Westfälische Wilhelms-Universität Münster

Astroparticle School
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A cryogenic distillation column for the XENON1T experiment

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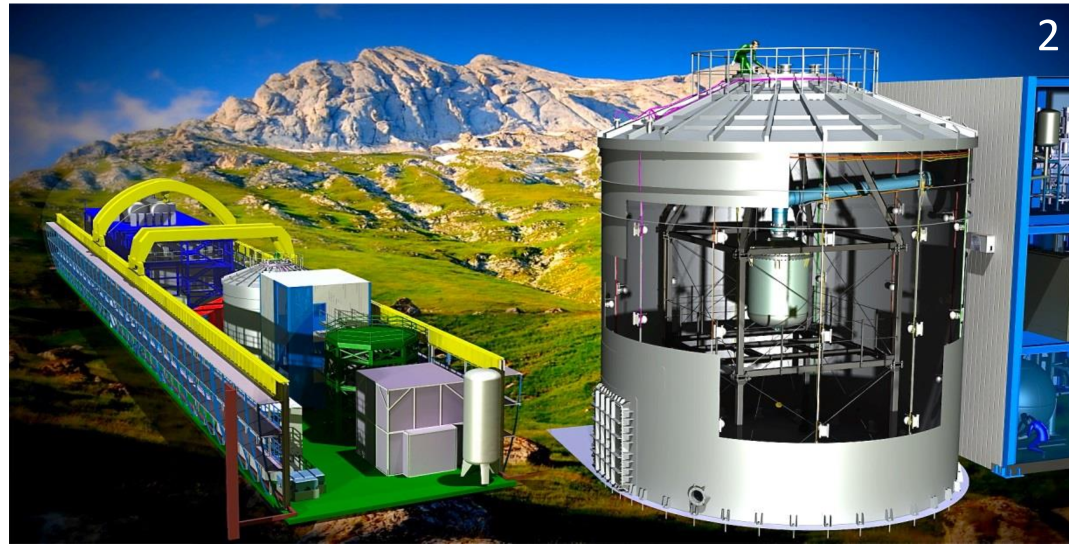
12. October 2015

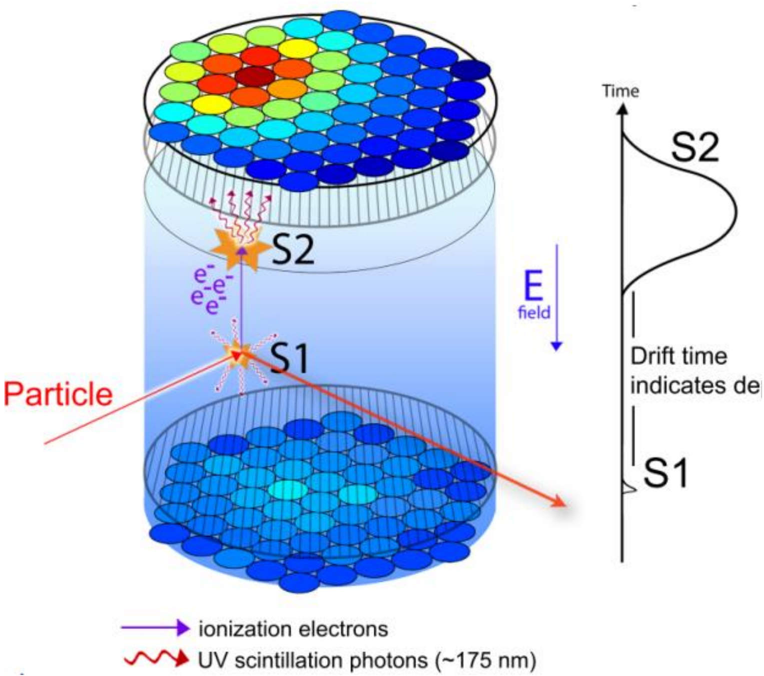
XENON Dark Matter Project

Direct Dark Matter detection searching for WIMPs
(Weakly Interacting Massive Particles)

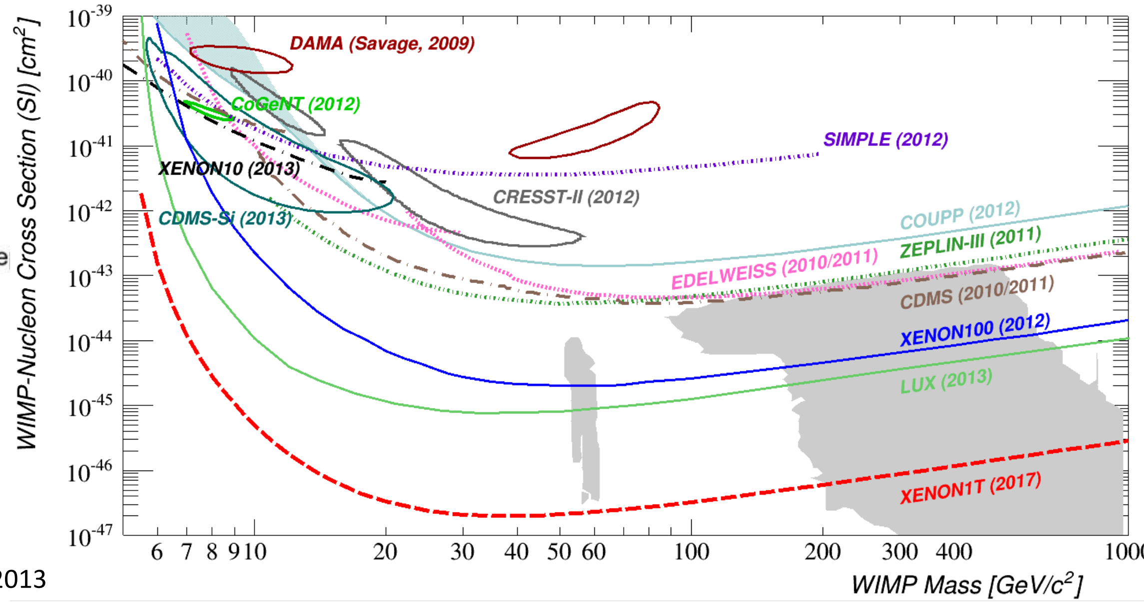
located at LNGS in Gran Sasso, Italy, at 3600 m water equivalent depth

