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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)	λ_{pZ} ($10^{10}s^{-1}$)	Ref	λ_{dZ} ($10^{10}s^{-1}$)	Ref
N	0.04	3.4 ± 0.7		14.5 ± 0.2	
O	0.04	8.5 ± 0.2		6.3 ± 0.5	

Table 1: Muon transfer rates from μp and μd 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}/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_2O contribution and the relative contribution of humidity and nitrogen. The nitrogen concentration contributing to this yield was determined to be $\approx 7 \pm 5$ ppb.

In terms of N2 concentration c_N the requirements are much harder in MuSun than in MuCap. According to α given above a precision $\Delta c_N \leq 20$ ppb is required for MuCap. In order to have the same correction $\Delta\lambda \propto \bar{Y}_{EVH}$ for MuCap and MuSun, the following condition must be fulfilled.

$$\phi^{MuSun} \Delta c_N^{MuSun} \lambda_{dN} = \phi^{MuCap} \Delta c_N^{MuCap} \lambda_{pN} \tag{1}$$

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 ΔY_{EVH} to 1 ppm or alternatively Δc_N to 1 ppb. The former conditon was easily met in MuCap, the latter condition was not reached and the different temperature of target (30K) and monitor (300K) will complicate the interpretation.

2 Chromatographics 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 [1], which gives

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

for T down to 45 K. Fig 1 plots this curve, albeit outside its experimental range. 27 K is probably not 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_2 impurities?

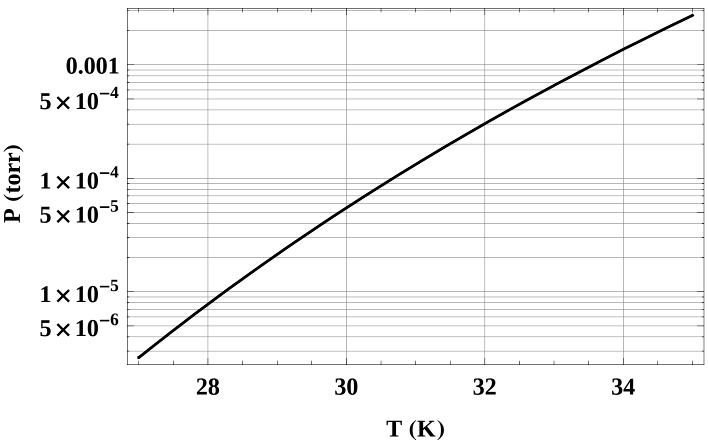

Figure 1: Solid nitrogen saturated vapor pressure.

The CHUPS team proposed an idea discussed over the past years. A N_2 getter should be placed directly in the CHUPS flow. In this way several 1000 l of D_2 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 please discuss a plan.

3 Purity Monitoring by Particle Detection

A direct in-situ signal proportional to the N2 contamininination 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/μ	efficiency estimate	total observed events
$\mu \rightarrow e\nu\bar{\nu}$	el(t)	0.9992	0.37	1.3×10^{10}
$dd\mu \rightarrow {}^3He + n + \mu$	fus(t)	0.0305	1.00	1.1×10^{9}
$\mu + d \rightarrow n + n + \nu$	capN(t)	0.0015	0.02	1.1×10^{6}
$\mu + {}^3He \rightarrow t + \nu$	capT(t)	1.2×10^{-5}	1.00	4.3×10^{5}
$\mu + N \rightarrow C^* + \nu$				3.5×10^{5}

Table 2: Total number of events for different processes based on N=3.5×10^{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

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[1] http://www.npl.uiuc.edu/exp/musun/literature/technology/purity/frels74.pdf, http://www.npl.uiuc.edu/exp/musun/literature/technology/purity/scott76.pdf

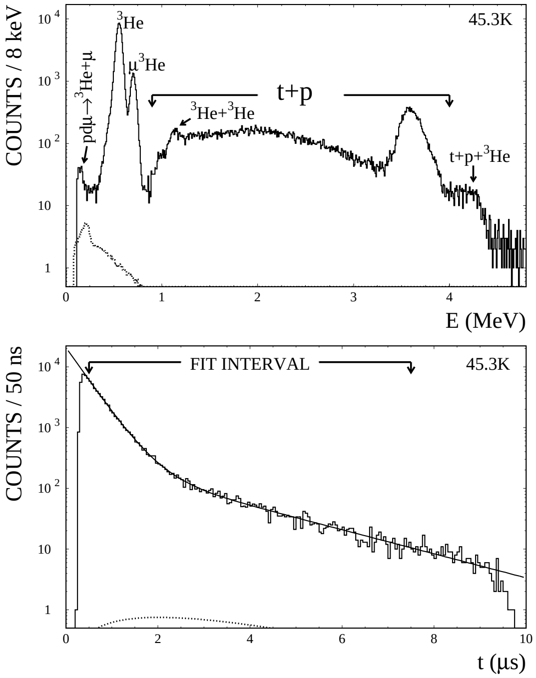

Figure 2: Charged particle spectra after muon stop from Ref. [2]. The conditions were T=45.3 K, ϕ=0.0524 and nitrogen impurity level $c_N \approx 41$ ppb.

