×10^{21} y

*Candidate for double-beta decay

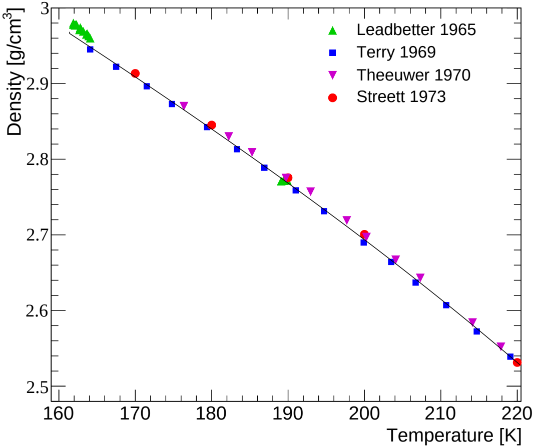
Liquid xenon as detector



Data from the online Air Liquide encyclopedia

- Xenon is liquid above its triple point at 161.4 K and 0.817 bar
- Typically it is operated at $\sim$ 2 bar and -100°C **Q**
- High density in the liquid phase: 2.85 g/cm^3

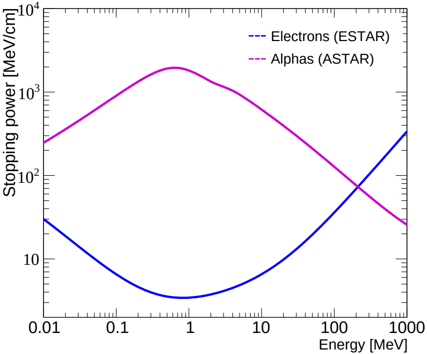
Liquid xenon density

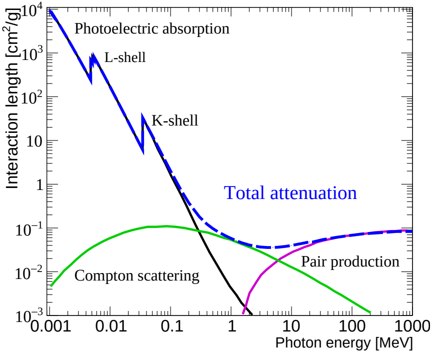


Data from various experiments & black curve from the online Air Liquide encyclopedia

- Typical operating temperature between 170 and 180 K
- Corresponds to a density of $\sim$ 2.85 g/cm^3

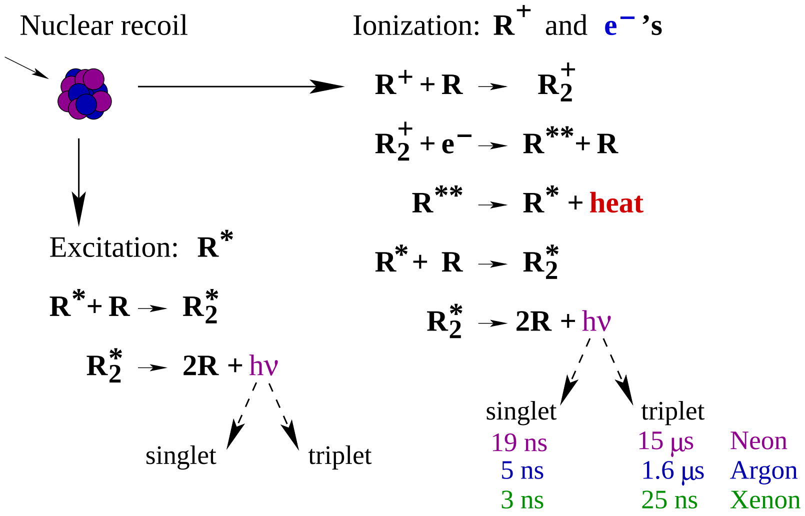
Particle interactions





- Alpha decays from natural radioactivity with energies of $(5-8)$ MeV $\rightarrow \mathcal{O}(\mu\mathrm{m})$ range
- MeV electrons reach $\mathcal{O}$(cm) ranges