Using dual phase xenon TPC

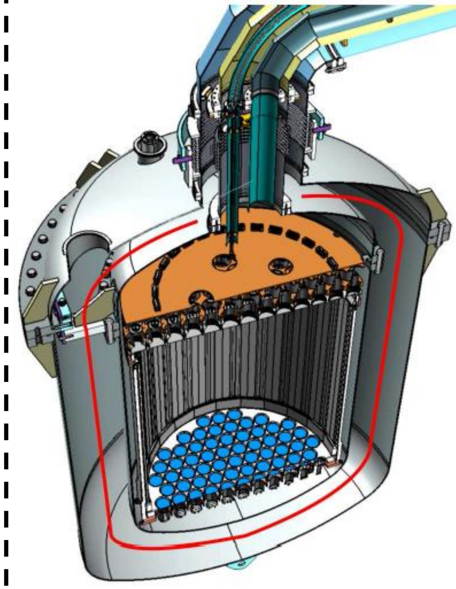




http://luxdarkmatter.org/talks/20131030_LUX_First_Results.pdf, 2013



XENON Dark Matter Project

XENON10	XENON100	XENON1T	XENONnT
			
2005	2009	2015	2018+
25 kg	161 kg	3300 kg	~7000 kg
$<8.8 \times 10^{-44}$	$<2 \times 10^{-45}$	$\sim<2 \times 10^{-47}$	$\sim<3 \times 10^{-48}$
5 ppb	19 ppt	<0.5 ppt	<0.2 ppt

Time

Target mass

WIMP-nucleon cross section [cm^2]

Krypton in xenon concentration

3

200 … me

25 k … ass

<8.8 … n^2]

5 pp … ion

→ **Bac … ON100**

3

Background for XENON1T has to be reduced by 2 orders of magnitude w.r.t. XENON100

200 … me

25 k … ass

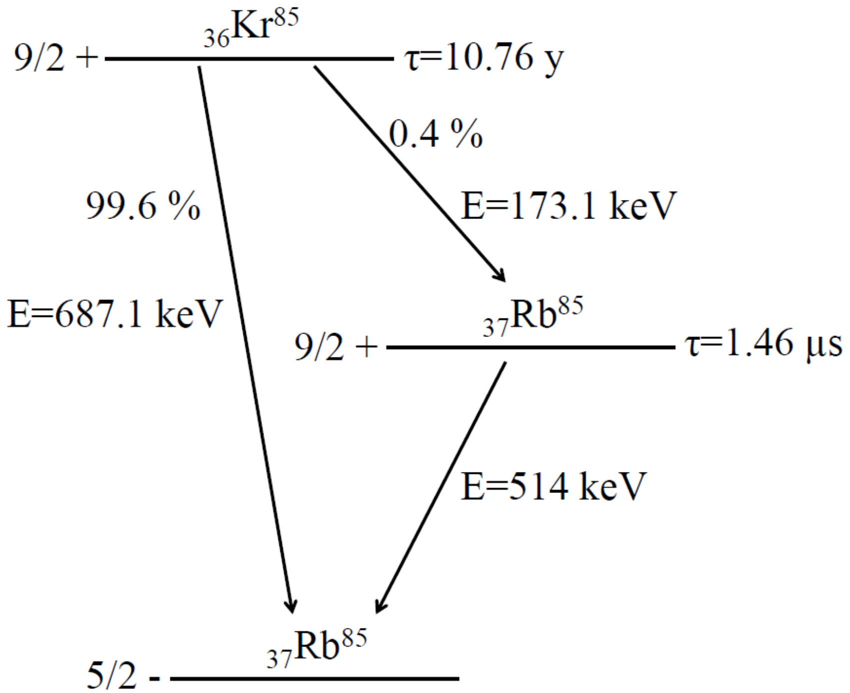
<8.8 … n^2]

5 pp … ion

→ Bac … ON100

Intrinsic contamination by ^{85}Kr

^{85}Kr : β-emitter with endpoint energy of E=687.1 keV and a half-life of $t_{1/2}$=10.76 y



intrinsic contamination of the xenon itself

→ homogenously distributed inside the detector

→ leakage events from the low energy β-spectrum contaminate region of interest for dark matter search

created in nuclear fission

→ homogenous distributed in the air

commercial xenon: $^{nat}Kr/Xe \sim 10^{-9} - 10^{-6}$ (ppb – ppm)

$^{85}Kr/^{nat}Kr \sim 10^{-11}$

For XENON1T:

$^{nat}Kr/Xe < 5 \cdot 10^{-13}$ (0.5 ppt) ←→ $0.5 \frac{evt}{y \cdot ton}$

Principle of a distillation column

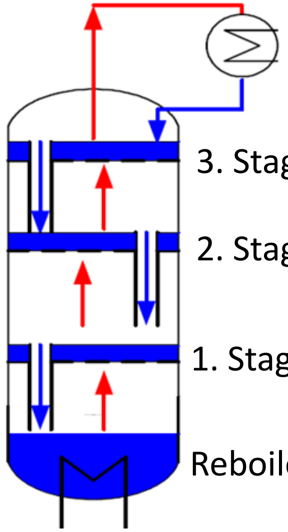
„Multi-stage"distillation with partial reflux:

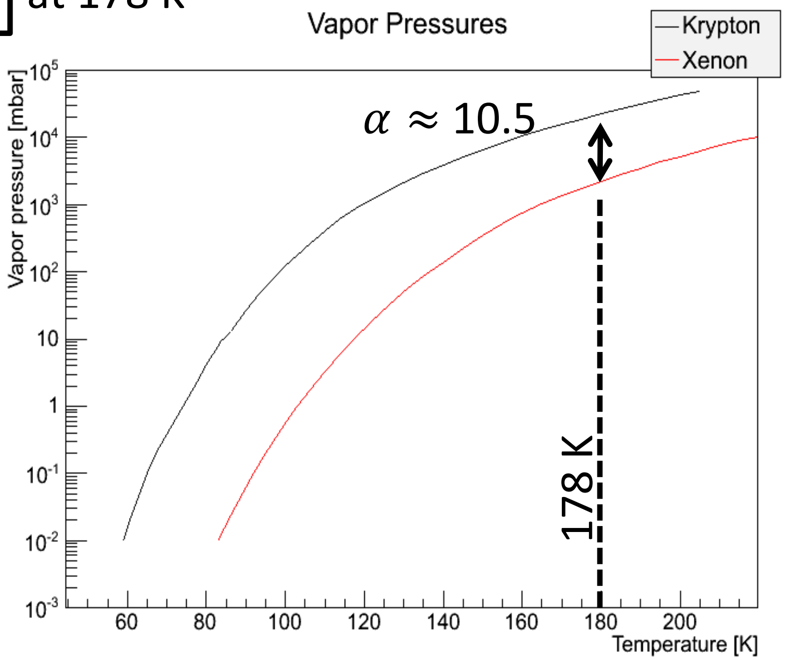
Separation is based on the difference in vapor pressure of the two components:

relative volatility: $\alpha = {}^{p_{Kr}}/_{p_{Xe}} \approx 10.5$ at 178 K

series of distillation stages for desired purity

→ Common approach is the **McCabe-Thiele** method
→ Calculation of the number of theoretical stages for a idealised mixture of two gases: 9-10





→ Krypton as more volatile gas is collected at the top, while the purified liquid xenon is enriched in the bottom

