

# Purity Requirements and Monitoring in MuSun Experiment

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## 1 Purity Requirements

The purity requirements are estimated based on experiments [1, 2]. The literature values for the transfer rates are given in table 1.

Nucleus	E (eV)	$\lambda_{pZ}$ ( $10^{10}s^{-1}$ )	Ref	$\lambda_{dZ}$ ( $10^{10}s^{-1}$ )	Ref
N	0.04	$3.4 \pm 0.7$		$14.5 \pm 0.2$	
O	0.04	$8.5 \pm 0.2$		$6.3 \pm 0.5$	

Table 1: Muon transfer rates from  $\mu p$  and  $\mu d$  atoms to N and O, respectively. Transfer rates given for thermal energies, as thermalization is much faster than transfer at MuSun experimental conditions.

Let us first estimate the requirements based on the MuCap experience. The MuCap run 8 (and run 10 for CalibN) gives an observed EVH yield of  $Y_{EVH} = 10.67 \pm 0.08$  ppm from the production data. The CalibN runs determine  $\beta = \frac{\Delta\lambda}{Y_{EVH}} = 1.30 \pm 0.08$  ( $s^{-1}/\text{ppm}$ ). The detection efficiency was  $\epsilon_N = 0.64$ . The lifetime effect is  $\alpha = \frac{\Delta\lambda}{c_N} = 96$  Hz/ppm. Accordingly the yield  $Y_{EVH}$  has to be measured or constraint to better than 1.5 ppm to limit  $\Delta\lambda \leq 2$  Hz. This level of precision was achieved already in run 8. The yield uncertainty was only 0.08 ppm. The main error came from the uncertainty in the H<sub>2</sub>O contribution and the relative contribution of humidity and nitrogen. Overall, based on the experience of runs 8-11 we could argue that we can determine the nitrogen concentration to about  $7 \pm 5$  ppb.

In terms of N<sub>2</sub> concentration  $c_N$  the requirements are much harder in MuSun than in MuCap. According to  $\alpha$  given above a precision  $\Delta c_N \leq 20$  ppb is required for MuCap. In order to have the same correction  $\Delta\lambda \propto Y_{EVH}$  for MuCap and MuSun, the following condition must be fulfilled.

$$\phi^{MuSun} \Delta c_N^{MuSun} \lambda_{dN} = \phi^{MuCap} \Delta c_N^{MuCap} \lambda_{pN} \quad (1)$$

i.e.  $\Delta c_N^{MuSun} = \Delta c_N^{MuCap} / 21 \approx 1$  ppb.

In summary, it is very likely that we will achieve the required 1 ppb purity at cryo temperatures. However, the explicit verification of this fact will be hard. It requires to determine  $\Delta Y_{EVH}$  to 1 ppm or alternatively  $\Delta c_N$  to 1 ppb. The former condition was easily met in MuCap, the latter condition was not reached and the different temperature of target (30K) and monitor (70-300K?) will complicate the interpretation.

## 2 Chromatographic Purity Monitoring

As pointed out by Bernhard, the N vapor pressure around 30 K is a steep function of temperature: “Looking at the vapor pressure curve for nitrogen (from Wutz-Adam-Walcher - Handbuch Vakuum Technik) given to be

T (K)	34.1	31.4	29.0	27.0
P (mbar)	E-3	E-4	E-5	E-6

... Should this be an argument to design the muSUN working temperature to be 29 K or even 27 K this does not make a big difference from the kinetics point of view and from the cooling requirements, but likely a large difference from the impurity level.”