Noble gas scintillation process



Nuclear recoil

Ionization: $\mathbf{R^+}$ and $\mathbf{e^-}$’s

$$\mathbf{R^+ + R \rightarrow R_2^+}$$

$$\mathbf{R_2^+ + e^- \rightarrow R^{**} + R}$$

$$\mathbf{R^{**} \rightarrow R^* + heat}$$

$$\mathbf{R^* + R \rightarrow R_2^*}$$

$$\mathbf{R_2^* \rightarrow 2R} + h\nu$$

singlet	triplet	
19 ns	15 µs	Neon
5 ns	1.6 µs	Argon
3 ns	25 ns	Xenon

Excitation: $\mathbf{R^*}$

$$\mathbf{R^* + R \rightarrow R_2^*}$$

$$\mathbf{R_2^* \rightarrow 2R} + h\nu$$

singlet triplet

Noble gas scintillation process

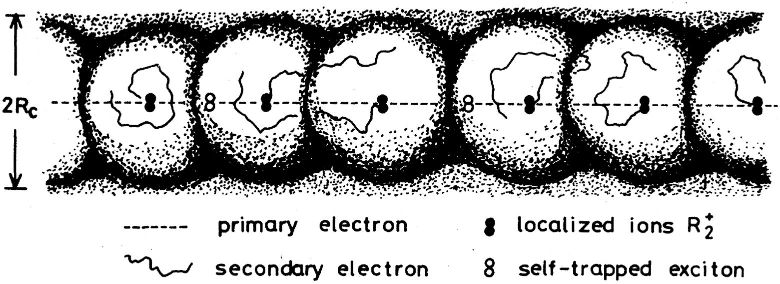
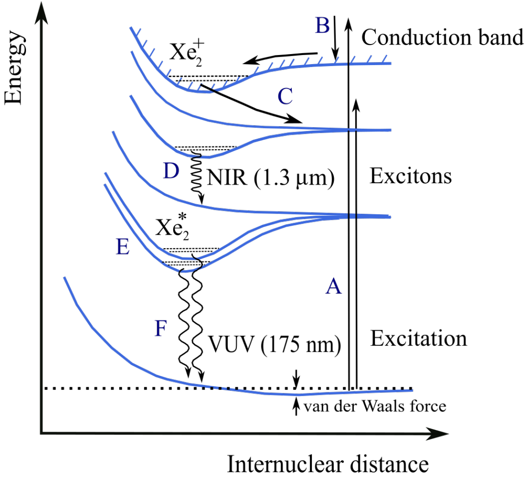


Figure from Kubota et al. PRD 20 (1979) 8

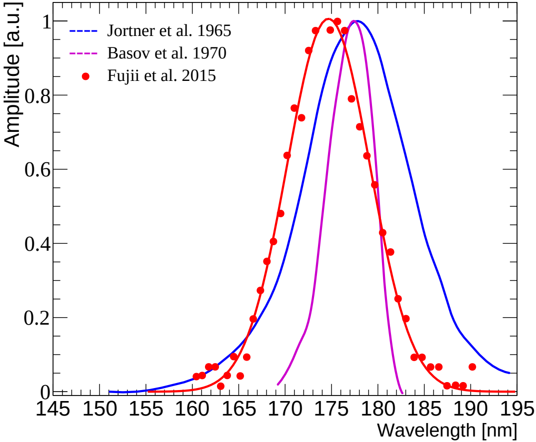
- Ionized electrons diffuse in the presence of the R_2^+ Coulomb attraction
  - Some trapped in the spheres of Coulomb attraction of their parent ions
  - Some trapped in the spheres of attraction of other ions
  - Some escape from the Coulomb attraction

Scintillation process



- Xenon is repulsive in the ground state
- Weak van der Waals force (-0.024 eV at 4.4 Å)
- Dimers Xe_2^* are responsible for the scintillation light

