Production of Muonium in Vacuum

Glen Marshall, TRIUMF

KEK-TRIUMF Workshop on Ultra Slow Muons

March 8-9, 2012

Outline

- Methods of production
  - in-flight charge exchange
  - thermal from hot metal foils
  - thermal from oxide nanostructures
- Production of μ^+e^- from powders and aerogels
  - muonium production in various oxides
  - yield into vacuum using $\mu\mathcal{SR}$
  - yield from layer of oxide material via decay position
- Recent TRIUMF experiments – S1249
  - material tests
  - decay positron and remnant electron imaging
  - diffusion model and preliminary comparisons to data
  - outlook for vacuum ionization of muonium for ultraslow μ^+ beams

Methods of μ^+e^- production in vacuum

- Formation via muons in flight
  - energy determined by charge exchange cross sections
  - P.R. Bolton et al., Phys. Rev. Lett. 47, 1441 (1981).
- Applied to μ^+e^- (Mu) Lamb shift
  - C.J. Oram et al., Phys. Rev. Lett. 52, 910 (1984)
  - A. Badertscher et al., Phys. Rev. Lett. 52, 914 (1984).

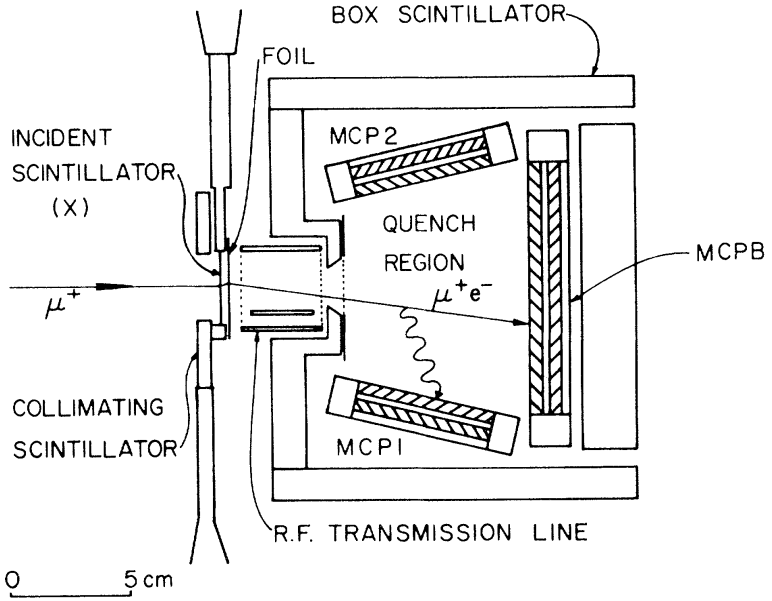


FIG. 2. A schematic of the apparatus, showing a good event in which a Lyman α photon is detected in microchannel plate (MCP1) from deexcitation of $\mu^+e^-(2S)$ in the quench region.

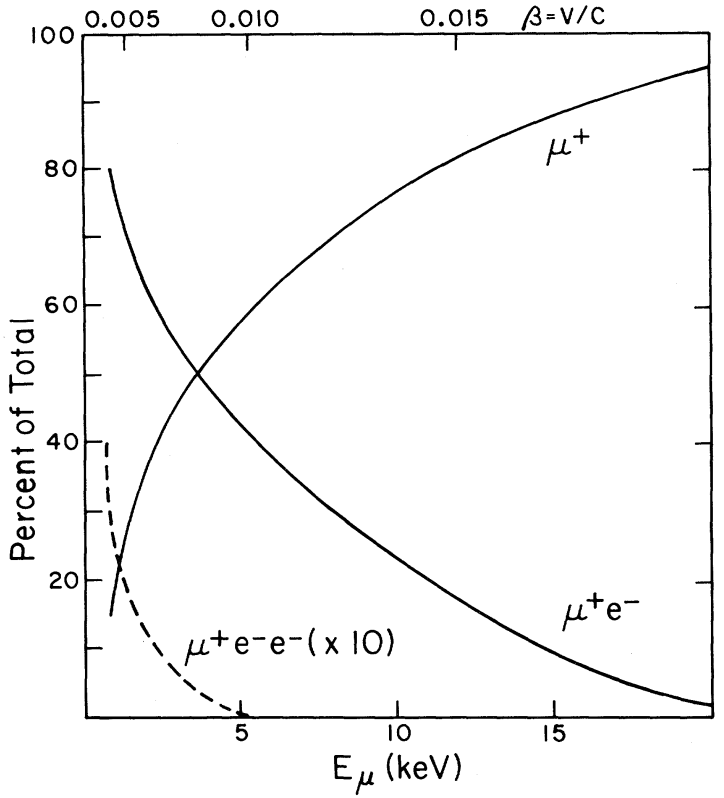


FIG. 1. Expected charge-state distribution for muons emerging from foil targets.

Methods of μ^+e^- production in vacuum

- Emission from hot metal foil
  - emission of μ^+ from surface as Mu
  - analogy to proton diffusion in metal
- Early development by University of Arizona group at LBL
  - for $\mu^+e^- \rightarrow \mu^-e^+$ search
  - first application of "Arizona" or surface muons (T. Bowen)
  - K.R. Kendall, PhD, University of Arizona (1972)
- Demonstration by AT&T/UT-MSL/Tsukuba at KEK
  - for experiment on Mu in vacuum and slow μ^+ beam; W target, yield and temperature dependence
  - A.P. Mills et al., Phys. Rev. Lett. 56, 1463 (1986)
- Laser ionization by UT-MSL/RIKEN group at KEK
  - to produce slow muon beams
  - K. Nagamine et al., Phys. Rev. Lett. 74, 4811 (1995)
- Thermal emission from Pt group metals
  - Pt, Ir, W comparison; diffusion analysis
  - A. Matsushita and K. Nagamine, Phys. Lett. A 244, 174 (1998)

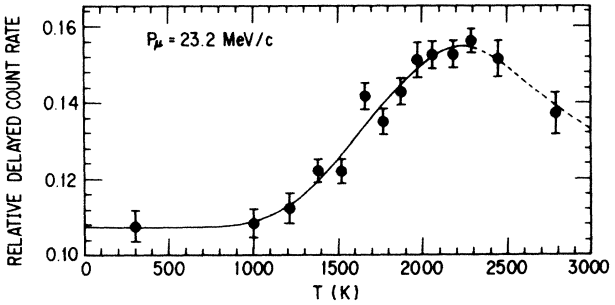


FIG. 3. Temperature dependence of the delayed events in Fig. 2(a) summed over the time interval from 2 to 6 μsec. The fitting curve represents an Arrhenius-type activation with a correction due to μ^+ trapping at thermal vacancies at high temperature.

