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Distillation column for the XENON1T experiment

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Abstract. The XENON1T experiment will probe a new parameter space in the direct dark matter search. Besides the enlargement of target mass to the ton scale, a further background reduction with respect to its predecessor XENON100 is necessary. A major contribution to the intrinsic contamination is the β -decaying isotope ^{85}Kr , which leads to the requirement of a concentration less than 0.2 ppt of natural krypton in xenon. Its removal from the xenon gas is achieved by cryogenic distillation. For the new experiment a custom-build distillation column with a separation factor larger than 10^5 and a throughput of 3 kg/h has been designed and built at the University of Muenster. Furthermore its performance has been characterized using different trace gas detection techniques, e.g. a novel ^{83m}Kr -tracer method, and its functionality has been tested successfully. The distillation column, which is installed and commissioned at the XENON1T experiment, is ready to process the 3.5 tons of xenon.

1. Introduction

Given the strong evidence for dark matter throughout our universe, its direct detection is of key importance for our understanding of its nature. Dark Matter candidates which belong to the class of Weakly Interacting Massive Particles (WIMPs) are the main object of interest of the XENON Dark Matter Project. Its next-stage experiment will be XENON1T which utilizes 3.5 tons of xenon with 2.2 ton of liquid xenon as an active target volume and 1 ton for dark matter searches after fiducialization aiming for a sensitivity down to $2 \times 10^{-47} \text{ cm}^2$ for the spin-independent WIMP-nucleon cross section at 50 GeV after 2 years of data taking.

In order to enter this new parameter space not only the increase of the target mass, but also a further background reduction with respect to XENON100 plays a crucial role. A key background for noble gas experiments due to their fabrication process is the krypton isotope ^{85}Kr which is abundant in traces in the atmosphere. While commercially available xenon contains a fraction of natural krypton to the ppb¹-level, the required purity for an experiment on the ton scale as XENON1T or the successor XENONnT is below 0.2 ppt² [1]. The approach for the purification used within the XENON Dark Matter Project is the removal of krypton via cryogenic distillation, which has been successfully used in XENON100 [2]. However, for the challenging requirements in purity, which are far beyond common applications, and due to the large amount of detector medium of the upcoming XENON1T experiment a custom-designed column has been built [3]. It is designed to purify the xenon below the required 0.2 ppt with a processing speed of 3 kg/h. This leads to a total distillation time of around 7 weeks for the total detector content.

¹ ppb = 10^{-9} mol/mol

² ppt = 10^{-12} mol/mol



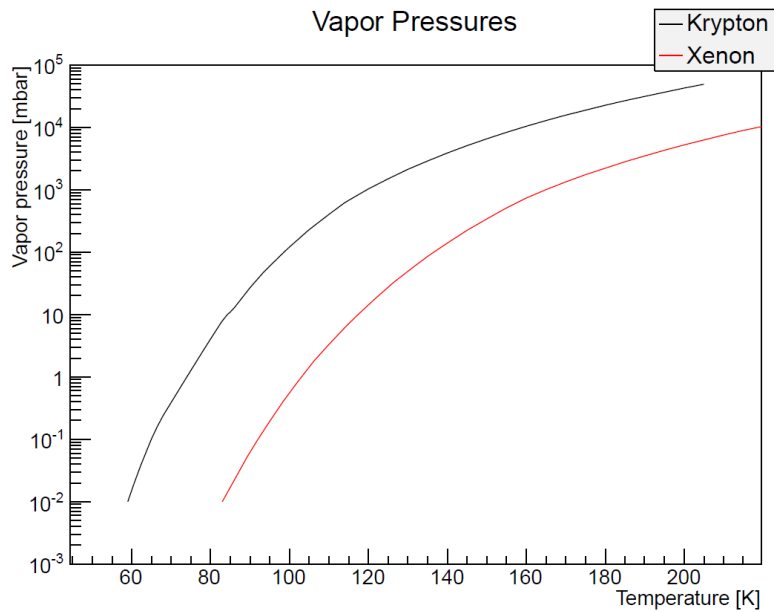


Figure 1. Vapor pressures of xenon and krypton. Data taken from [6].