Technical realisation of a multi-stage distillation: Package Column

heat- and mass transfer on huge surface: package material

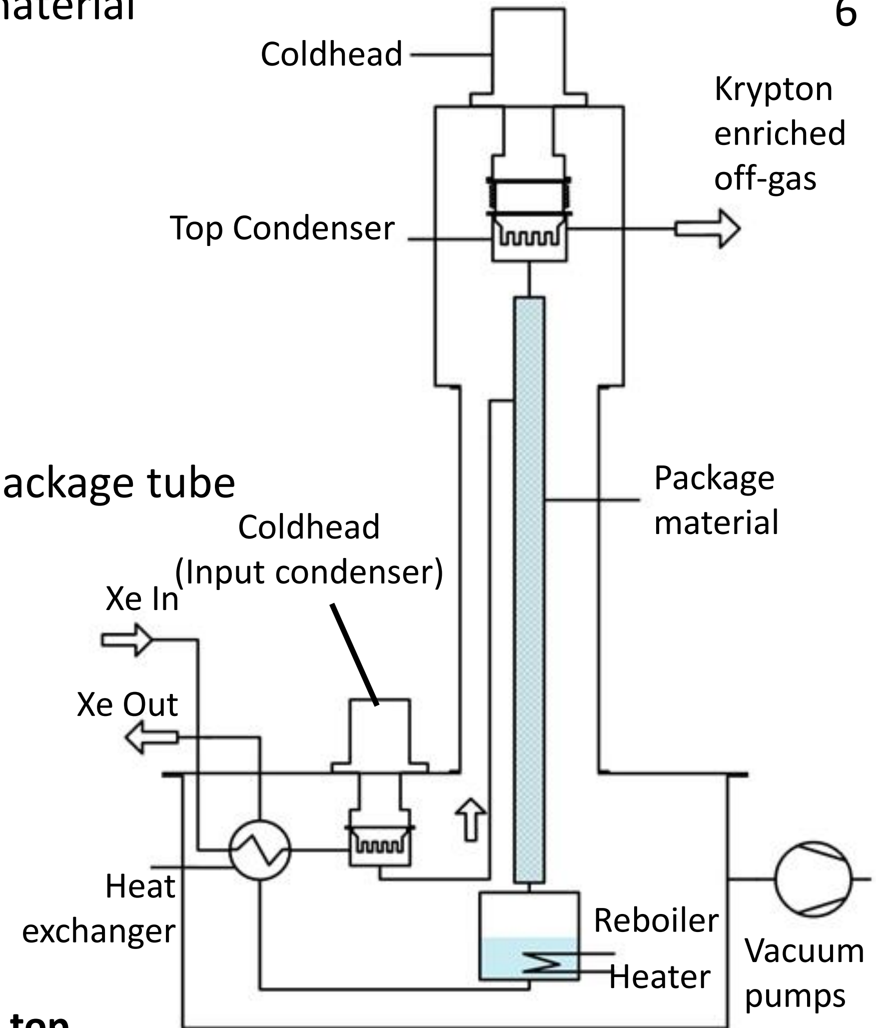
HETP:
Height equivalent of one theoretical plate

Processing:
incoming xenon is cooled, liquefied and injected to package tube

Heater in the bottom (reboiler):
- → evaporate the mixture
- → mass transfer along the package tube.
- → **purified xenon extracted from the reboiler**

Coldhead at the top (Condenser)
- → re-condense xenon and feed back to the package
- → **krypton-enriched off-gas extracted from the top**

Strategy: Divide the project into different phases



Scheme of the package column for XENON1T

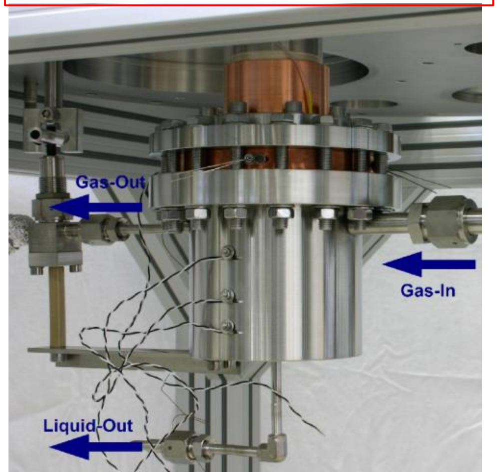
Design in collaboration with Dr. Ion Cristescu, KIT/ITER

Different phases of distillation project

Design Parameter for XENON1T

feeding flow rate:
3kg/h = 8.3 SLPM
separation factor: $10^4 - 10^5$
Kr removal:
$^{nat}Kr/Xe < 5 \cdot 10^{-13} = 0.5$ ppt
Xe recovery: 99%
T = 178 K and p = 2 bar

Single distillation stage

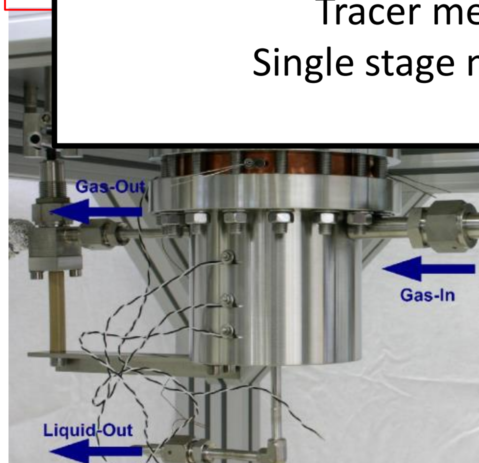


Different phases of distillation project

Design Parameter for XENON1T

feed
3kg/
sepa
Kr re
^{nat}Kr
Xe r
T = 1

Si



Single distillation stage main results:

Separation factor in the order of 10 as expected ($\alpha \approx 10$)

Cryogenic distillation is working in the sub-ppt concentrations shown with Kr-83m tracer method*

*See talk by Christian Wittweg
Tracer method concept: S. Rosendahl et al, JINST 9 P10010 (2014)
Single stage measurements submitted to Review of Scientific Instruments

Different phases of distillation project

Design Parameter for XENON1T

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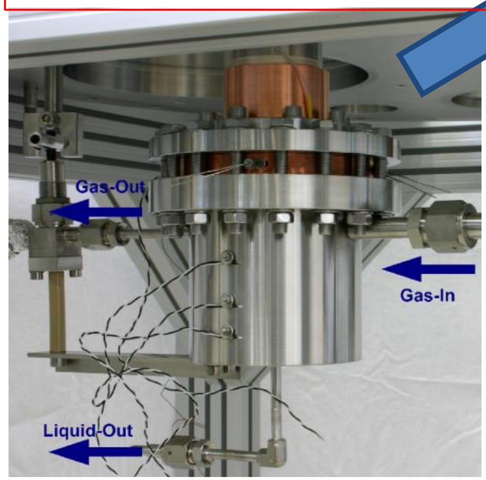
Xe recovery: 99%
T = 178 K and p = 2 bar

Phase 1 distillation column

Single distillation stage



Design Parameter for XENON1T

feed
3kg/
sepa
Kr re
^{nat}K
Xe r
T = 1

Si

Phase-1 main results:

(S. Rosendahl, Dissertation, 2015)

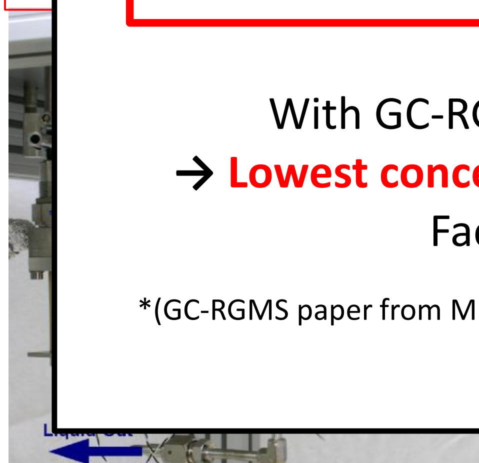
Thermodynamic stability under design parameters

Separation factor > 5.000

Purified liquid out: $^{nat}Kr/Xe < 26 \cdot 10^{-15}$ = 26 ppq (90% c.l.)