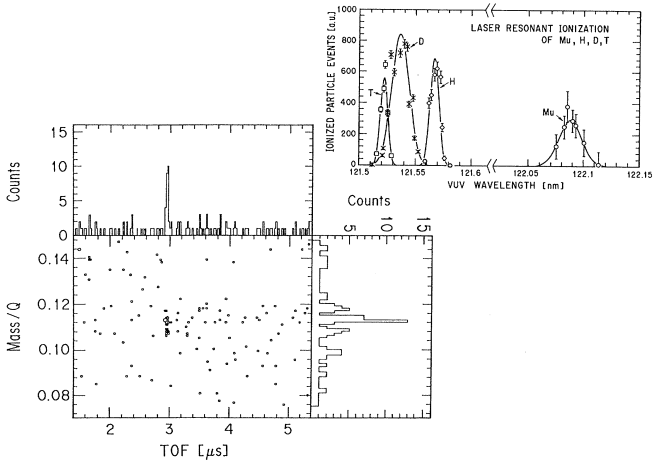


FIG. 2. Evidence for the ultraslow μ^+ production seen in the mass-TOF two-dimensional histogram and a resonance curve for the laser ionization of thermal Mu obtained by changing the VUV frequency. The inset shows resonance curves for the laser ionization of thermal Mu with reference to those of thermal H from residual H_2 gas, thermal D from introduced D_2 gas, and from thermal T of reaction products.

Methods of μ^+e^- production in vacuum

- Emission from oxide nanostructures
  - diffusion of muonium at room temperature
  - analogy to positronium emission
- Early development by TRIUMF/UBC
  - for $\mu^+e^- \rightarrow \mu^-e^+$ search
  - $\mu\mathcal{SR}$ shows depolarization of Mu by O_2 in silica powder, fast release from 7 nm particles
  - G.M. Marshall et al., Phys. Lett. 65A, 351 (1978)
  - silica shows more Mu formation (60%) and less depolarization (0.2/μs) than Al_2O_3, MgO, CaO
  - R.F. Kiefl et al., Hyperfine Interactions 6, 185 (1979)
- Observation of emission by TRIUMF/UVic/Arizona/Wyoming
  - more Mu in vacuum than predicted
  - D=80 cm^2/s, not 8 cm^2/s
  - G.A. Beer et al., Phys. Rev. Lett. 57, 671 (1986)
- Confirmation and polarization demonstration by Heidelberg/Yale
  - even more Mu in vacuum, D=1000 cm^2/s
  - K.A. Woodle et al., Z. Phys. D 9, 59 (1988)
- Different materials
  - aerogel: W. Schwarz et al., J. Non-Crystalline Solids 145, 244 (1992).
  - mesoporous thin films: A. Antognini et al., arXiv: 1112.4887

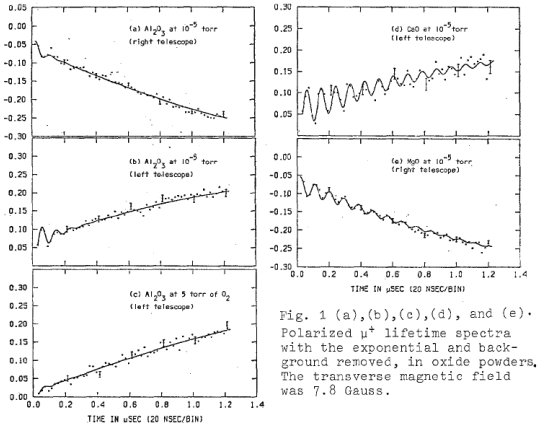


Fig. 1 (a),(b),(c),(d), and (e). Polarized μ^+ lifetime spectra with the exponential and background removed, in oxide powders. The transverse magnetic field was 7.8 Gauss.

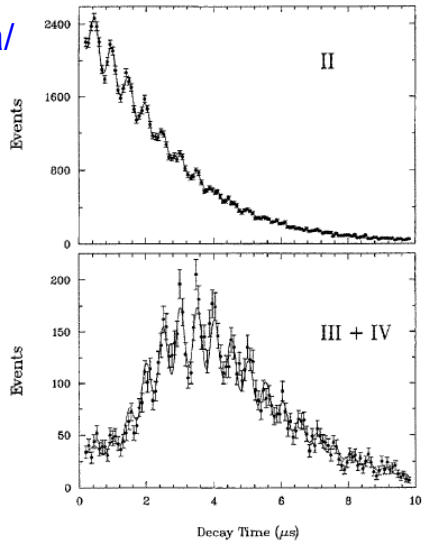


Fig. 4. Observed number of positrons as a function of time with an applied magnetic field of 1.4 G. The upper histogram corresponds to decays from Region II of Fig. 2 and the lower histogram to decays from Regions III and IV

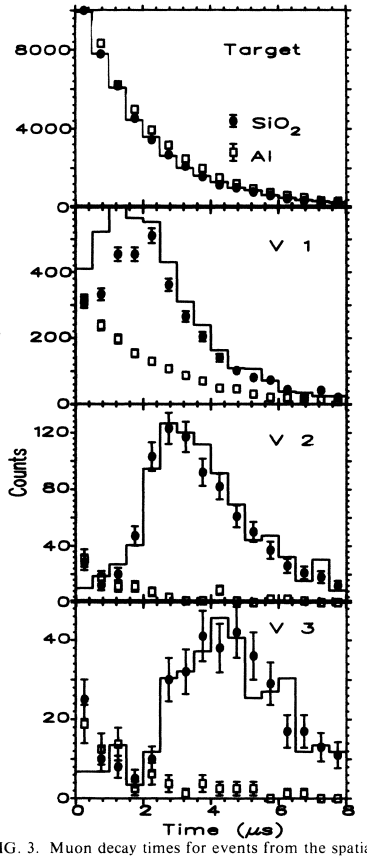


FIG. 3. Muon decay times for events from the spatial regions defined in Fig. 2. Filled circles represent the data from a 1-mg/cm^2 powder, open squares, those from a 3-mg/cm^2 Al foil, and the histograms result from the simulation calculation with diffusion constant of 80 cm^2/s.