Scintillation spectrum



- Xenon scintillation at $(174.8 \pm 0.1(stat.) \pm 0.1(syst.))$ (Fujii 2015)
- UV regime → but possible to detected directly
- Lower wavelengths for argon (125 nm) or neon (78 nm) detectors

Decay time constants

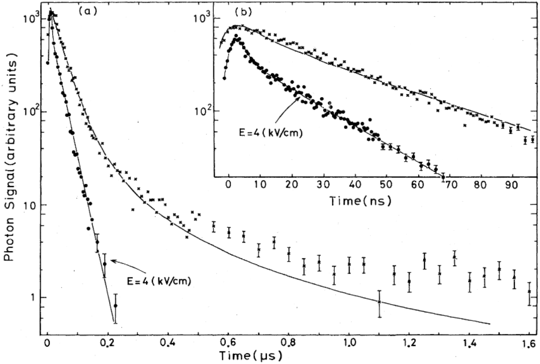
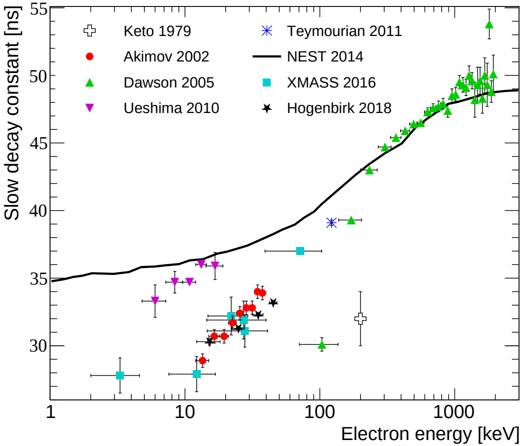


Figure from S. Kubota et al., Phys. Rev. B 20 (1979) 3486.

$$F(t) = \frac{f_s}{\tau_s} \exp\left(\frac{-t}{\tau_s}\right) + \frac{f_t}{\tau_t} \exp\left(\frac{-t}{\tau_t}\right) \qquad (1)$$

- Amplitudes of singlet and triplet are dE/dx dependent and also electric field dependent

Role of recombination



- Longer τ_t for increasing particle energy
- The higher the energy the higher dE/dx → recombination
- Recombination time is absorbed in the slow fluorescence constant

Pulse shape discrimination for particle identification

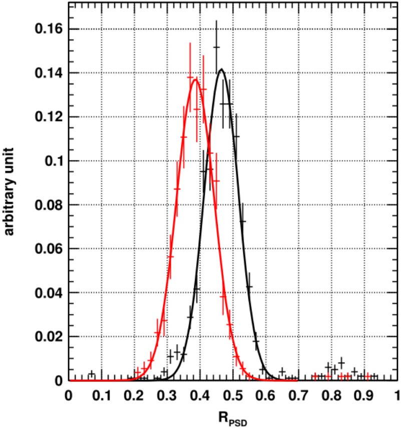


Figure from XMASS data, NIM. A659 (2011) 161

- Separation of electronic recoils (from ^{137}Cs) from **nuclear recoils** (from ^{252}Cf)

- PSD not very powerful in LXe: similar decay constants of about 3 and 30 ns

- Note: very different singlet and triplet lifetimes in argon & neon

  → better PSD achieved

Light propagation

Total attenuation length, λ_{att}:

$$\frac{1}{\lambda_{att}} = \frac{1}{\lambda_{abs}} + \frac{1}{\lambda_{scat}} \tag{2}$$

- λ_{abs}: absorption length including both absorption by impurities and absorption at the detector surfaces
- λ_{scat} is the scattering length

The light intensity after a distance r:

$$I(r) = I_0 \cdot \exp^{-(r/\lambda_{att})} \tag{3}$$

with I_0 being the initial light intensity.