With GC-RGMS* system in Heidelberg only a limit could be set!
→ **Lowest concentration of $^{nat}Kr/Xe$ measured so far (to our knowledge)**
Factor ≈20 better than required for XENON1T!!

*(GC-RGMS paper from MPIK claiming sup-ppt sensitivity: S. Lindemann and H. Simgen Eur.Phys.J. C74 (2014) 2746)



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Different phases of distillation project

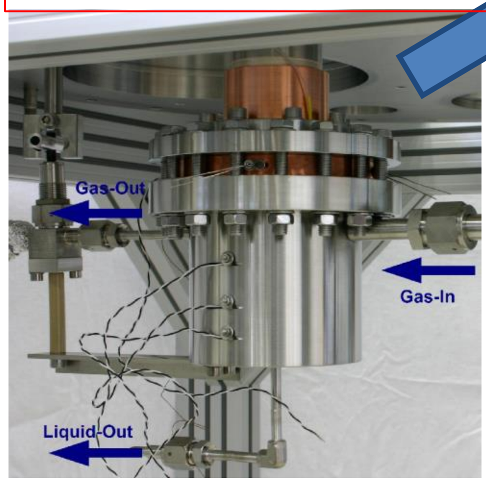
Phase 2 distillation column

Design Parameter for XENON1T

feeding flow rate:
3kg/h = 8.3 SLPM
separation factor: $10^4 – 10^5$
Kr removal:
$^{nat}Kr/Xe < 5 \cdot 10^{-13}$ = 0.5 ppt
Xe recovery: 99%
T = 178 K and p = 2 bar

Phase 1 distillation column

Single distillation stage



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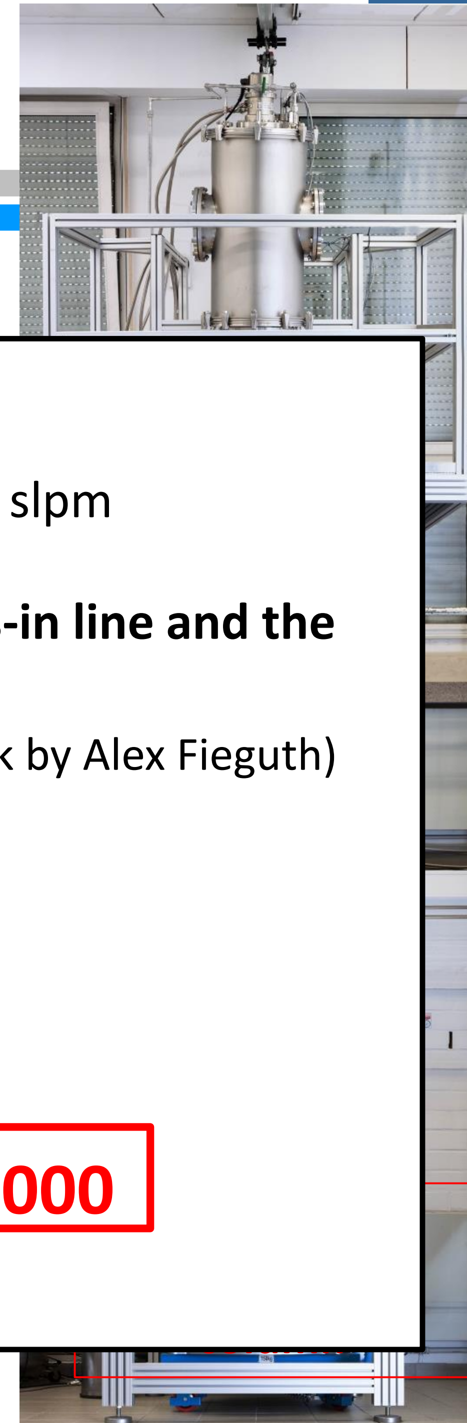
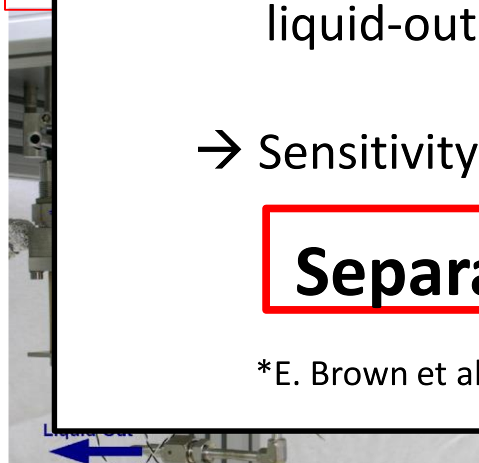
Different phases of distillation project



Design Parameter for XENON1T

feed
3kg/
sepa
Kr re
^{nat}Kr
Xe r
T = 1

Si



Phase-2 main results:

Thermodynamic stability for flows up to 18 slpm

Measurements of the absolute concentration in the gas-in line and the purified liquid-out line:

RGA with cold-trap enhanced sensitivity* (→ See talk by Alex Fieguth)

gas-in concentration: 25 ppm
liquid-out concentration: < 200 ppm

→ Sensitivity limit of RGA method 200 ppt

Separation factor ^{nat}Kr/Xe > 125.000

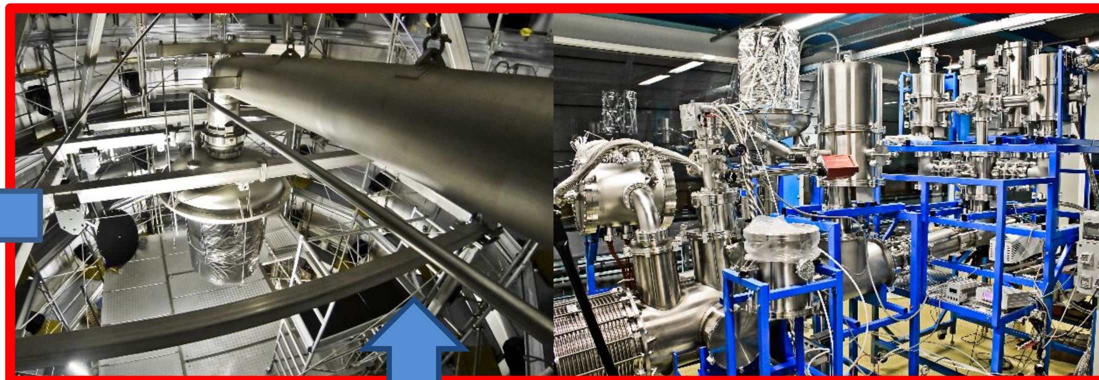
*E. Brown et al, 2013_JINST_8_P02011 (2013)