Summary of muonium in oxide powders

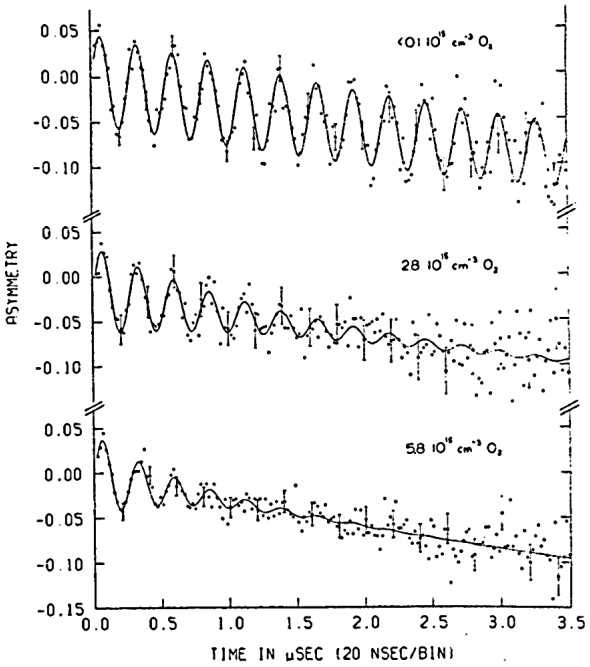
TABLE I

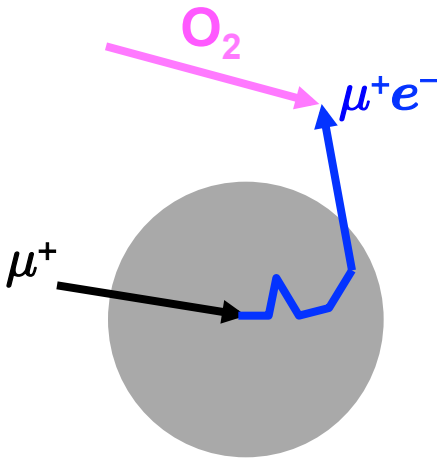
Sample (powder description)	μ^+ Asymmetry at time=0 $A_o^{\mu+}$	μ^+ Relaxation Rate $\lambda_R^{\mu+}$ μsec^{-1}	Mu Asy. at time=0 A_o^{Mu}	Mu Relax. Rate λ_R^{Mu} μsec^{-1}	Polarized μ^+ Fraction $F_{\mu+}$ %	Polarized Mu Fraction F_{Mu} %	Missing Fraction %	o-Ps Quench Rate λ_{o-Ps} μsec^{-1}	o-Ps Inter-granular Fraction F_{o-Ps} %
Al	.342±.006	.031±.009							
Fe_2O_3(coarse)	.070±.006	.009±.009							
SiO_2(35A)	.17 ±.02	.03 ±.02	.083±.004	.18±.04	35±5	61±3	4±6	.16±.08	26.4±2.6
CaO(coarse)	.185±.010	.07 ±.02	.047±.005	2.5±.6	43±3	35±4	22±5		
MgO(fine)	.262±.016	.05 ±.04	.020±.004	1.9±.5	71±6	15±3	14±7	.37±.09	14.3±1.4
Al_2O_3(150A)	.267±.013	.08 ±.02	.047±.018	11.3±4.4	72±4	35±14	-7±15	1.33±.14	24.6±2.4
GeO_2(coarse)	.18 ±.03	.044±.016	no signal		40±7		60±7		
SnO_2(coarse)	.336±.019	.056±.025	no signal		98±5		2±5		
SiO(coarse)	.24 ±.01	.049±.009	no signal		63.5±1		36±1		

R.F. Kiefl et al., Hyperfine Interactions 6, 185 (1979).

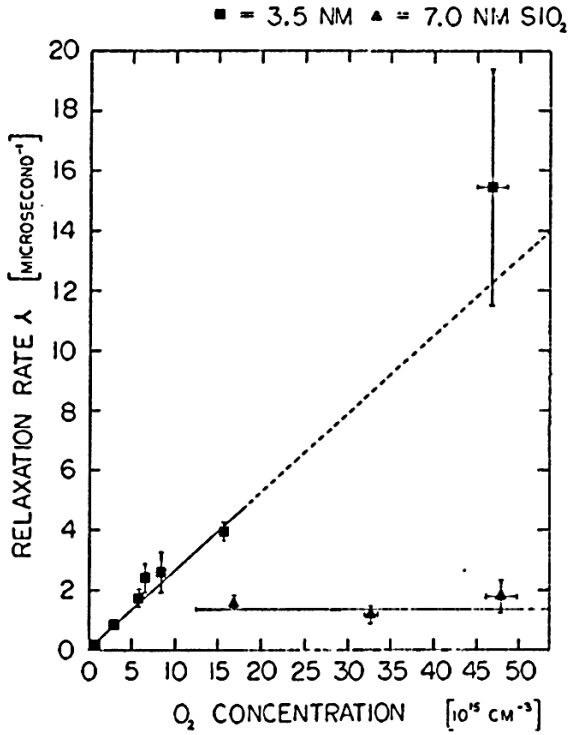
Muonium emission from fine silica

- What happens to the $\mu\mathcal{SR}$ signal when O_2 is added?
  - in an argon moderator, Mu polarization is destroyed by O_2 from spin exchange reaction.
- Disappearance of Mu polarization interpreted as evidence of μ^+e^- emission from powder particles into vacuum between particles.
  - particle sizes of 3.5 nm and 7.0 nm radius were measured
    - BET surface adsorption: 400 m^2/g, ρ = 2.2 g/cm^2, spherical geometry → r = 3.5 nm
  - diffusion constant $D_S=(2.2\pm0.4)\times10^{-7}$ cm^2/s, emission probability before decay ~97%
    - but note that muonium is still among the powder particles → surface interactions