I tried to verify the numbers and found only Ref <sup>1</sup>, which gives

$$\log_{10}P = 7.614676 - 356.281/T(\text{torr}) \quad (2)$$

for T down to 45 K. Fig 1 plots this curve, albeit outside its experimental range. 27 K is probably not

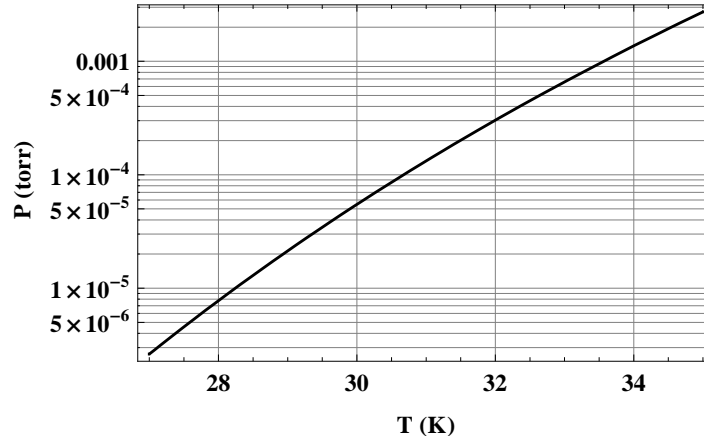


Figure 1: Solid nitrogen saturated vapor pressure.

possible with the Ne cryogen, but the CHUPS team should investigate the impact and consequences of this curve. How sensitive are we to the exact temperature stabilization? Can we use temperature variations to extrapolate the N<sub>2</sub> impurities? Sasha et al comments in the appendix.

The CHUPS team proposed an idea discussed over the past years. A N<sub>2</sub> getter should be placed directly in the CHUPS flow. In this way several 1000 l of D<sub>2</sub> would be passed through this getter per day, dramatically increasing the sensitivity compared to our 20 l typical gas samples. Apart from the technical implementation, the calibration of the getter at this extreme sensitivity level has to be addressed. Moreover, since the target is at low temperatures with T sensitive vapor pressure, a detailed strategy on how to relate the target conditions to the getter measurements, probably performed in a higher temperature environment is needed. Sasha et al comments in the appendix.

### 3 Purity Monitoring by Particle Detection

A direct in-situ signal proportional to the N<sub>2</sub> contamination would be by far the best. However, the detection of  $\mu + N$  capture products is complicated by the intense fusion physics background. The chances for selecting the capture products are estimated based on the spectra shown in Ref. [2].

process	distribution	yield/ $\mu$	efficiency estimate	total observed events
$\mu \rightarrow e\nu\bar{\nu}$	el(t)	0.9992	0.37	$1.3 \times 10^{10}$
$dd\mu \rightarrow {}^3\text{He} + n + \mu$	fus(t)	0.0305	1.00	$1.1 \times 10^9$
$\mu + d \rightarrow n + n + \nu$	capN(t)	0.0015	0.02	$1.1 \times 10^6$
$\mu + {}^3\text{He} \rightarrow t + \nu$	capT(t)	$1.2 \times 10^{-5}$	1.00	$4.3 \times 10^5$
$\mu + N \rightarrow C^* + \nu$				$3.5 \times 10^5$

Table 2: Total number of events for different processes based on  $N=3.5 \times 10^{10}$  and estimated detection efficiencies (column 3). The impurity capture events are based on typical MuCap conditions of  $10^{-5}$  observed captures/muon. The impurity level should improve at low T=30 K.

The expected time spectra and total statistics for some observable particles in MuSun are summarized in figure 3 and table 2. For our 30 K condition a delayed time window, which excludes the

<sup>1</sup><http://www.npl.uiuc.edu/exp/musun/literature/technology/purity/frels74.pdf>,  
<http://www.npl.uiuc.edu/exp/musun/literature/technology/purity/scott76.pdf>

