Krypton Removal for the XENON Dark Matter Project

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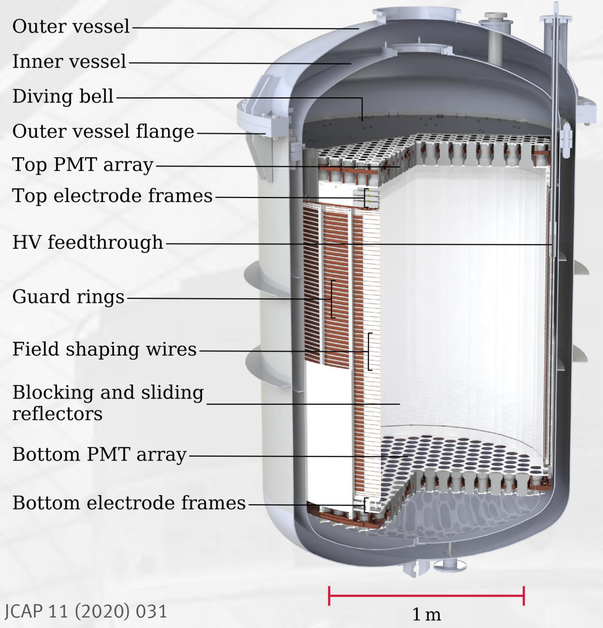
XENON dark matter project

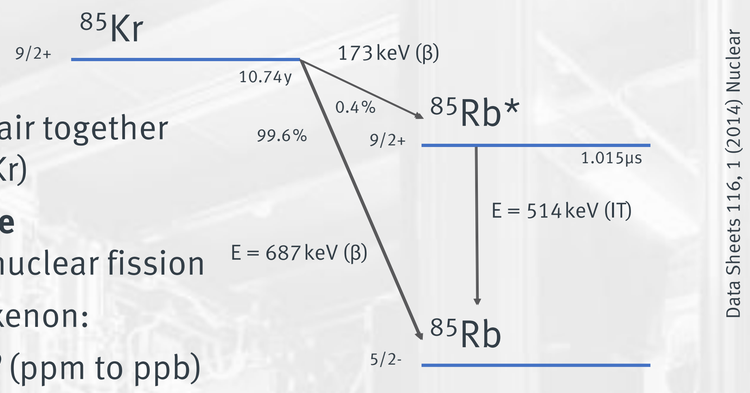
- WIMP search via **direct detection** of recoils in liquid xenon (LXe)
- Dual-phase LXe time projection chamber (TPC) located at LNGS in Italy
- Currently: **XENONnT** with 5.9 t of active LXe mass and total xenon mass of 8.6 t



JCAP 11 (2020) 031

- 494 PMTs monitor XENONnT TPC with diameter of 1.33 m and 1.49 m height
- **Nuclear recoil** (NR) and **electronic recoil** (ER) identified via ratio of light and charge signals
- Intrinsic background contributions from ^{222}Rn, ^{85}Kr, radioactive xenon isotopes
- Low background: In Science Run 0 **(15.8 ± 1.3) events/(t · y · keV)** in ER rate reached below 30 keV recoil energy