Commissioning at XENON1T

RESTOX:
Storage vessel for up to 7 tons of xenon

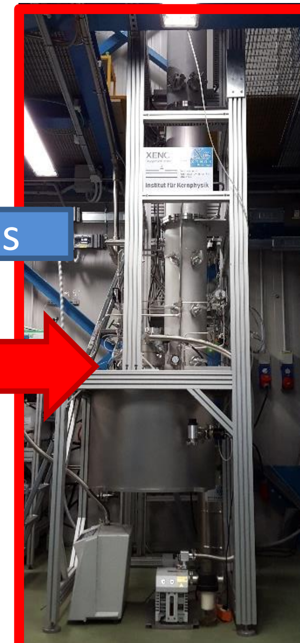
store

CRYOSTAT + CRYOGENICS: Housing of TPC + Liquefaction of xenon

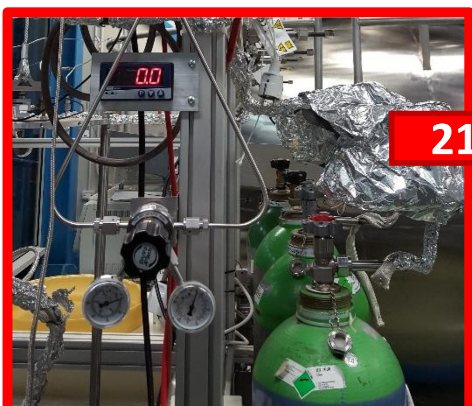


distribute

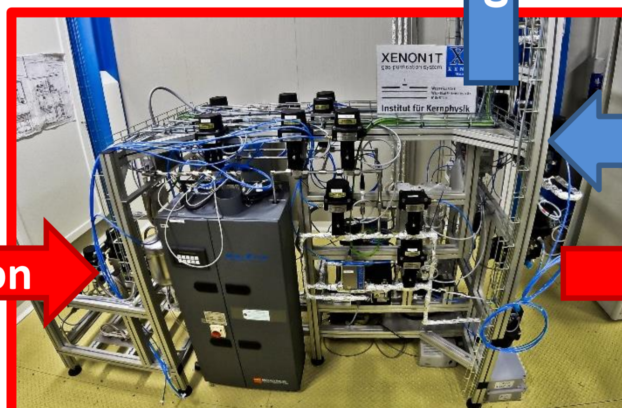
DISTILLATION COLUMN:
Krypton removal



BOTTLE RACK:
Fill xenon from bottles
+ analyse impurities



210 kg xenon

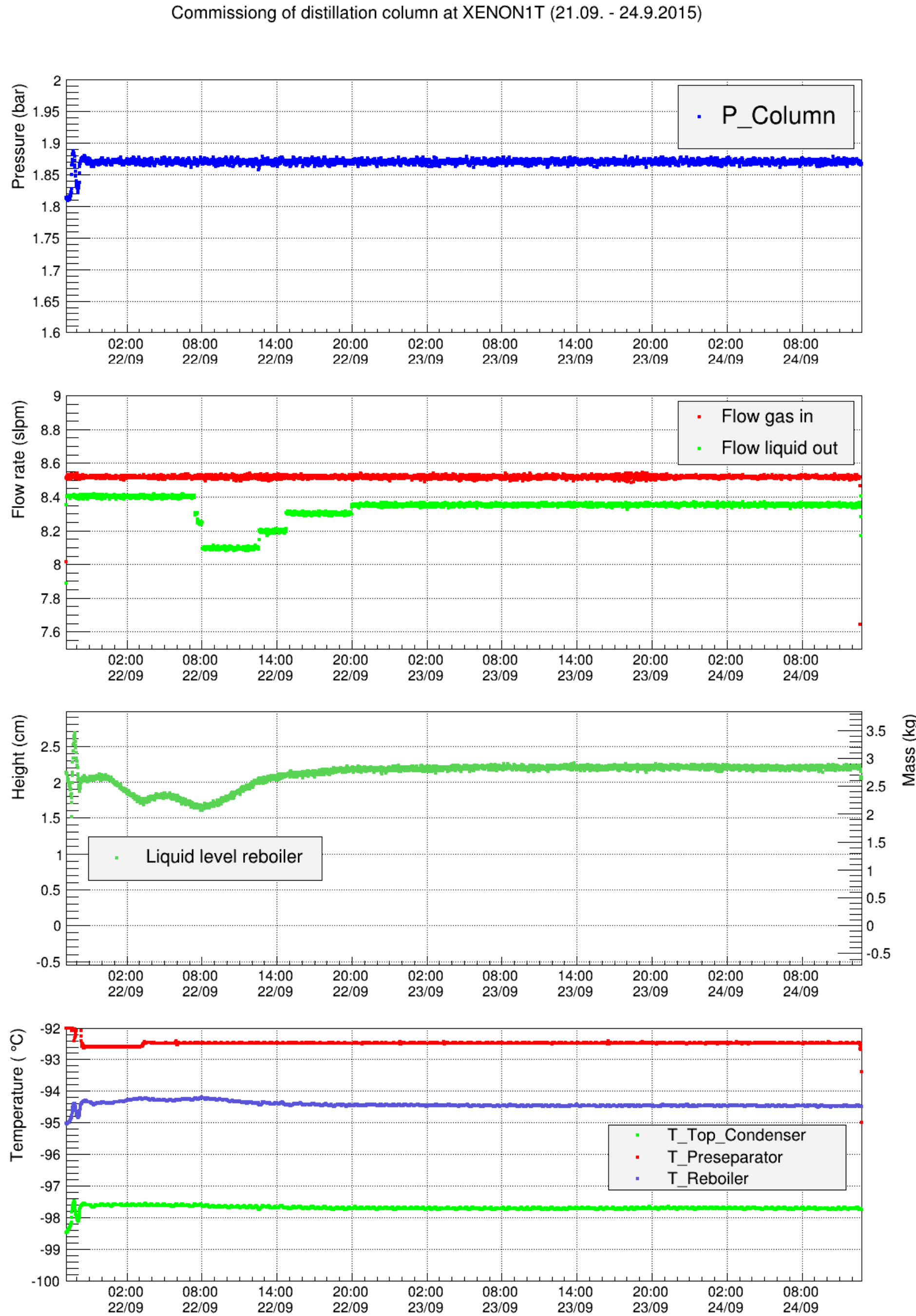


purified gas

raw gas

PURIFICATION SYSTEM:
Gas distribution + hot getter purification

g at XENON1T



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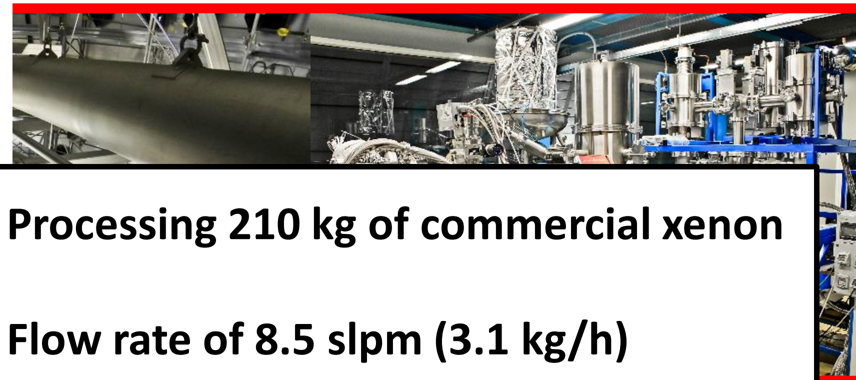
· **CRYOGENICS**: Housing of TPC + Liquefaction of xenon



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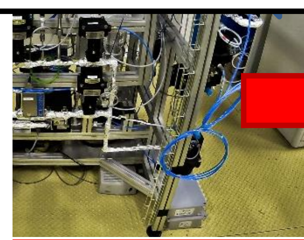
Processing 210 kg of commercial xenon

Flow rate of 8.5 slpm (3.1 kg/h)

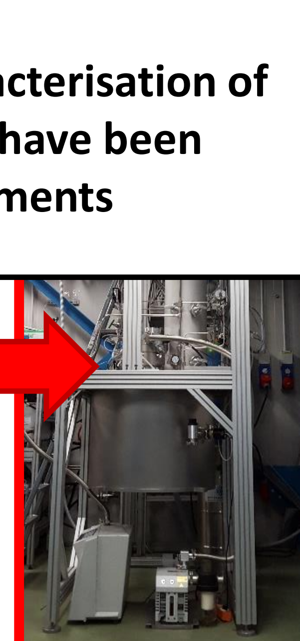
~ 3 days of continuous distillation

Gas samples for the characterisation of the column performance have been taken for RGMS measurements