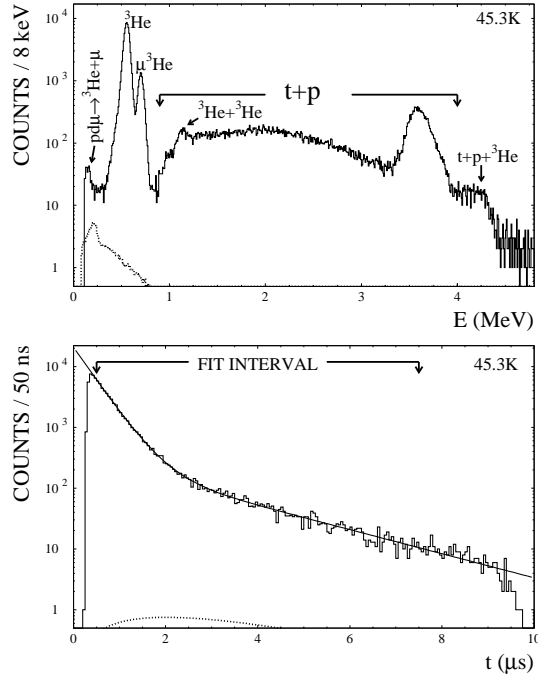


Figure 2: Charged particle spectra after muon stop from Ref. [2]. The conditions were  $T=45.3$  K,  $\phi=0.0524$  and nitrogen impurity level  $c_N \approx 41$  ppb.

intense quartet  $dd\mu$  formation, will reduce the He background 10 fold compared to fig.2. An additional factor 1.4 suppression can be gained by requiring events with no decay electron. If this factor 14 is sufficient for 1 ppb sensitivity, we would get an impurity capture statistics of several  $10^4$ , which is more than sufficient. Note that the  $^3\text{He}$  tail under the capture spectrum can be measured precisely with the survived muon method.

But more likely an additional tag (X-ray, capture FADC signature, capture neutron) is required. Define the tagging efficiency as  $\kappa$ . If  $\kappa \approx 0.01$  then we would expect some 1000 tagged capture events over the whole run, which already gets marginal. Probably a  $^3\text{He}$  suppression by the tag by an order of magnitude is sufficient.

We need to compare configuration a), where the additional tagging detector is part of the main set-up, which has the price of reducing its solid angle, with configuration b), where it is positioned close to the TPC vessel wall and a dedicated run without the eDet is performed. We will modify the beam pipe such that the eDet can be rolled upstream, and the new detectors placed around the TPC, which is rolled a bit downstream relative to its nominal detection position.

From fig. 5 we see that the additional detectors can be placed at  $R_o=390$  mm and  $R_i=185$  mm for configuration a) and b), respectively. Naively the ratio of solid angles is  $(\frac{R_o}{R_i})^2 \approx 4$  and the signal/noise is favorable for configuration b).

The tagging processes considered are the following

### Capture recoil topology in TPC

Not much is known about the proton emission after  $\mu^{14}\text{N} \rightarrow \nu + ^{14}\text{C}^*$  capture. Measday estimates its BR to about 13% probably based of Ref. <sup>2</sup>, Ref.[3], Fig. 6. But Morinaga and Fry don't really mention nitrogen. Peter W will study our data. We have to carefully consider what to expect from the protons, they may be high energy with small  $dE/dx$ . Moreover, the overlap with the muon will be large given the poor TPC granularity. Also the recoil proton will overlap with the C recoil, smearing up the resolution. This would be a reason for cathode induction wires? Do we need additional detectors on the TPC side to tag the protons? We need guidance from Peter's analysis and a dedicated study. The