Summary of optical properties

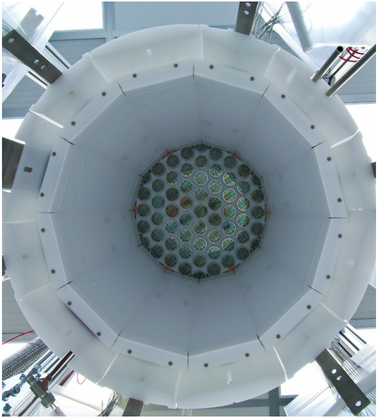
Optical property	Values [unit]
Absorption length	> 100 [cm]
Scattering length	30, 35 [cm] (calculated)
Attenuation length	29, 36, 40, 50 [cm]
Refractive index	1.69

- The short attenuation length affects the light propagation for large detectors

  → timing information is lost

- For double phase detectors, total reflection of photons at the liquid gas interphase occurs

PTFE: reflectivity

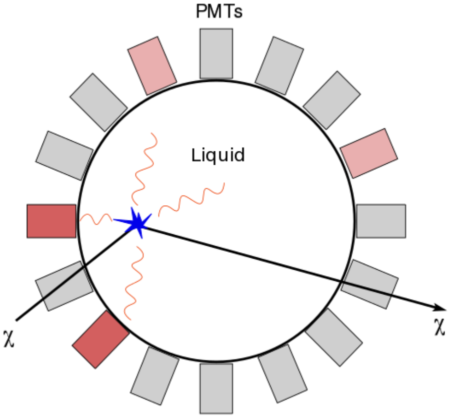


View inside the LUX TPC

- Large amounts of PTFE (teflon) are used as reflectors for UV photons
- Reflectivity estimated to be at 99% – 100% (in LXe)

  (Note that teflon reflectivity is significantly lower in vacuum or in argon gas)
- PTFE disadvantages:
  - Outgassing of impurities
  - Contribution to neutron background
  - Thin teflon required **Q**
    → UV teflon transmission relevant
    Cichon et al., JINST 15 (2020) 09, P09010

Single phase (liquid) detectors



- High light yield using 4π photosensor coverage
- Position resolution in the cm range
- Pulse shape discrimination (PSD) from scintillation

Single phase: XMASS experiment

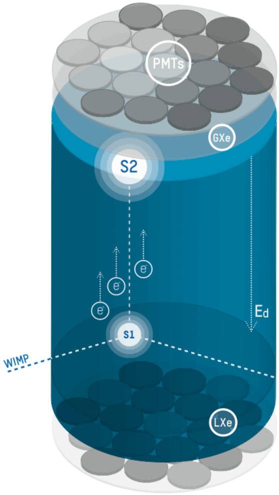

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

XMASS – LXe multipurpose detector at Kamioka (Japan)

- 1 ton total LXe mass & 800 kg FV
- High light yield measured: 14.7 PE/keVee, $E_{th} = 0.3\,\text{keV}_{ee}$
- PMTs directly in contact with the LXe target

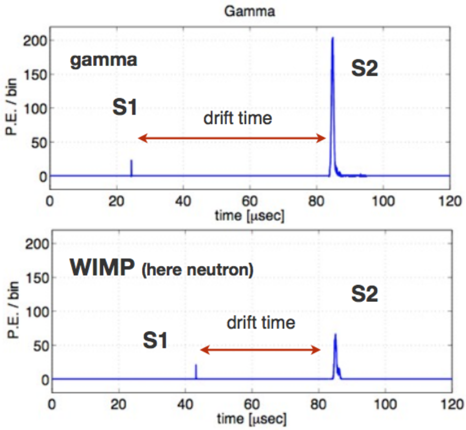
  → radioactive contamination on the PMT-window sealing reduced the physics potential of the experiment

Two phase noble-gas TPC



- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)

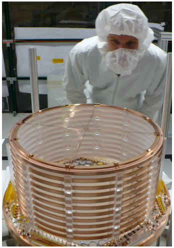
→ Electron- /nuclear recoil discrimination