2. ^{85}Kr as an intrinsic background source

Introduced by nuclear weapon tests and the nuclear waste reprocessing the isotope ^{85}Kr is abundant nowadays at the level of $^{85}\text{Kr}/^{nat}\text{Kr} \approx 2 \times 10^{-11}$ mol/mol [4]. Since xenon is extracted from the atmosphere, this leads to a contamination of the used xenon gas by natural krypton in the range of ppm³ to ppb although it has been purified already by a company. Despite the low concentration of ^{85}Kr in the xenon gas it still contributes to the background level of noble gas experiments via its beta decay. Even considering the high electronic recoil rejection efficiency of 99.75 % as used in XENON100 [2] the accidental leakage events of this decay into the signal region are a main background, especially if it is considered that the self-shielding capability of the xenon is useless for this intrinsic contamination. Since XENON1T aims for a background level of only a few events per ton and year, the natural krypton concentration has to be below 0.2 ppt and therefore a removal by a factor greater than 10^5 is necessary.

3. Removal of krypton by cryogenic distillation

A technique to provide pure xenon down to the ppt-level and below is the removal of krypton by cryogenic distillation which has been proven successful in previous experiments [2][5]. This method uses the difference in vapor pressures of a two-component mixture, in this case xenon and krypton (see figure 1), to separate them. The relative volatility which is defined as the ratio of the vapor pressures is 10.8 at the temperature of interest at 175 K around the xenon boiling point for a given pressure of around 2 bar.

Given this, it is expected that in a static two-phase equilibrium system the gaseous phase is enriched by a factor of ~ 10.8 in terms of krypton concentration. This two-phase system is a single-distillation stage and has a separation efficiency which is directly related to the relative volatility.

³ ppm = 10^{-6} mol/mol

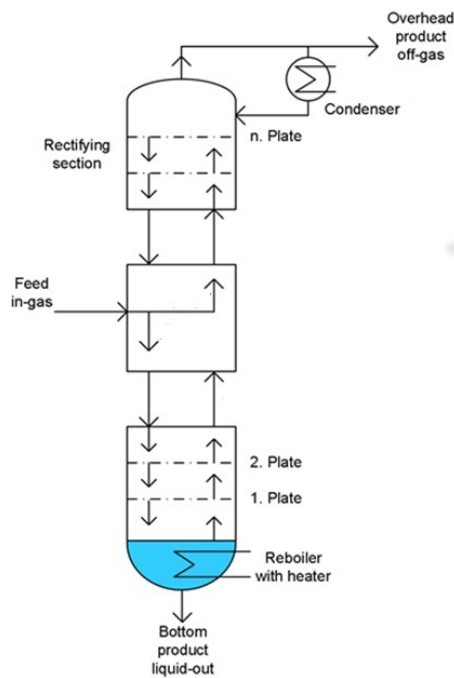


Figure 2. Scheme of a multi-stage distillation setup. Drawing based on [7]

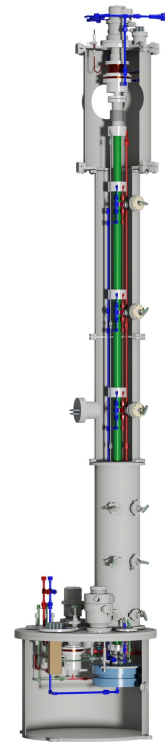


Figure 3. CAD-drawing of the XENON1T distillation column. In-gas flow is indicated in red, out-gas flow in blue. Drawing by C. Huhman.