<sup>2</sup>H. Morinaga, W.F. Fry, Nuovo Cimento Ser. 9 (10) (1953) 308

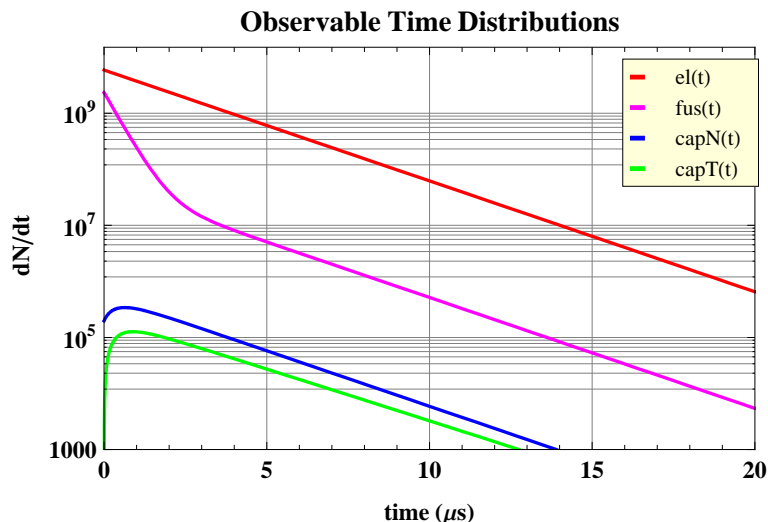


Figure 3: Observable time distributions for total good muon statistics  $N=3.5 \times 10^{10}$ .

first goal is to parameterize run10 nitrogen events with charged particle emission in terms of BR and ( $t_{capture}$ , length of observable track, blue/green at end, leaving TPC y/n).

#### Characteristic X-rays after transfer

Transition	$\mu N$ energies (keV)	Tn (H2 + 1.99% N2)	Tn (D2 + 1.07% N2)
2-1	102.403	0.363	0.370
3-1	121 <sup>*</sup> )	0.252	0.252
4-1	128	0.263	0.251
5-1	131	0.122	0.127

Table 3: Relative intensities Tn for ground-state transfer from both mp and md atoms to nitrogen measured in hydrogen and in deuterium mixtures at 5 bar and room temperature [5]. <sup>\*</sup>) estimate.

material	Be	Al	NaI	Ge
$\rho$ (g/cm <sup>3</sup> )	1.85	2.7	3.67	2.3
mass attenuation (cm <sup>2</sup> /g)	0.133	0.169	1.65	0.555
attenuation length (mm)	40.6	21.91	1.65	7.834

Table 4: Attenuation for 100 keV gammas.

According to table 3 the probability of Lyman X-rays after transfer is nearly 100%. Table 3 indicates that 4 mm of Al leads to 20% attenuation. A 5 mm NaI has more than 90% absorption efficiency. As an example let's estimate the yield in a 5"  $\times$  1 cm NaI and a Ge (GEM-FX8530P4, diameter=8.5cm, length=3.0)<sup>3</sup>. We define the two positions as  $R_o=390$  mm and  $R_i=185$  mm, like above and get the following solid angles for NaI and Ge, respectively.

$$\begin{aligned}\Omega_i(NaI) &= 0.03 \\ \Omega_o(NaI) &= 0.007 \\ \Omega_i(Ge) &= 0.013\end{aligned}$$