Position resolution to define the innermost radiopure volume for analysis

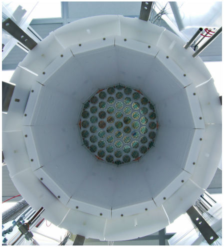
PMTs at top and bottom **Q**

Liquid xenon TPCs



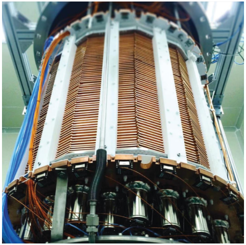
EXO-200

- 75 kg LXe fiducial mass (170 kg total)
- Search for $0\nu\beta\beta$



LUX

- 100 kg LXe fiducial mass (370 kg total)
- Dark matter



PANDAX-II

- 580 kg LXe fiducial mass (1.2 t total)
- Dark matter

XENON1T

- 1.3 t LXe fiducial mass (3.2 t total)
- Dark matter

Ionization process

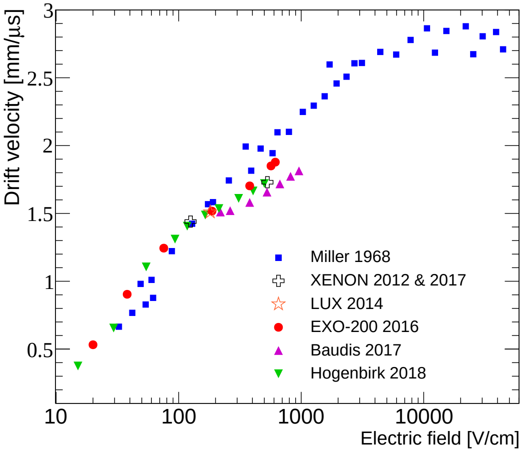
- Primary ionizations $N_i \gg N_{ex}$ number of excitations for electronic recoils and comparable $N_i \approx N_{ex}$ for nuclear recoils

  $\rightarrow$ Charge/light production are dE/dx dependent

$$E_t = N_i \cdot \overline{E}_i + N_{ex} \cdot \overline{E}_{ex} + N_i \cdot \overline{\epsilon} \tag{4}$$

  - E_t: total energy deposited
  - E_i & E_{ex}: average energy to ionize or excite an atom
  - N_i & N_{ex}: average number of ionized or excited atoms
  - $\overline{\epsilon}$: mean energy of sub-excitation electrons (only heating the medium)

Electron transport: drift



- Important to reconstruct the *z*-spatial coordinate
- High E drift-field → high drift velocity → less e^- diffusion
- Drifting e^- can be attached to electronegative impurities

Electron transport: diffusion

- Diffusion increases the relative distance between the electrons in the drifting cloud
- Some effect on position reconstruction
- Impact on the separation of charge pulses on the rejection of multiple scatters

Spread σ of the electron cloud can be expressed:

$$\sigma^2 = 2 \cdot D_T \cdot t_d \tag{5}$$

- $D_T = 55 \pm 4\,\mathrm{cm}^2/\mathrm{s}$ [EXO-200 measurement] transverse diffusion coefficient
- t_d the electron drift time

- The diffusion coefficient in the field direction is $D_L = D_T/10$

Diffusion: S2 width

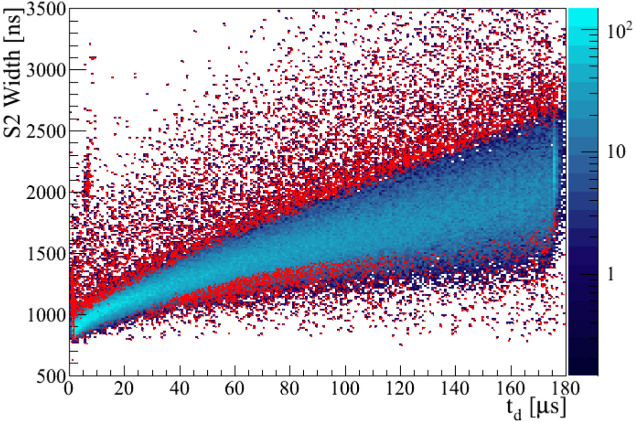


Figure from XENON100, Astropart. Phys. 54 (2014) 11

- The width of the charge pulses (S2) increases due to diffusion
- XENON100: 180 μs drift time corresponding to 30 cm distance with a drift field of 530 V/cm