In order to enhance the separation efficiency a series of theoretical single-distillation stages is connected, building a multi-stage distillation column (see figure 2). Technically, the theoretical stages can be realized by a package column with partial reflux: The raw xenon gas is liquefied by an input condenser and is fed to the package tube which houses a special structured stainless steel package material (Sulzer EX) providing a huge surface. The xenon rinses down to the bottom of the column into the reboiler, a stainless steel vessel filled with a liquid xenon reservoir. With partial evaporation of the liquid xenon at this location, an upstream of gaseous xenon is established along the package materi At the top of the column, the xenon is partially liquefied again and fed back to the tube, creating a down-streaming liquid flow on the surface of the package materi In this way a counterflow of gaseous and liquid xenon along the package tube is created and the more volatile krypton inside the xenon can migrate from the liquid phase into the gaseous phase, leading to an enrichment of krypton at the top of the column. By removing a small fraction of the krypton enhanced gas phase directly at the top (1% of the feed flow), the krypton content is lowered over time and the liquid reservoir at the bottom contains purified xenon which is used to fill the detector for a scientific run. In order to design a cryogenic distillation column, the theoretical number of necessary distillation stages can be estimated from the McCabe-Thiele method [7] and by multiplying the HETP⁴ value of the package material its final height can be calculated. The XENON1T column with a total height of 5.5 m (see figure 3) uses 2.8 m of package material to achieve the desired separation factor.

⁴ HETP = Height Equivalent for one Theoretical Plate

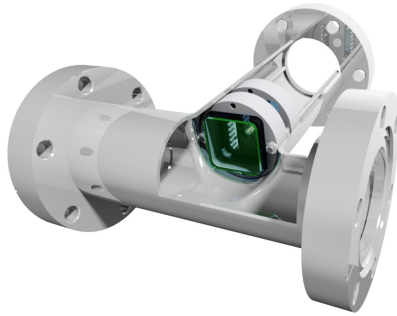


Figure 4. CAD-drawing of the ^{83m}Kr -detector. A VUV-sensitive PMT is centered in a t-shaped stainless steel tube facing xenon gas. Drawing by C. Huhmann

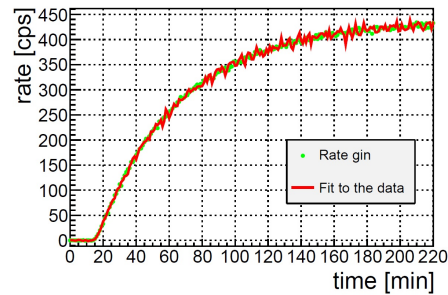


Figure 5. Measured example rate of the ^{83m}Kr -decay at the ingoing flow of a single-stage distillation setup and the resulting fit by applying a probabilistic model. Details in [8][11].

4. ^{83m}Kr -tracer for online diagnostics

In order to characterize the performance of the working distillation column and also to prove the validity of the separation at such a low concentration, a tracer method based on the meta-stable isotope ^{83m}Kr has been developed and implemented [8]. The isotope ^{83m}Kr , produced in the electron-capture decay of ^{83}Rb , has the advantage that it decays to the stable ground state ^{83}Kr with a half-life of 1.83 h. This is long enough that a sufficient amount of the tracer is fed into and circulated through the entire column, but short enough that it does not contaminate the column on a long-term scale. By using a zeolite-embedded rubidium source [9][10] (activity ≈ 60 MBq) the ^{83m}Kr -isotope is introduced in traces into the column. At the inlet, the decay rate is measured by a custom-developed detector (see figure 4), which registers the VUV-scintillation light produced in the xenon by the conversion electrons and gammas from the ^{83m}Kr decay via a photomultiplier tube (type R8520-06-AL, Hamamatsu). Since the decay rate is proportional to the concentration for a constant pressure, a measurement of the decay rate at both outlets of the column by two additional detectors allows a characterization of the krypton behavior within the column (see figure 5). In addition it can be used to calculate a separation efficiency of the system as long as a significant rate is measured at the purified outlet.

Furthermore, by using this method it is possible to determine an HETP value of the system experimentally. Detailed information on the tracer method and the probabilistic model used for the application on the working system can be found in [8], [11] and [12].