<sup>3</sup><http://www.ortec-online.com/detectors/photon/profile.htm>

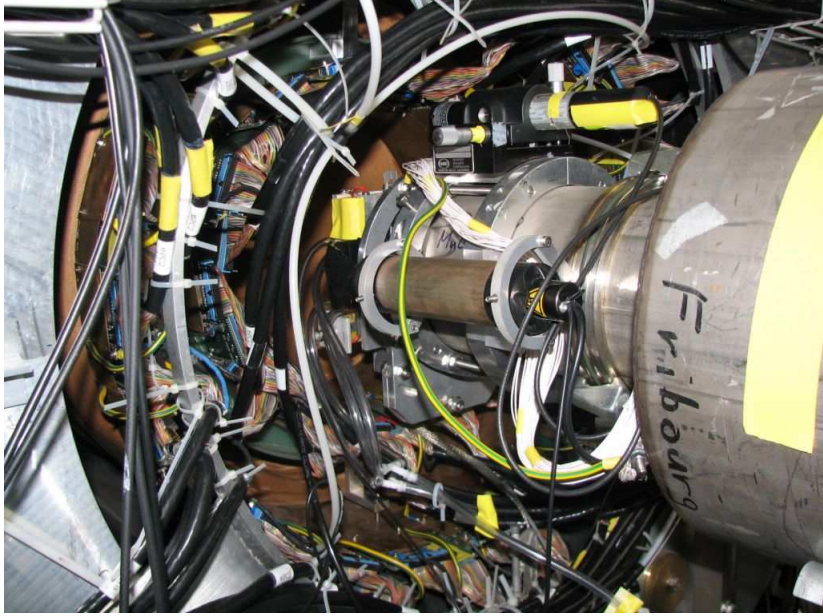


Figure 4: Beam pipe and detectors

$$\Omega_o(Ge) = 0.003 \quad (3)$$

Assuming the TPC fiducial stopping rate is  $1.2 \cdot 10^4$ , the X-ray & observed capture event rate branching ratio is  $10^{-5}$ , and the total X-ray detection efficiency is  $0.9 \times \Omega$ , we would observe the following event numbers per day

$$\begin{aligned} N_i(NaI) &= 274 \\ N_o(NaI) &= 61 \\ N_i(Ge) &= 123 \\ N_o(Ge) &= 27 \end{aligned} \quad (4)$$

Thus there might be two attractive options. i) Get two slabs of NaI into the insulation vacuum and read out through a flange window. This would be a powerful possibility if the signal to noise is good enough <sup>4</sup>. ii) Make 2-3 days runs interspersed during the run to measure  $N_i(Ge)$  with about 3-4 Ge detectors of the specifications above. Clearly these approaches should be tested in the fall 2008 run, to determine a viable solution.

### Neutrons from capture process

Neutron spectra for oxygen are given in Ref. [4]. I leave it to Tim to estimate what tagging efficiency we could get by observing capture recoils in the TPC in coincidence with neutrons above 2.5 MeV.

Their probabilities and detection efficiencies for different geometries have to be estimated.

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<sup>4</sup>In this case one would also check for nuclear gamma rays during capture