UMN:



raw gas



SYSTEM:

ot getter purification

Summary and Outlook

- XENON1T requests a high throughput and ultra-clean new distillation column

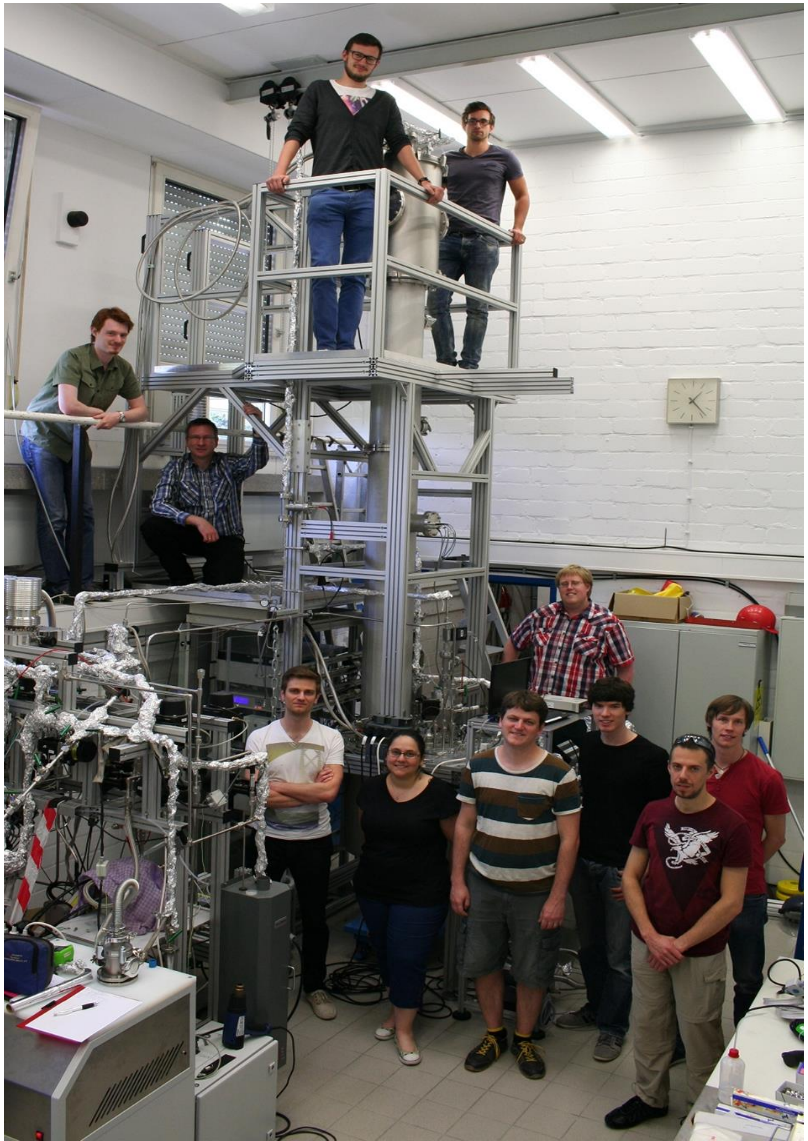
- Package column based on McCabe-Thiele method

- Thermodynamic stability at designed flow rate of 8.3 slpm (3kg/h) for different operation modes demonstrated

- **RGMS system at MPIK shows <26 ppq (0.026 ppt) with 90% confidence level**
- **Separation factor > 125.000**
  → XENON1T requirements more than fulfilled

- Installation and commissioning of Phase-2 at XENON1T experiment at LNGS has been done in September 2015

- **Ready for purification of 3.3 tons (~7 weeks of distillation) of xenon**



Thank you for your attention!

This project is supported by DFG Großgeräte (INST 211/528-1 FUGG, funded together with the state NRW and University of Münster) and by BMBF (05A11 PM1). Some aspects of the R&D for this project are funded by DFG (WE 1843/7-1) and by Helmholtz Alliance of Astroparticle Physics HAP.