5. Results and outlook

The cryogenic distillation column for the XENON1T experiment has been built and characterized at the University of Muenster. First tests show that it fulfills the design values by achieving sub-ppt concentrations at the outlet with a stable throughput of 3 kg/h [13]. In Summer 2015 it has been commissioned at the XENON1T experimental site in Hall B of the Laboratori Nazionali del Gran Sasso, Italy, where a first distillation test, processing 220 kg of xenon, demonstrated the long-term stability of the column. For the pressure, which is the key parameter for the quality of the distillation process, a maximal fluctuation of $\Delta p_{\text{column}} = 20$ mbar has been observed over the entire run time (see figure 6). Finally the setup is ready for processing the entire detector inventory for the first scientific run of XENON1T in 2016.

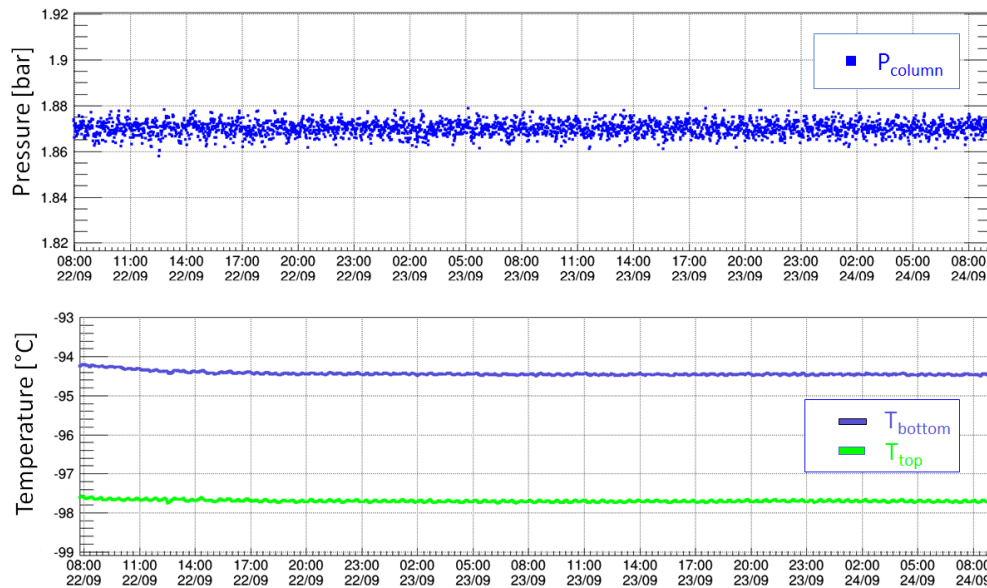


Figure 6. Long term stability (more than 2 days) of the thermodynamic parameters: pressure inside the column (top) and temperature at different positions within the column (bottom).

Acknowledgments

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References

- [1] Aprile E et (XENON collaboration) 2015 *Preprint* arXiv:1512.0750
- [2] Aprile E et (XENON collaboration) 2012 *Phys. Rev. Lett.* **109** 181301
- [3] Rosendahl S et 2014 *J. Phys. Conf. Ser.* **564** 162 012006
- [4] Du X et 2003 *Geophys. Res. Lett.* **30** 2068
- [5] Abe K et (XMASS collaboration) 2009 *Astropart. Phys.* **31** 290
- [6] Lide D R, 2006-2007 *Handbook of Chemistry and Physics*, 87th edition, CRC Press
- [7] McCabe W, Smith J and Harriott P 2005 *UNIT OPERATIONS OF CHEMICAL ENGINEERING* 7th edition (McGraw-Hill International Edition), 665
- [8] Venos D et 2005 *Appl. Radiat. Isotopes* **63** 323
- [9] Hannen V et 2011 *JINST* **6** P10013
- [10] Rosendahl S et 2014 *JINST* **9** 10 P10010
- [11] Rosendahl, S et al 2015 *Rev. Sci. Instrum.* **86** 11 115104
- [12] Rosendahl S et 2016 in preparation
- [13] Rosendahl S 2015 *Gas purification of the XENON dark matter search*, Dissertation, University of Muenster