Diffusion: S2 width

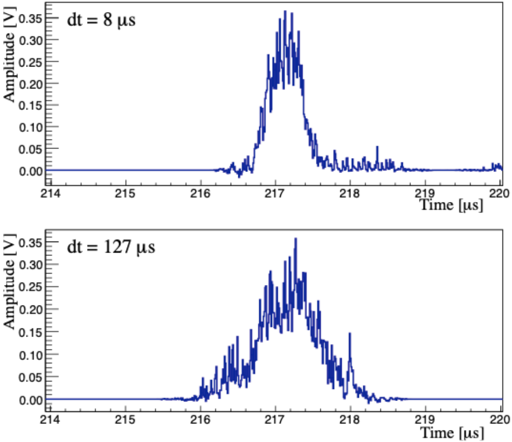
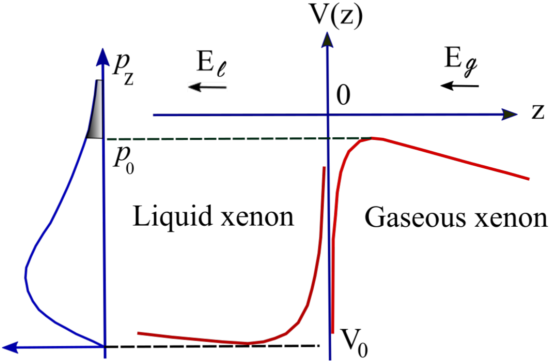


Figure from XENON100, Astropart. Phys. 54 (2014) 11

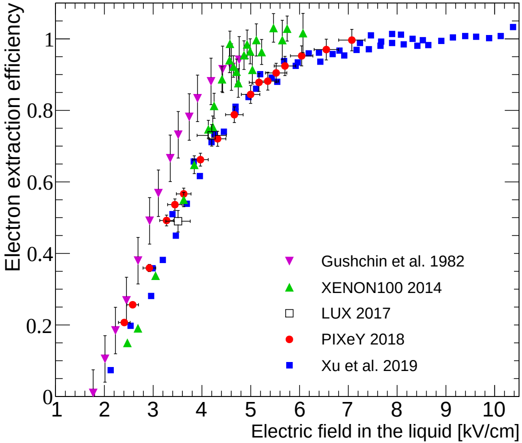
- The width of the charge pulses (S2) increases due to diffusion
- XENON100: 180 μs drift time corresponding to 30 cm distance with a drift field of 530 V/cm

Electron extraction



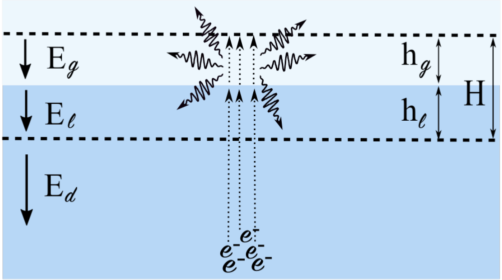
- Potential barrier in xenon: $(0.65 - 0.85)\,\text{eV}$
- Electrons need to be heated up to overcome the barrier
- A strong 'extraction field' is applied $E_\ell \gtrsim 7.5\,\text{kV/cm}$

Electron extraction efficiency



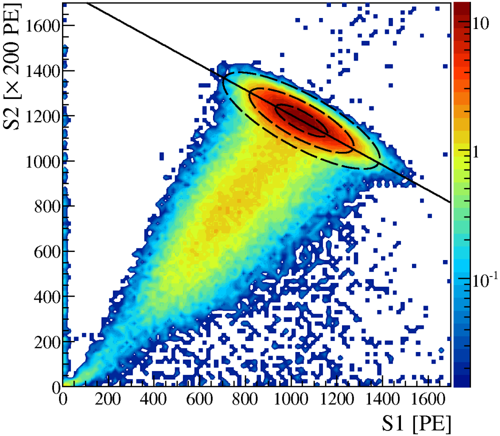
- Threshold effect at about 2 kV/cm
- Plateau observed above $\sim$ 7.5 kV/cm → complete extraction