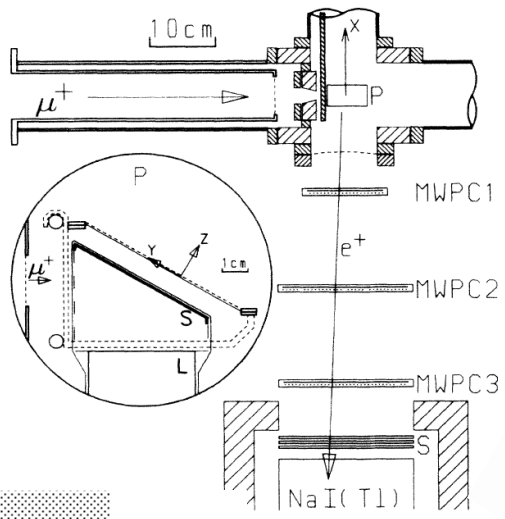


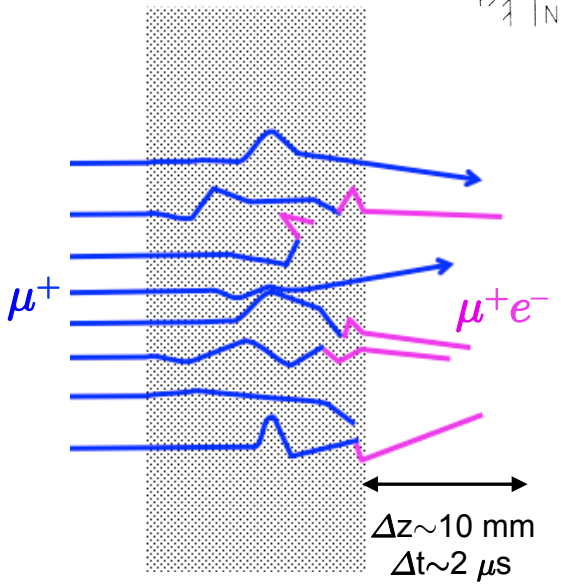


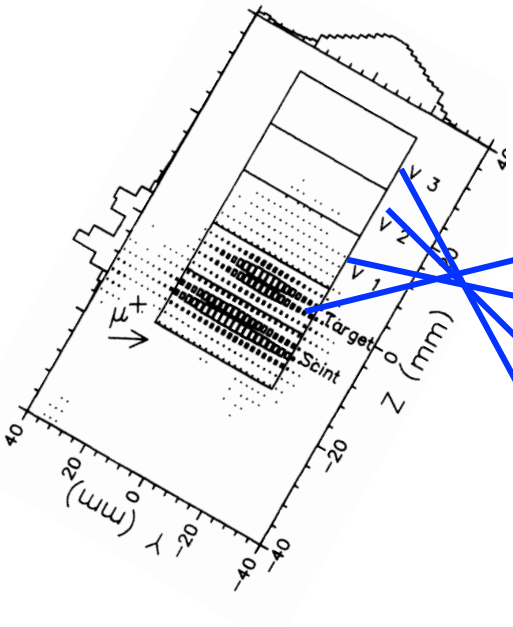
G.M. Marshall et al.,
Phys. Lett. 65A, 351 (1978)

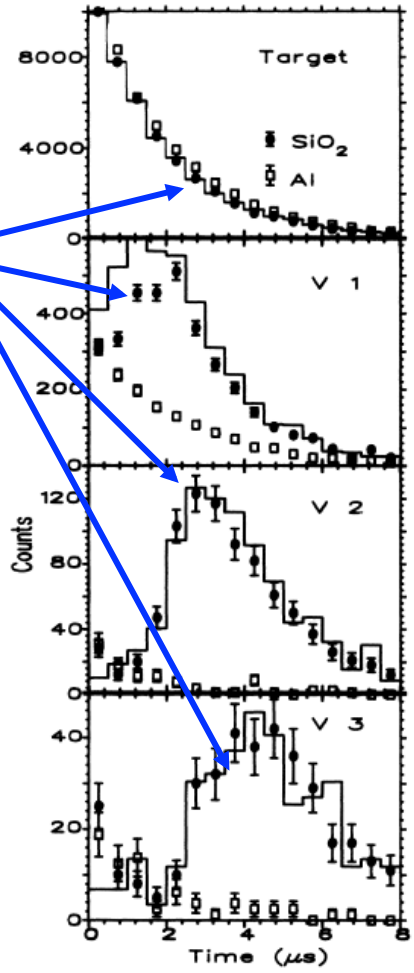


Muonium emission from a layer









Above: density plot of e^+ tracks extrapolated to beam axis.

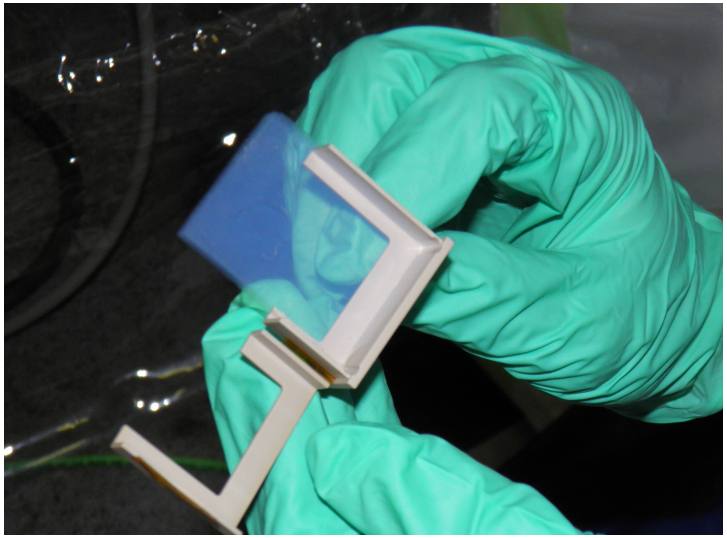
Right: time distributions for e^+ tracks for target and three vacuum regions.

μ^+e^- from SiO_2 powder layers: applications

- An incomplete bibliography
  - Muonium conversion experiments:
    - G.M. Marshall et al., Phys. Rev. D25 (1982) 1174
      - updated following G.A. Beer et al., Phys. Rev. Lett. 57 (1986) 671
    - T.M. Huber et al., Phys.Rev. D41 (1990) 2709
    - B.E. Matthias et al., Phys. Rev. Lett. 66 (1991) 2716 (erratum PRL 67 (1991) 932)
    - R. Abela et al., Phys. Rev. Lett. 77 (1996) 200
    - L. Willmann et al., Phys. Rev. Lett. 82 (1999) 49
  - Muonium 1S-2S experiments:
    - Steven Chu et al., Phys. Rev. Lett. 60 (1988) 101
    - V. Meyer et al., Phys. Rev. Lett. 84 (2000) 1136

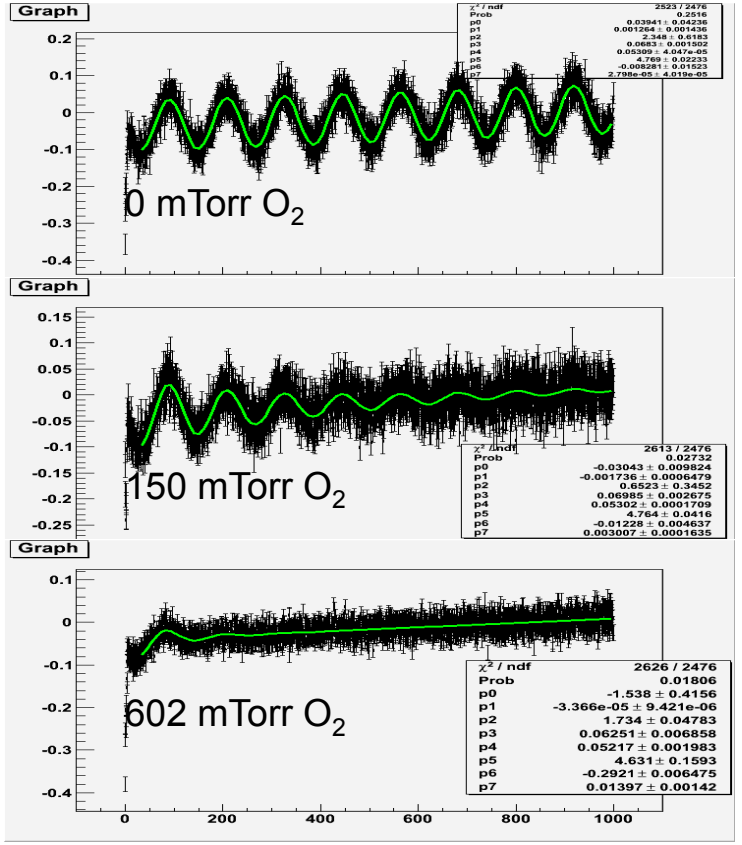
Recent results – S1249 at TRIUMF

- Motivated by J-PARC muon g–2 proposal
  - laser ionization of room-temperature Mu in vacuum
  - re-acceleration maintaining low transverse velocities
  - see following presentation of T. Mibe
- Is there a better Mu production and emission material?
  - powder is not easy to use
  - silica aerogels
    - ➤ new fabrication methods
  - newer mesoporous materials