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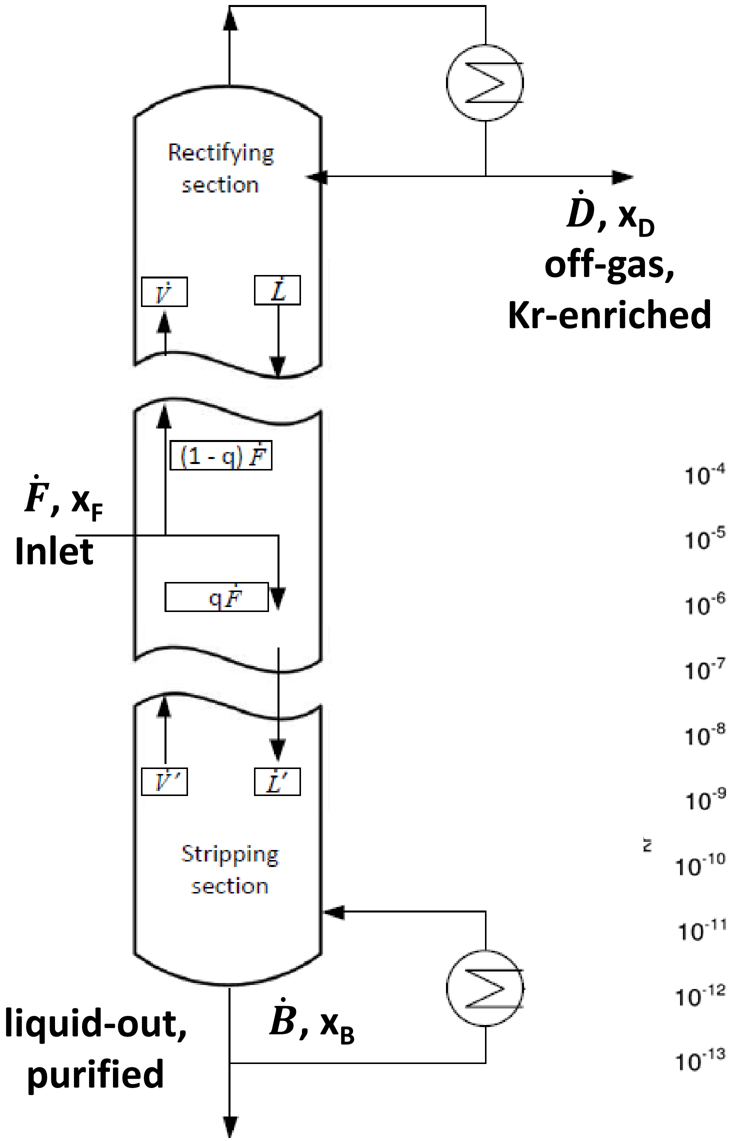
Bundesministerium für Bildung und Forschung

McCabe-Thiele calculation for the XENON1T column

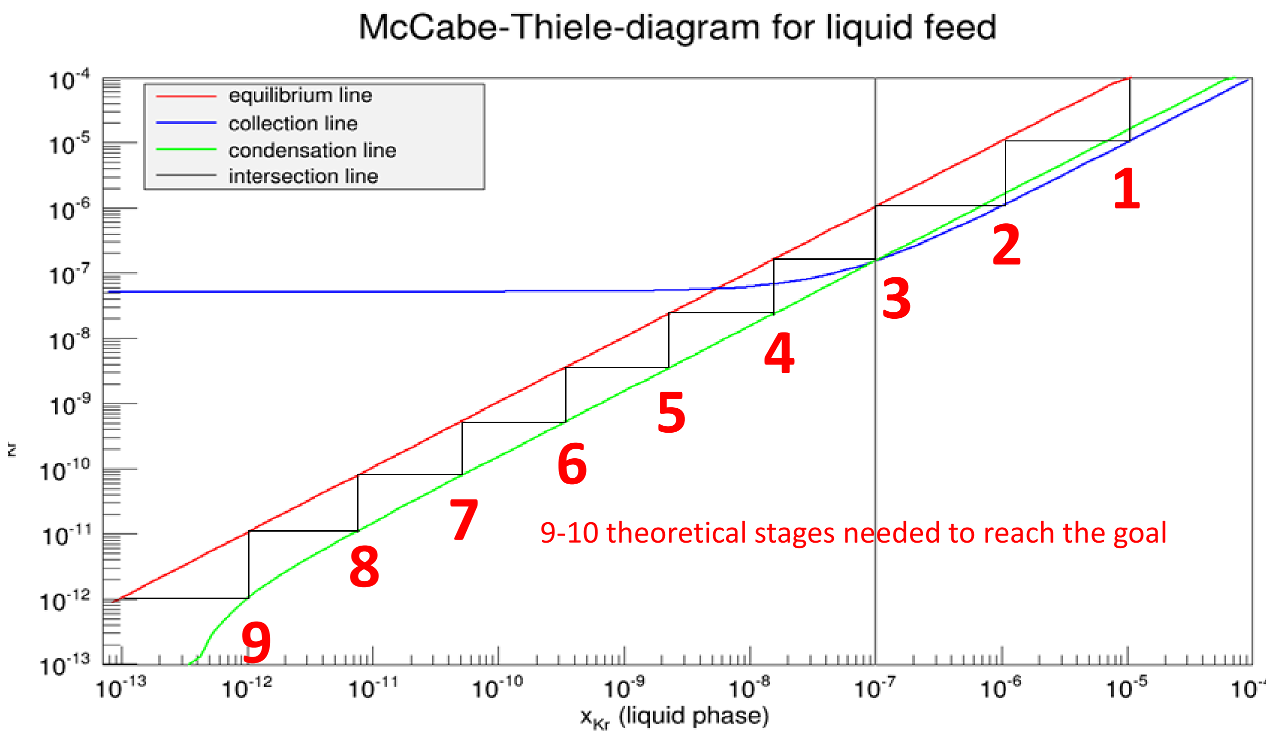


Krypton particle mass balance: Input = Output

„Flow · Concentration“

$$\dot{F} \cdot x_F = \dot{D} \cdot x_D + \dot{B} \cdot x_B$$

→ Calculation for a series of distillation stages leads to **McCabe –Thiele diagamm**



Design parameters

Distillation Column of XENON100:

- throughput: 0.6 kg/h

→ $^{nat}Kr/Xe = (19 \pm 4)$ ppt

E. Aprile et al, arXiv: 1207.5988v1

XMASS achieved $^{nat}Kr/Xe = 3$ ppt

K. Abe et al, arXiv: 0809.4413v3

Panda X achieved $^{nat}Kr/Xe = (21 \pm 3)$ ppt (with a 5m tall column)

Z. Wang et al, 2014 JINST 9 P11024

LUX achieved $^{nat}Kr/Xe = (4 \pm 1)$ ppt (with charcoal chromatography)

Lux Collaboration, arXiv:1403.1299v1

Design Parameters for XENON1T:

- feeding flow rate: 3kg/h = 8.3 SLPM
- separation factor: $10^4 - 10^5$
- Kr removal: $^{nat}Kr/Xe < 0.5$ ppt
- Xe recovery: 99%
- T = 178 K and p = 2 bar

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Determination of column performance using RGMS at MPIK, Heidelberg