Proportional scintillation



- Field in the gas phase $E_g = \frac{\epsilon_\ell \cdot \Delta V}{h_g \cdot (\epsilon_\ell - 1) + H}$ with $\epsilon_\ell = 1.95$
- Yield $Y = \left(a \cdot \frac{E_g}{P_g} + b \right) \cdot h_g \cdot P_g$
  - Important to keep the liquid level stable over the whole surface! **Q**
- Amplification: typically $20 - 30$ PE per electron extracted

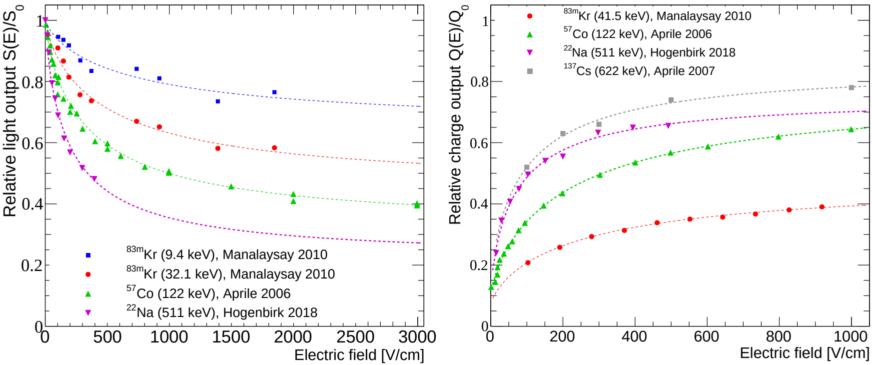
Anti-correlation of light and charge signals



^{137}Cs calibration in the XENON100 detector, Astropart. Phys. 35 (2012) 573 & arXiv:1107.2155.

- Signal fluctuations at the interaction point
  → anti-correlation of light and charge

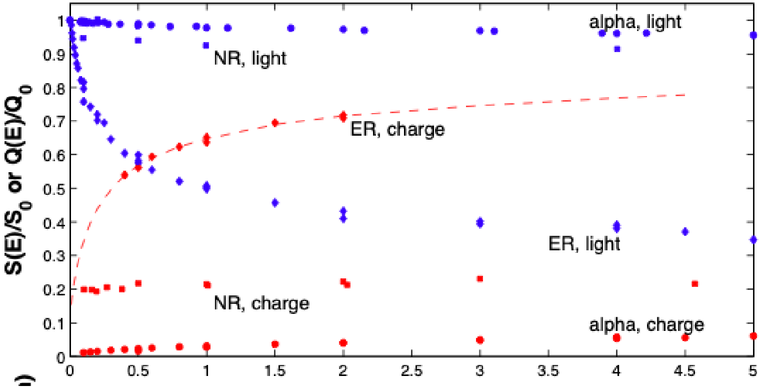
Anti-correlation of signals: field dependence



- Light yield decreases with increasing electric field
- Charge can be extracted more effectively for higher fields