S1249 − initial material selection

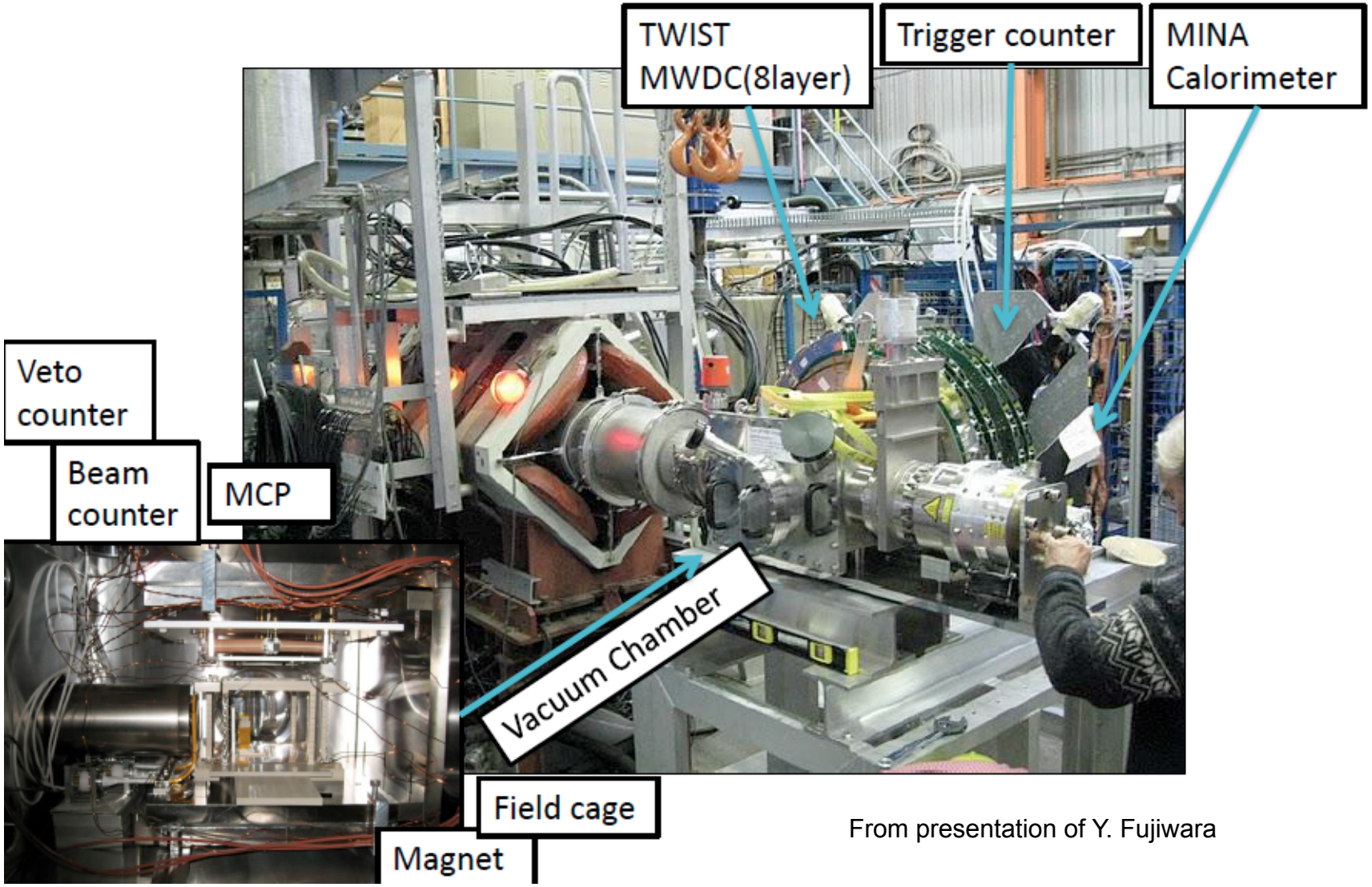
- A suitable target must have:
  - high probability of μ^+e^- formation.
    - insulating oxides
  - small muonium depolarization.
    - pure, with only weak depolarization mechanisms
  - significant emission of μ^+e^- from material into vacuum.
    - high specific surface area or small dimension unit structure
  - self-supporting structure, if possible.
    - powders difficult to evacuate
- Use TF-$\mu\mathcal{SR}$ to identify possibilities:
  - initial asymmetry of muonium precession → formation probability.
  - time dependence → depolarization.
  - fast depolarization with addition of O_2 → emission into voids.
- Promising materials with O_2 depolarization (F_{Mu}):
  - Aerogel* (0.60), nanogel® granules (0.70), and Cab-O-Sil® powder (0.65).
  - Aerogel is self-supporting!
- Others rejected
  - mesoporous silica – lower F_{Mu} (0.2), no relaxation from O_2, sensitive to preparation details
  - alumina − weak F_{Mu} (0.02), faster vacuum relaxation



Asymmetries vs time (ns) for 0.1 g/cm^3 aerogel
Analysis and graphs by S. Hirota.
Results of data taken in June 2010.