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 his factor 14 is sufficient for 1 ppb sensitivity, we would get an impurity capture statistics of several 10^4, which is more than suffient. Note that the ^{3}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 κ. 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}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_a=390 mm and R_b=185 mm for configuration a) and b), respectively. Naively the ratio of solid angles is $(\frac{R_a}{R_b})^2 \approx 4$ and the signal/noise is favorable for configuration b).

The tagging processes considered are the following

- Capture recoil topology in TPC [2], Ref.[3], Fig. 6. We have to carefully discuss what to expect from the protons, they may be high energy with small dE/dx. Do we need additional detectors?
- Characteristic X-rays after transfer. 2p-1s energy= 102.403 keV.
- Neutrons from capture process [4].

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

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[2] H. Morinaga, W.F. Fry, Nuovo Cimento Ser. 9 (10) (1953) 308

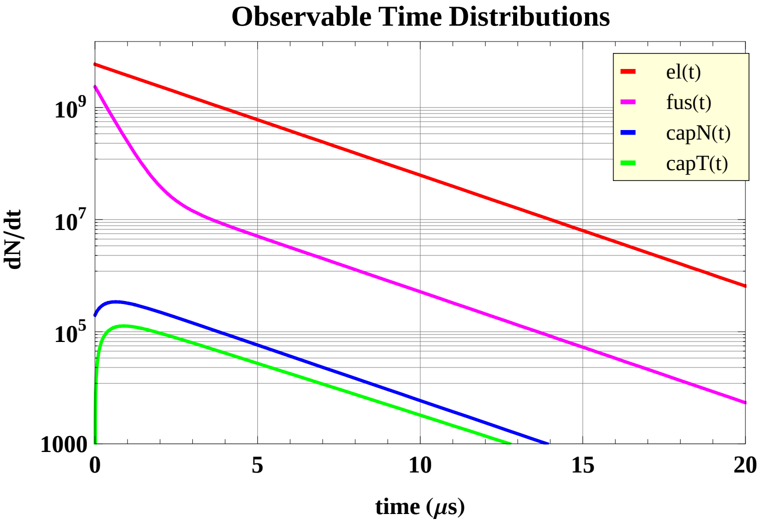


Figure 3: Observable time distributions for total good muon statistics N=3.5× 10^{10}.