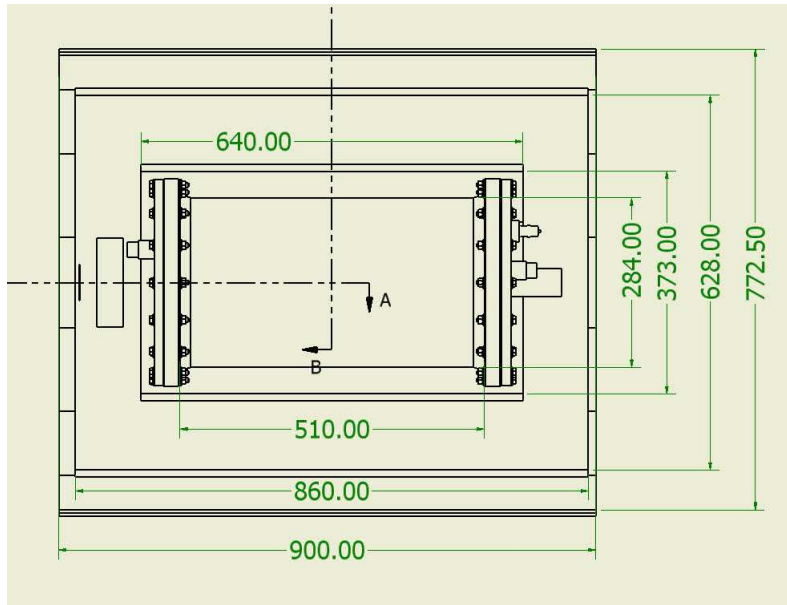


Figure 5: Detector dimensions

### Muon Capture in "Gases"

	C	N	O	Ne	Si	Ar
+1uff factor	1.00	1.00	0.998	0.997	0.992	0.988
$\mu^-$ decay rate ( $10^3 \text{ s}^{-1}$ )	455.16	455.16	454.2	453.8	451.5	449.7
Capture rate ( $10^3 \text{ s}^{-1}$ )	37.9(5)	66(4)	102.5(10)	231(10)	871.2(18)	1270(80)
Total rate ( $10^3 \text{ s}^{-1}$ )	493.1(5)	521(4)	556.7(10)	685(10)	1322.7(18)	1720(80)
$\tau(\mu^-)$ ns	2028(2)	1919(15)	1796(3)	1460(21)	756(1)	581(25)
Capture/Total (%)	7.69(9)	12.7(6)	18.4(2)	33.7(10)	65.87(4)	73.8(12)
Bound states (%)	18.6(7)	9(2)	11(1)	~15	26(3)	~15
1n	50	47(8)	66	<b>55</b>	46	57
2n	18	31(8)	10	10	13	20
p d $\alpha$	13(2)	13(2)	13(2)	20(4)	15(2)	8
Recoil Energy ( $85 \text{ MeV}/c$ )(MeV)	0.35	0.30	0.26	0.20	0.14	0.10
Range in $\text{H}_2$ 10bar (mm)	0.65		0.41			

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March 27, 2000

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Figure 6: Dave Measday's table

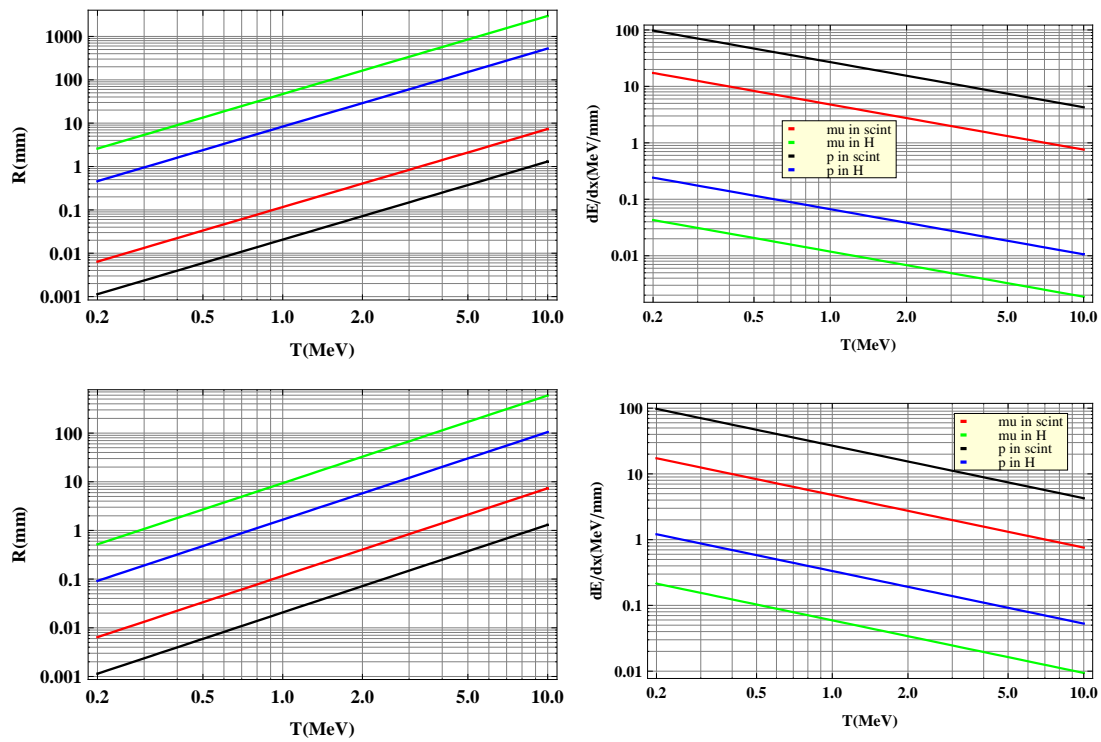


Figure 7: Calculated range and  $dE/dx$ . top: Density  $\phi=1\%$ , bottom: Density  $\phi=5\%$

## 4 Test Measurement with Protium

A protium measurement should easily allow us to obtain the required capture yield sensitivity. While a lot can be learned with such a measurement, our MuCap experience up to now shows that the purity situation in each filling is somewhat different, so some uncertain extrapolation between the H2 and D2 measurements is required.