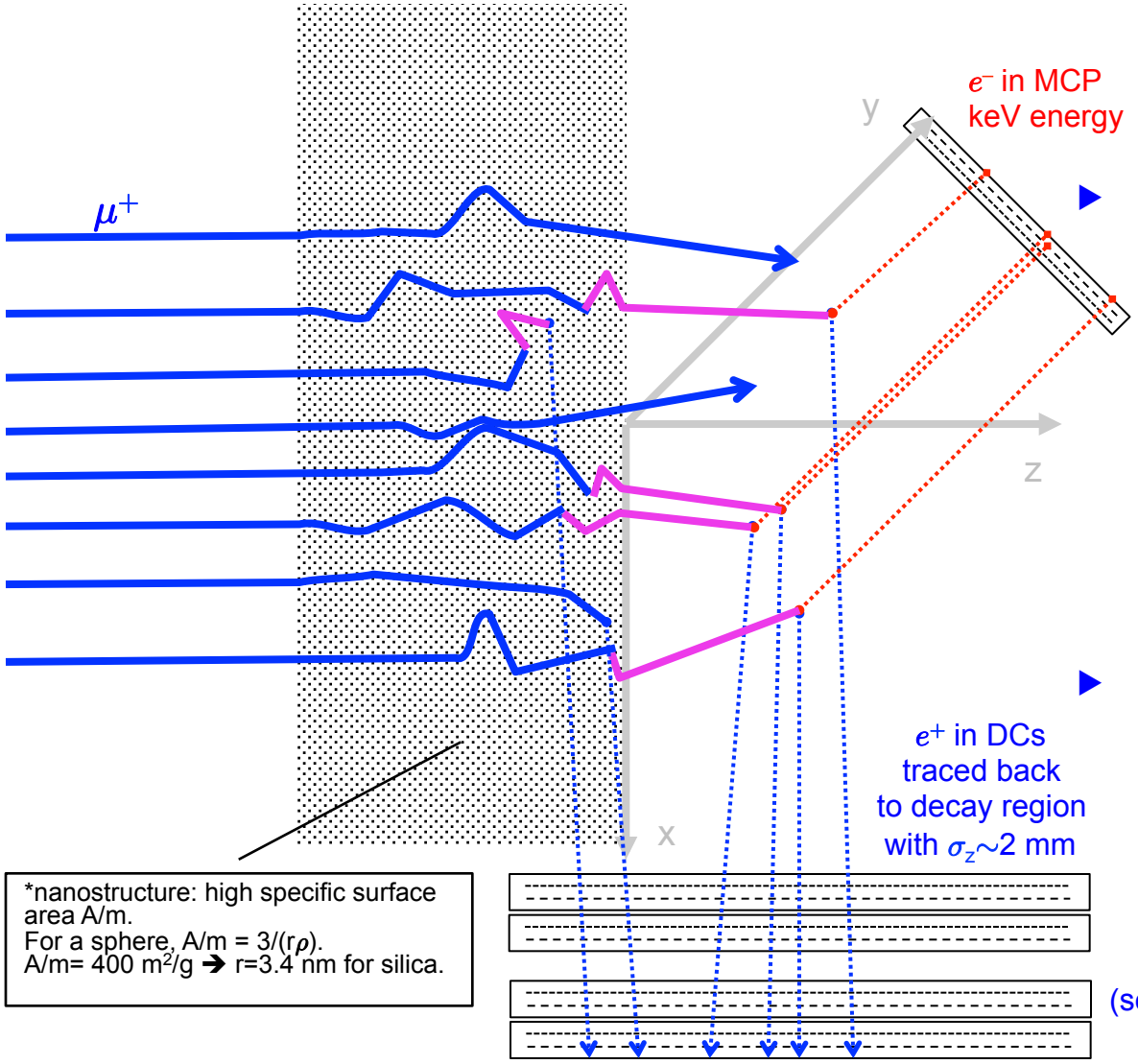
*Hydrophobic silica aerogel production reference:
M. Tabata et al., Nuclear Instruments and Methods A 668, 64 (2012)

S1249 – emission experiments



From presentation of Y. Fujiwara

S1249 – detect decay e^+ and atomic e^-

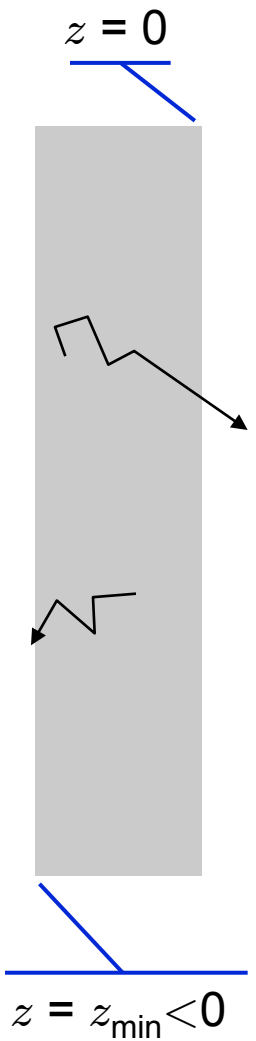


*nanostructure: high specific surface area A/m.
For a sphere, A/m = 3/(rρ).
A/m= 400 m^2/g ➔ r=3.4 nm for silica.

- Identify and characterize μ^+e^- decay position by:
  - time and position(y,z) correlations of muon decays from e^+ tracking (drift chambers).
    → "coincidence experiment"
  - further correlation with time and position(x,z) of atomic e^- after μ^+ decay (position-sensitive MCP), guided by parallel E and B fields.
- Muons decay in:
  - the target, as μ^+e^- and μ^+.
  - vacuum, in flight, as μ^+e^-.
  - surrounding materials.

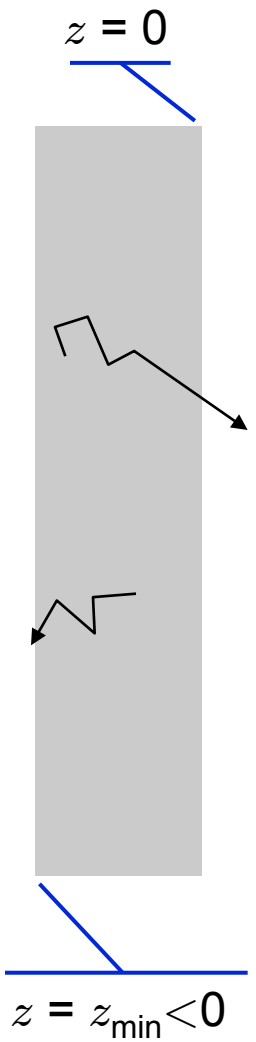
S1249 – simulation of diffusion

- How does the simulation work?
  - Geometry assumes material occupies region of $z_{min} \leq z \leq 0$:
    - diffusing particle exits material upon reaching z = 0 (or is trapped at opposite surface at $z = z_{min}$).
  - Three-dimensional random walk starts in a region $z_{min} \leq z \leq 0$, with a distribution of initial z coded on an event-by-event basis.
    - e.g., from G4 simulations verified by momentum scans of target stops
  - Particles make random walk within the material in three dimensions in layer infinite in x,y.
  - Event decay time selected from an exponential distribution of mean τ_μ.
  - Step size of walk is a time t_{step} determined by two parameters:
    - input temperature (e.g., 293K) that determines a thermal speed distribution (v_{th})
    - input diffusion constant D in cm^2/s and the derived path length of the step l.
  - Step length l from exponential distribution of mean $l_{mfp}=\alpha(D/\langle|v_{th}|\rangle)$.
    - coefficient α is adjusted to 3.82 from theoretical value of 3.0 that is valid for Gaussian distributions of time intervals and jump lengths.