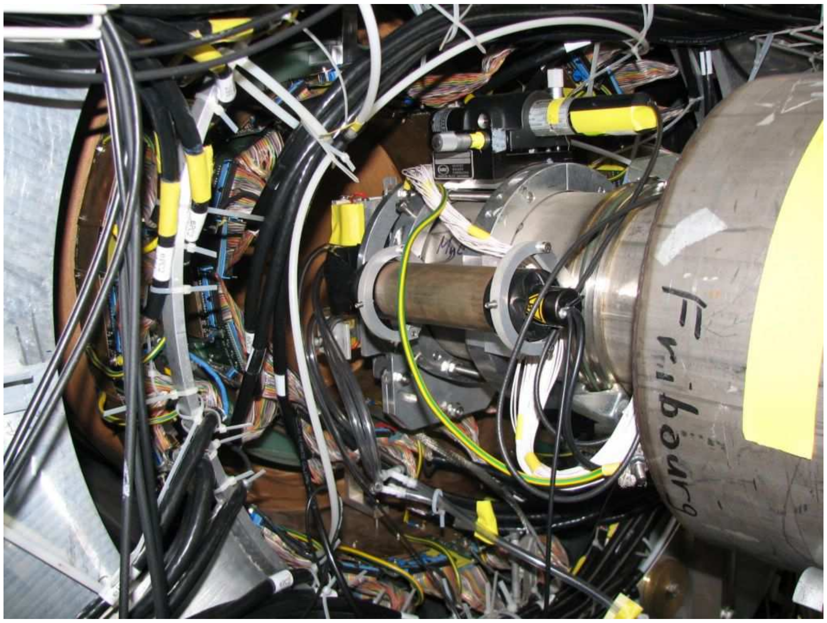


Figure 4: Beam pipe and detectors

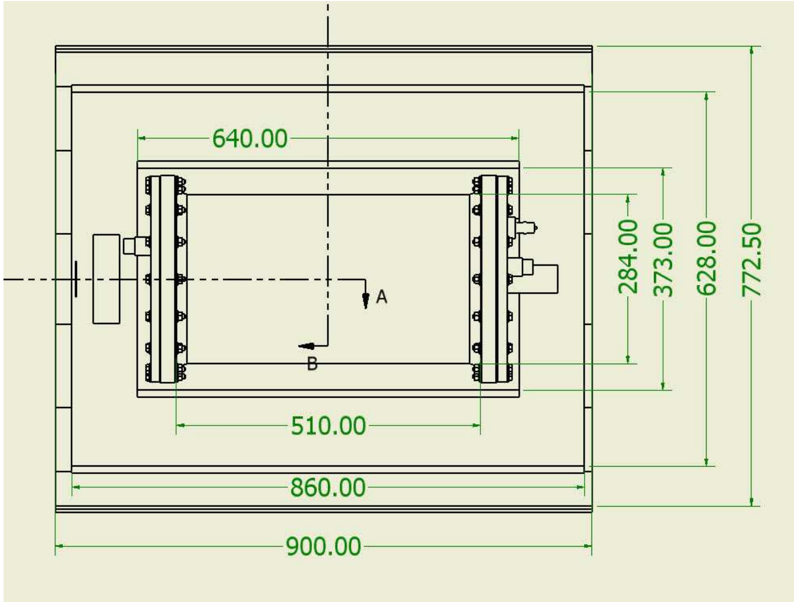
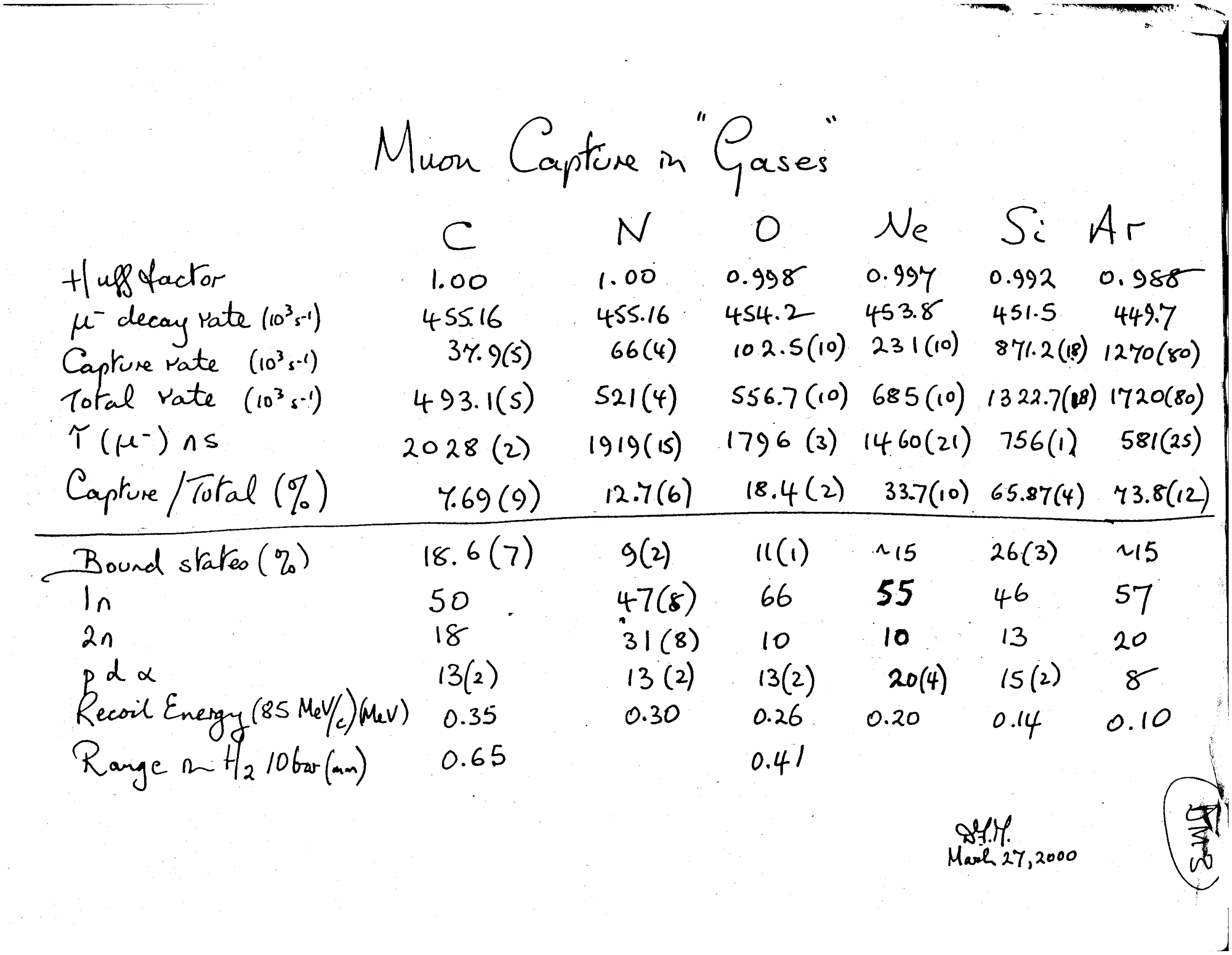