^{85}Kr background



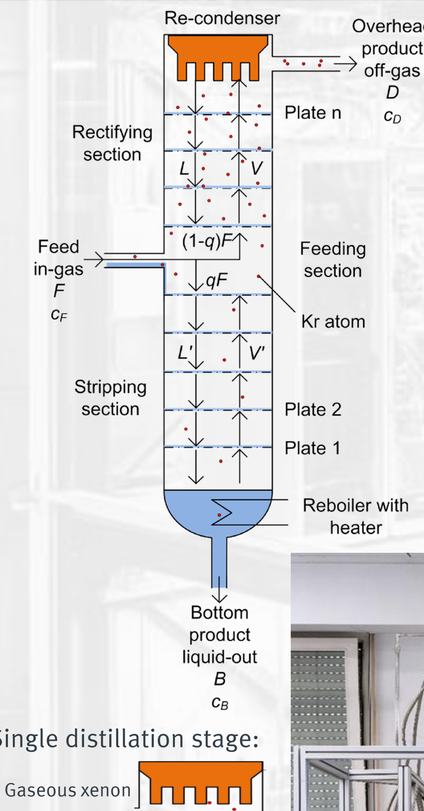
Data Sheets 116, 1 (2014) Nuclear

- Xenon is extracted from air together with natural krypton (^{nat}Kr)
- **^{nat}Kr contains radioactive isotope ^{85}Kr** created by nuclear fission
- Commercially available xenon:
  - ^{nat}Kr/Xe ∼ 10^{-6} to 10^{-9} (ppm to ppb)
  - ^{85}Kr/^{nat}Kr ∼ $2 \cdot 10^{-11}$
  - ^{85}Kr/Xe ∼ $2 \cdot 10^{-17}$ to $2 \cdot 10^{-20}$
- ^{85}Kr as a noble gas is not removed by liquid and gas purification or rejected by fiducialization
- ER background from ^{85}Kr spectrum **leaks into NR ROI** for WIMP search
  → Without removal: ^{85}Kr dominating ER background contribution
- XENONnT sensitivity requires target concentration of 0.1 ppt ^{nat}Kr/Xe or 1.1 events/(t · y · keV) at low ER energies

1 ppm = 10^{-6} mol / mol (parts per million)
1 ppb = 10^{-9} mol / mol (parts per billion)
1 ppt = 10^{-12} mol / mol (parts per trillion)
1 ppq = 10^{-15} mol / mol (parts per quadrillion)

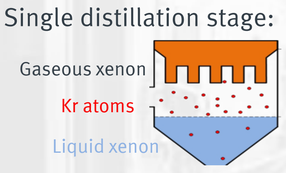
Cryogenic distillation

- Uses the **difference in vapor pressure** of Kr ($P_{Kr} = 20.9$ bar) and Xe ($P_{Xe} = 2.0$ bar) at LXe temperature (∼ − 98°C)
- **Raoult's law**: Relative volatility (ratio of vapor pressures) $\alpha = \frac{P_{Kr}}{P_{Xe}} = 10.4$ describes enhancement in gaseous phase
  → Kr as the more volatile component is **enriched in the gaseous phase** above a LXe reservoir
- Series of distillation plates successively reduces level of Kr impurities
- Re-condenser: vapor is partially liquefied and fed back to the column (partial reflux or rectification)
- Krypton-enriched xenon extracted as off-gas, **purified xenon extracted at the bottom**



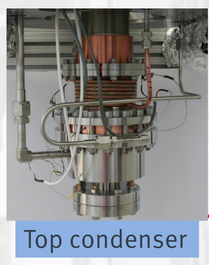
Eur. Phys. J. C (2017) 77:275

Single distillation stage:

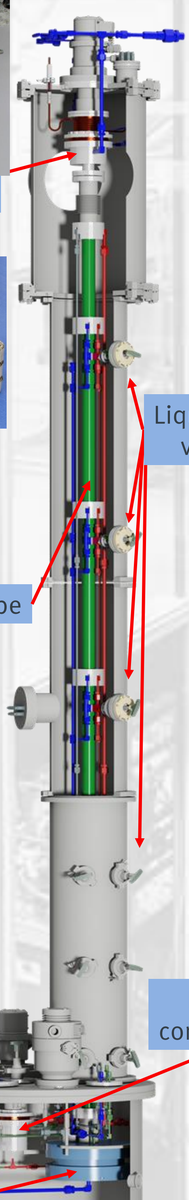


XENON Kr distillation column

- 5.5 m high distillation column located in the XENON service building
- Built for XENON1T, also sufficient Kr suppression for XENONnT and Darwin/XLZD
- Multiple distillation stages **realized with structured package material**
- Column capable of xenon purification of **up to 6.5 kg/h or 18 slpm**
- Due to partial reflux 1 % of xenon input is lost as off-gas