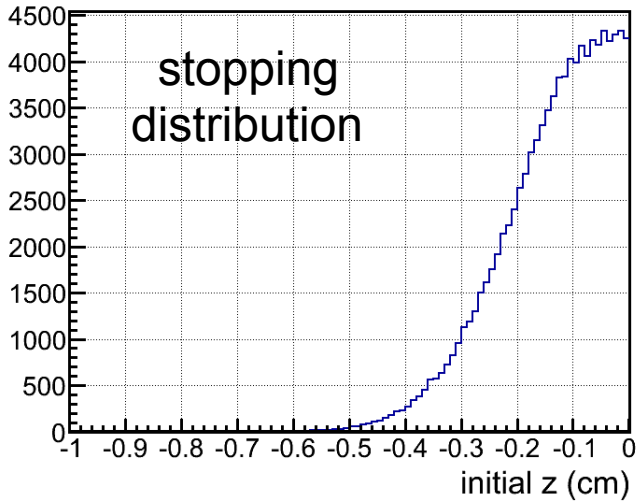


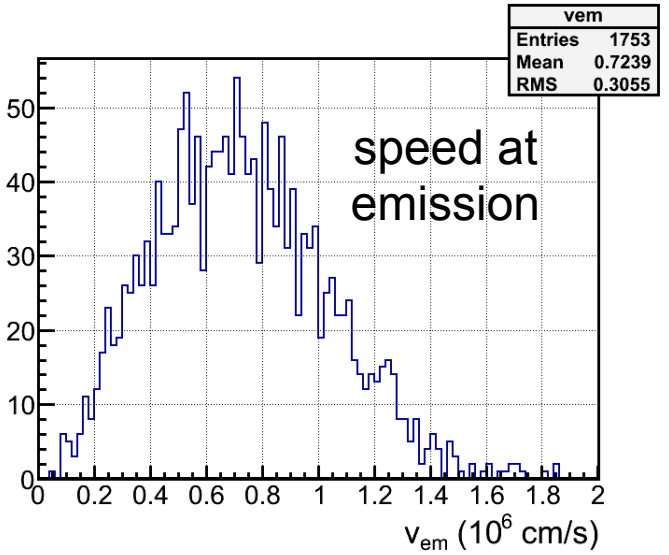
S1249 – simulation of diffusion

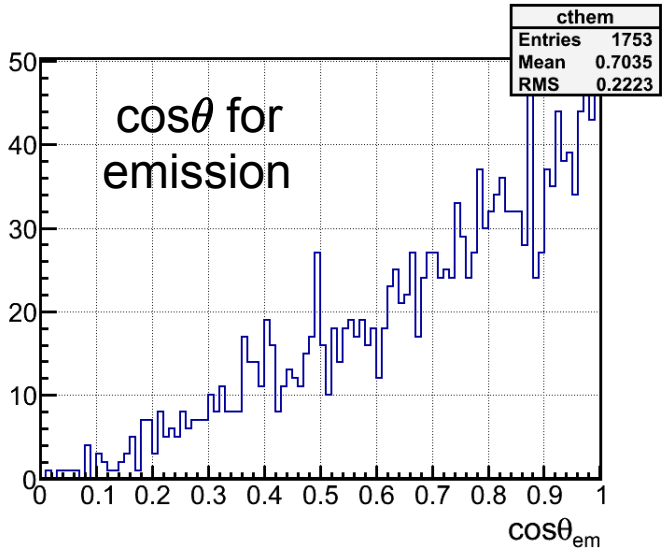
- How does the simulation work (continued)?
  - Step speed v from a Maxwellian distribution of mean <|v_{th}|>.
  - Step time is l/v: distribution is convolution of distance and speed.
  - Step direction ϕ uniform in [0,2π) and cosθ uniform in [-1.,+1.].
  - Time after each step is compared to event decay time:
    - if not decayed, location after each step is determined by path length l and randomized direction.
    - if decayed, path length assumed for the final step is reduced proportionally to time left to decay prior to step, divided by assume step time.
  - Position in z is checked at each step; if $z > 0$, then:
    - emission flag is set.
    - final step time and position are corrected to the surface crossing point, time remaining is set to time left before decay to simulate free propagation in vacuum, with direction as determined from final step.
      - gives approximate cosθ emission angle distribution naturally.
    - similar check and behavior for $z < z_{min}$, except no further motion.