## 5 Appendix

### 5.1 Sasha's comments

#### p.1.

“Table nitrogen vapor pressure.”

This table is correct ONLY in vacuum. It is not correct for the small admixtures in another gas. There are no real data for it because it strongly depends from the TYPE OF SURFACE. Physical explanation is very simple. In the main gas (deuterium) you have Maxwell's distribution of velocities (energy of molecule). It means at any temperatures you will have the molecules which push admixture atoms on the surface and increase the admixture partial pressure. Tendency is correct, but to say these will be the real numbers in deuterium will be absolutely incorrect. We had the water in liquid hydrogen! So, I propose to say "in a soft way" decreasing of temperature decreases the outgasing rate inside the chamber and presented table "demonstrate" this process.

We can decrease the temperature of the chamber up to 25-26K without big problems. But you have to understand that at low temperatures you will have the LOWER gas density. (see <http://webbook.nist.gov/chemistry/fluid/>). If you change temperature from 28K to 35K the density

27K	1.2 mol/l
29K	1.8
32K	3.2
34K	4.7 mol/l

We prefer to work at low temperature (purity + low pressure) but you will have lower density.

#### p.2.

“temperature and pressure stabilization.”

We will have temperature stabilization +/-0.05K independently on the both ends of the chamber. The knowledge of the absolute temperature will be +/-0.1K for each temperature sensor. It means the average temperature in the chamber (gas temperature) will be about +/-0.15K.

This value we can reach WITHOUT any additional calibrations. If we will make special calibrations we can reach +/-0.05 - 0.07K. Pressure will be stabilized +/- 1 mbar by CHUPS.

“getter”

We did not propose any new ideas. Idea of getter implementation is simple expansion of the probe up to few cubic meters. Calibration is clear (not simple, but clear).

If we have gas flux from the chamber and you ONLY increase the gas temperature after the chamber you will get after the some time (for oxygen and nitrogen fast enough) absolutely the same ppb concentration as in chamber. You can change concentration ONLY if you have temperature points on the line LOWER than in chamber. This is the reason why I refused to cool getter by liquid Ne. Getter will be at temperature of liquid N2.

This structure will kill our water measurements but with water we really can not make correct measurements with the cold chamber. Out output tube will be more wet than the cryogenic chamber.

I want to say that we are going to have the zeolite box just before the chamber at temperature 26-27K (lower than the chamber itself). This will be the temperature of the cooling Ne. I hope that this one produce the super pure gas.



## 6 References

### References

- [1] V. A. Andreev et al. Measurement of the rate of muon capture in hydrogen gas and determination of the proton's pseudoscalar coupling  $g_p$ . *Phys. Rev. Lett.*, 99:032002, 2007.
- [2] D.V. Balin et al. *PNPI Preprint*, 2729, 2007.
- [3] D. F. Measday. The nuclear physics of muon capture. *Phys. Rept.*, 354:243–409, 2001.
- [4] M. E. Plett and S. E. Sobottka. Effects of the giant resonance on the energy spectra of neutrons emitted following muon capture in c-12 and o-16. *Phys. Rev.*, C3:1003–1010, 1971.
- [5] Y.-A. Thalmann et al. Muon transfer from excited states of hydrogen and deuterium to nitrogen, neon, and argon. *Phys. Rev. A*, 57(3):1713–1720, Mar 1998.