Top condenser


Package material



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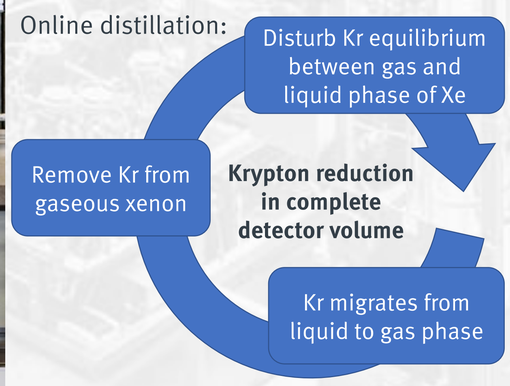
- Reduction factor F_{red} at 8.3 slpm:

$$F_{red} = \frac{^{nat}Kr/Xe_{in\text{-}gas}}{^{nat}Kr/Xe_{liquid\text{-}out}} = (6.4^{+1.9}_{-1.4}) \cdot 10^5$$

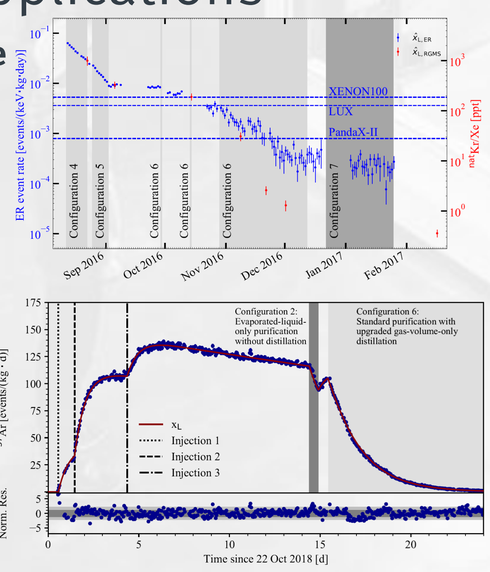
- Krypton concentration of **‹48 ppq** reached
- Column operated via overpressure at inlet
- Input condenser: Liquefaction for liquid feed and additional pre-separation stage
- **Online mode**: continuous distillation of gaseous xenon volume of the detector

Online distillation:

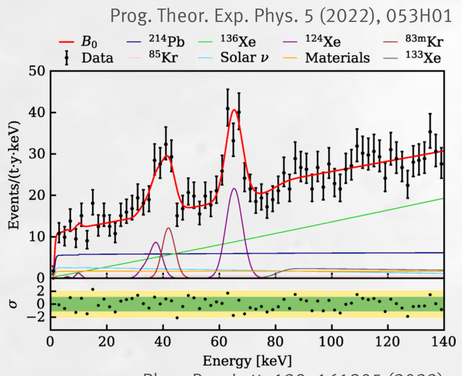


Performance and applications

- Reached **360 ± 60 ppq ^{nat}Kr/Xe in XENON1T** Science Run 0 by online distillation
- **Argon** online **distillation** demonstrated with an effective time constant of $\tau_{eff,\,Ar} = 1.7$ d
  → Allows ^{37}Ar to be used as low energy calibration source
- XENONnT: offline distillation of new xenon, three weeks of online distillation of complete xenon inventory
  → **56 ± 36 ppq ^{nat}Kr/Xe in XENONnT** Science Run 0
- With online mode: **krypton level negligible** w.r.t. radon
- Next challenge: radon removal, see radon column poster



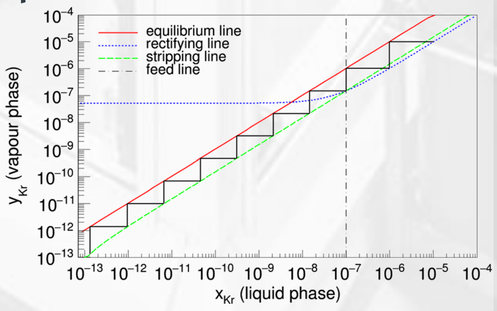
Prog. Theor. Exp. Phys. 5 (2022), 053H01



Phys. Rev. Lett. 129, 161805 (2022)

Design goals

- Krypton concentration of 0.2 ppt ^{nat}Kr/Xe (for XENON1T)
- Feeding flow rate: **3 kg/h = 8.3 slpm**
- Separation factor of **10^4 to 10^5**
- Xenon recovery of 99%
- $T = 178$ K and $p = 2$ bar
- McCabe-Thiele approach used to estimate number of required distillation stages



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This work is supported by BMBF under contract 05A20PM1 and by DFG within the Research Training Group GRK-2149

GRK 2149