Figure 5: Detector dimensions



Muon Capture in "Gases"

	C	N	O	Ne	Si	Ar
Huff factor	1.00	1.00	0.998	0.997	0.992	0.988
μ^- decay rate ($10^3 s^{-1}$)	455.16	455.16	454.2	453.8	451.5	449.7
Capture rate ($10^3 s^{-1}$)	37.9(5)	66(4)	102.5(10)	231(10)	871.2(18)	1270(80)
Total rate ($10^3 s^{-1}$)	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	55	46	57
2n	18	31(8)	10	10	13	20
p d α	13(2)	13(2)	13(2)	20(4)	15(2)	8
Recoil Energy (85 MeV/c) (MeV)	0.35	0.30	0.26	0.20	0.14	0.10
Range in H_2 10bar (mm)	0.65		0.41			

D.F.M.
March 27, 2000

Figure 6: Dave Measday's table

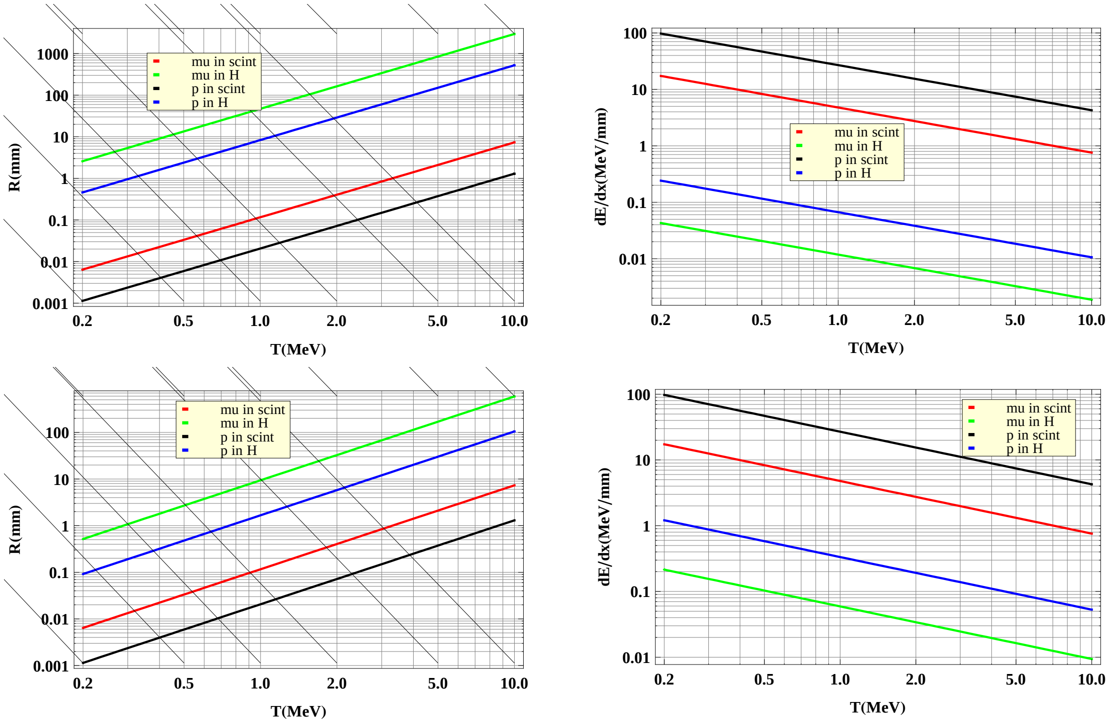


Figure 7: Calculated range and dE/dx. top:Density ϕ=1%, bottom: Density ϕ=5%. Have to fix the ugly guys

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 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.