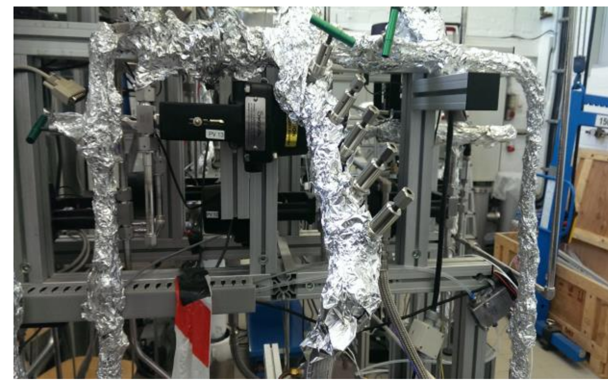
XENON Dark Matter Project

Measurements of krypton in xenon to the ppq level should be possible with RGMS

Mounting of ultra-clean pipettes from MPIK to the distillation column

Extensive pumping and baking procedure to avoid contaminations of the samples

Taking several samples from the distillation column, during distillation run at 8.5 slpm



Main Result:

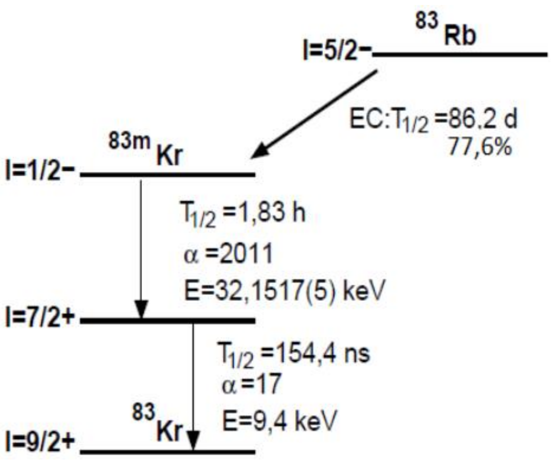
Purified liquid out: ^{nat}Kr/Xe < 26•10^{-15} = 26 ppq (90% c.l.)

With RGMS system in Heidelberg only a limit could be set!

→ **Lowest concentration of ^{nat}Kr/Xe measured so far (to our knowledge)**

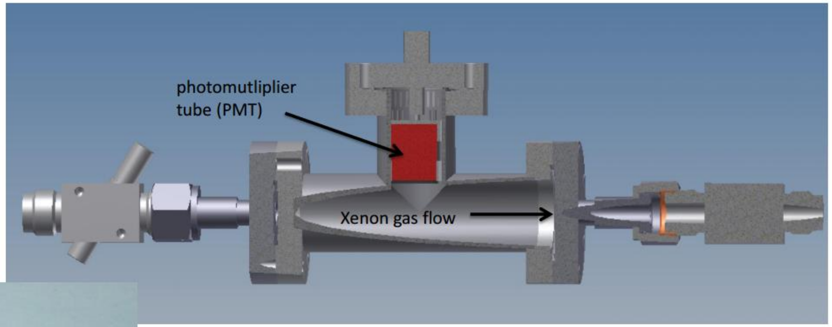
Factor ~20 better than required for XENON1T!!

^{83m}Kr Monitors

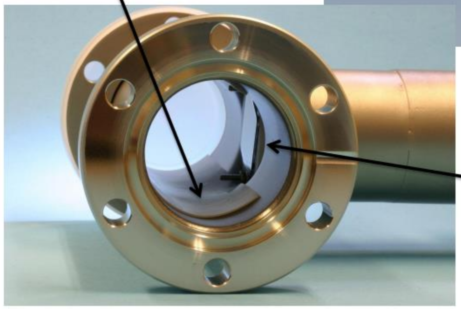


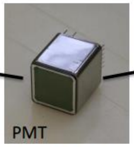
- doping Xe gas with ^{83m}Kr as a tracer, which has same chemical properties as ^{85}Kr
- measuring the Xe scintillation light from ^{83m}Kr decays
- signal rate is proportional to concentration
- monitor relative concentrations of different points in the column

→ determine separation efficiency

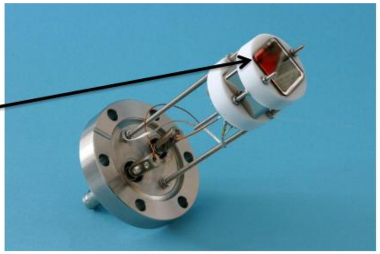


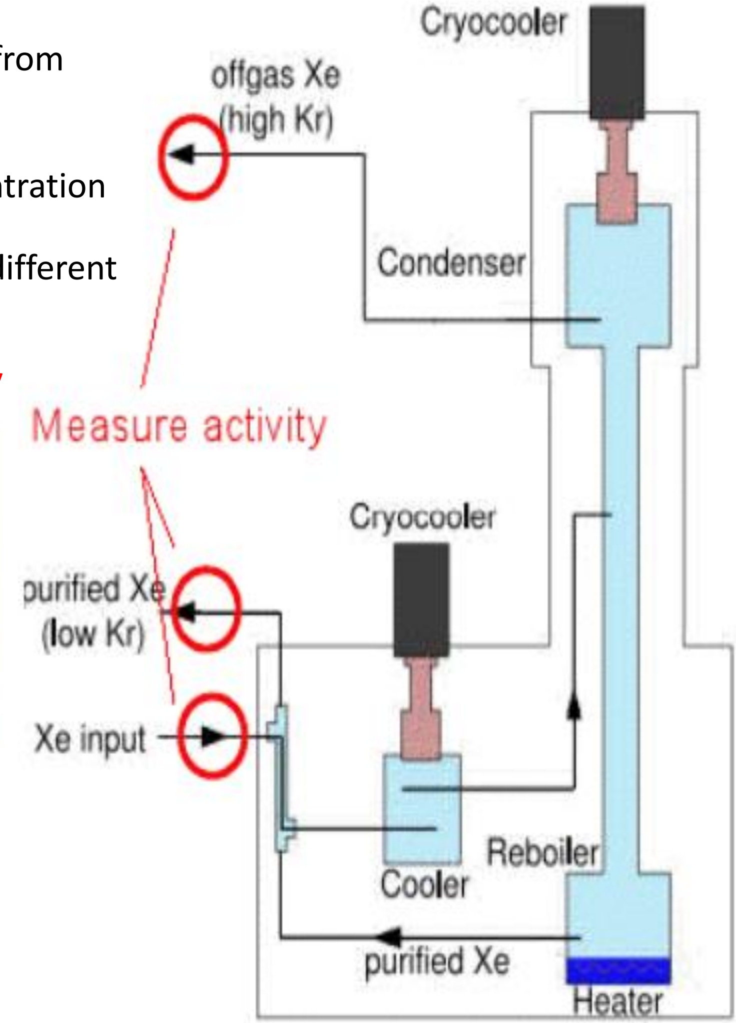
PTFE VUV light reflecting foil





R8520-06-Al by Hamamatsu





Gas diagnostics using RGA with cold-trap enhanced sensitivity

System is equipped with a RGA setup

→ Custom made differential pumping sections and a liquid nitrogen coldtrap allows to freeze out the xenon while the krypton passes nearly unattached

→ Custom made butterfly valve allows for reduced pumping speed which further increase the sensitivity

→ Increased sensitivity down to ~40ppt possible