→ variation energy dependent → dE/dx dependent

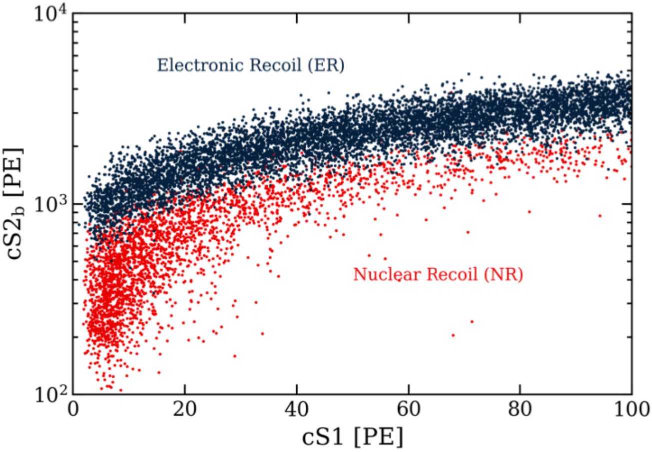
Field quenching for other particles



E. Aprile et al., Phys. Rev. Lett. 97 (2006) 081302 & arXiv:0601552

- Very low field quenching for α-particles and nuclear recoils

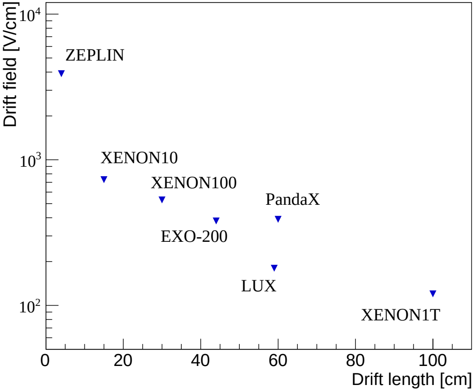
Particle identification based on S1 & S2



Calibration data from the XENON1T detector

- ER: calibrated using a ^{220}Rn source (β-decays of ^{212}Pb)
- NR: calibrated using a neutron generator / AmBe-neutron source

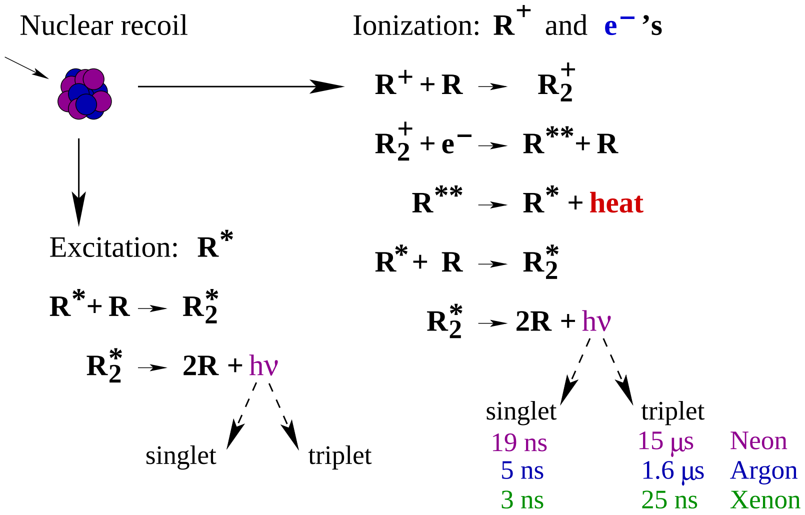
High voltage



- Large potentials have to be applied to the cathode
- Actually, only voltages up to 15 – 20 kV could be applied

Q

Summary



Nuclear recoil

Excitation: $\mathbf{R}^*$

$\mathbf{R}^* + \mathbf{R} \rightarrow \mathbf{R}_2^*$

$\mathbf{R}_2^* \rightarrow \mathbf{2R} + h\nu$

singlet triplet

Ionization: $\mathbf{R}^+$ and $\mathbf{e}^-$'s

$\mathbf{R}^+ + \mathbf{R} \rightarrow \mathbf{R}_2^+$

$\mathbf{R}_2^+ + \mathbf{e}^- \rightarrow \mathbf{R}^{**} + \mathbf{R}$

$\mathbf{R}^{**} \rightarrow \mathbf{R}^* +$ **heat**

$\mathbf{R}^* + \mathbf{R} \rightarrow \mathbf{R}_2^*$

$\mathbf{R}_2^* \rightarrow \mathbf{2R} + h\nu$

singlet	triplet	
19 ns	15 µs	Neon
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