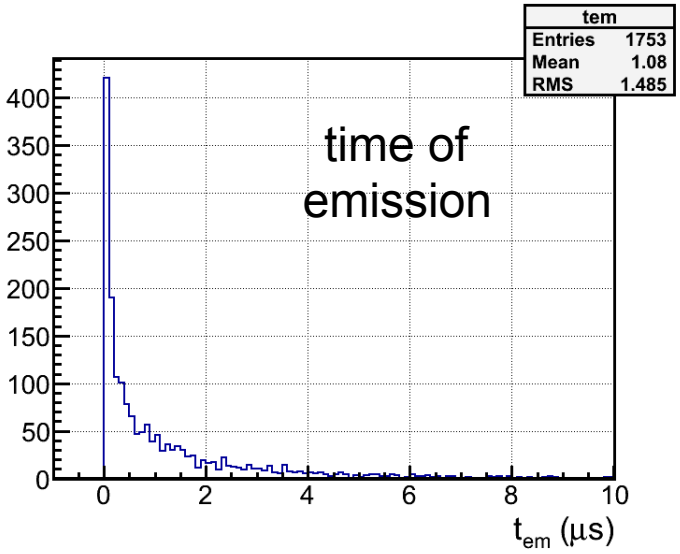


S1249 − distributions from simulation



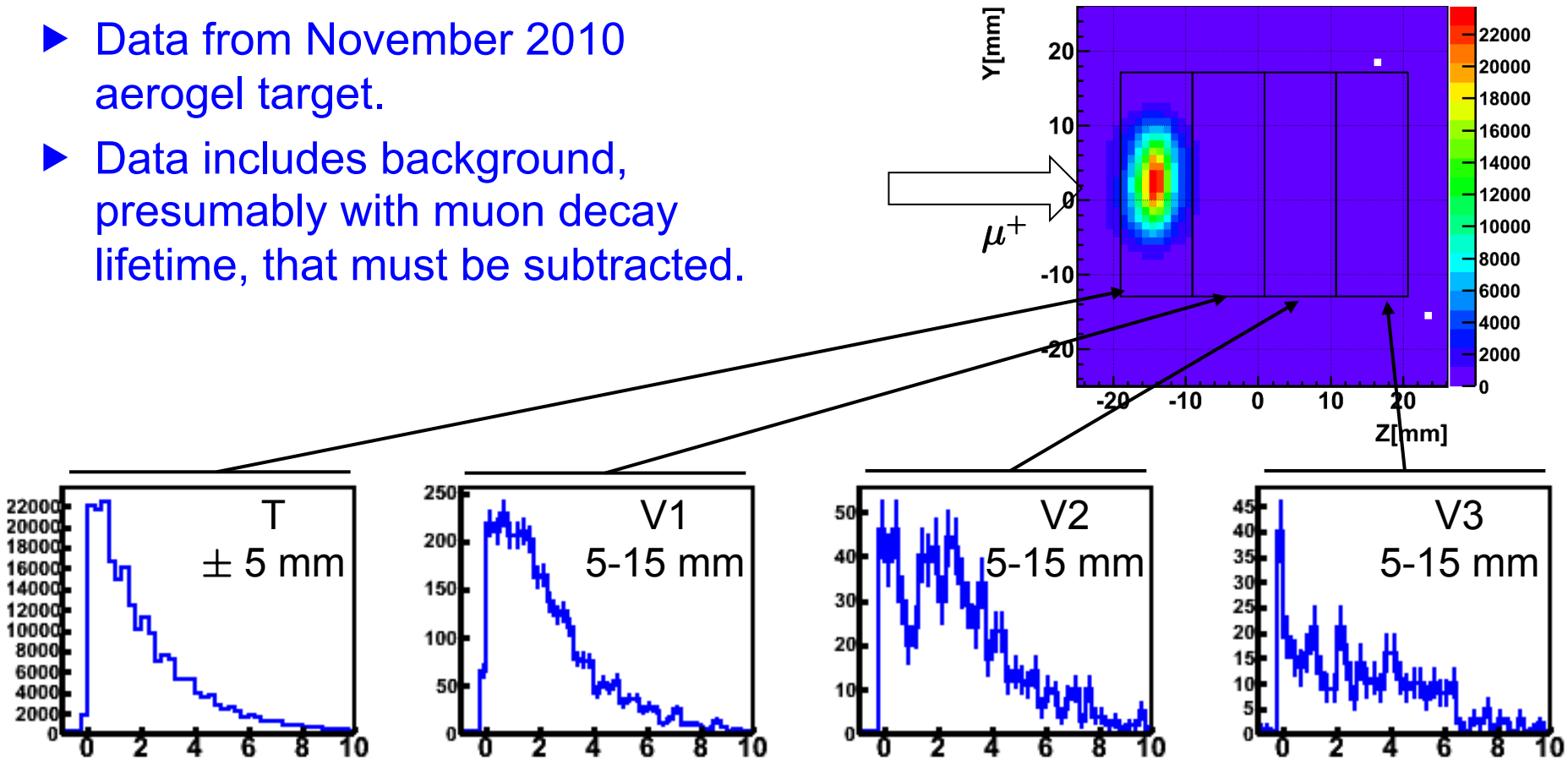






S1249 – decay time distributions

- Data from November 2010 aerogel target.
- Data includes background, presumably with muon decay lifetime, that must be subtracted.

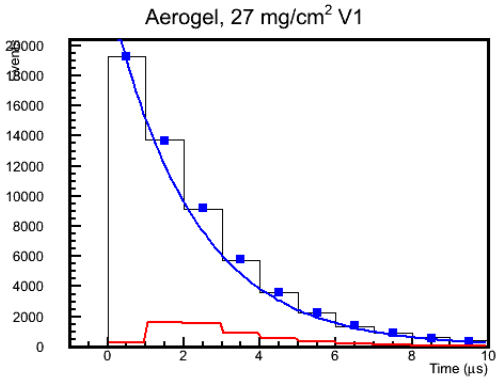


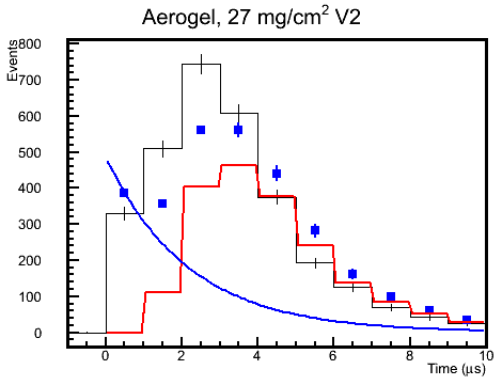
Muon decay time (μs)
for regions near aerogel target
(2010 data)

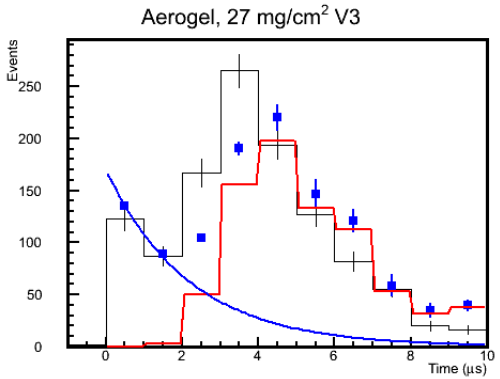
S1249 – e^+ time-position correlation

- Fit to single scale factor of simulation of 10^6 diffusing Mu at T=293K, plus independent exponential backgrounds
- Scale factor gives D=9.2±0.2 cm^2/s (preliminary, stat. only) for 0.027 g/cm^3 aerogel
- Residuals show evidence of higher speeds; χ^2/dof=190/26

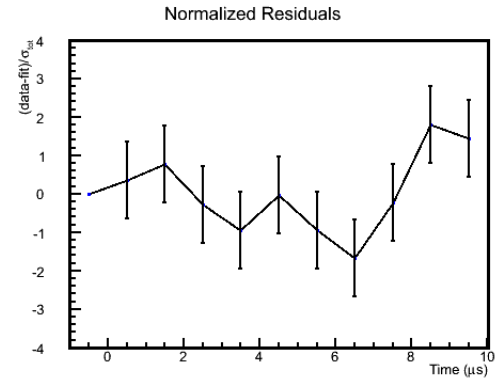
2011 data, preliminary only!

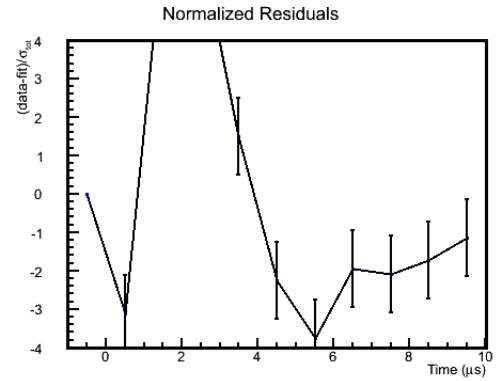


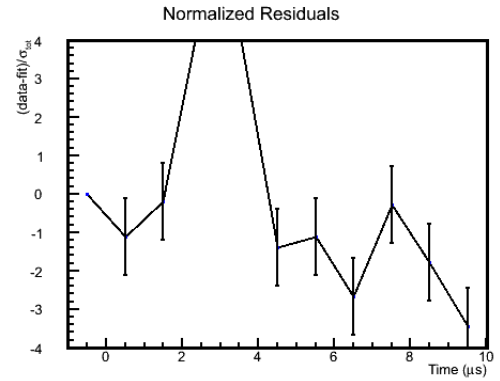




data – black histogram, fit – blue squares, simulation – red histogram, exponential background – blue curve



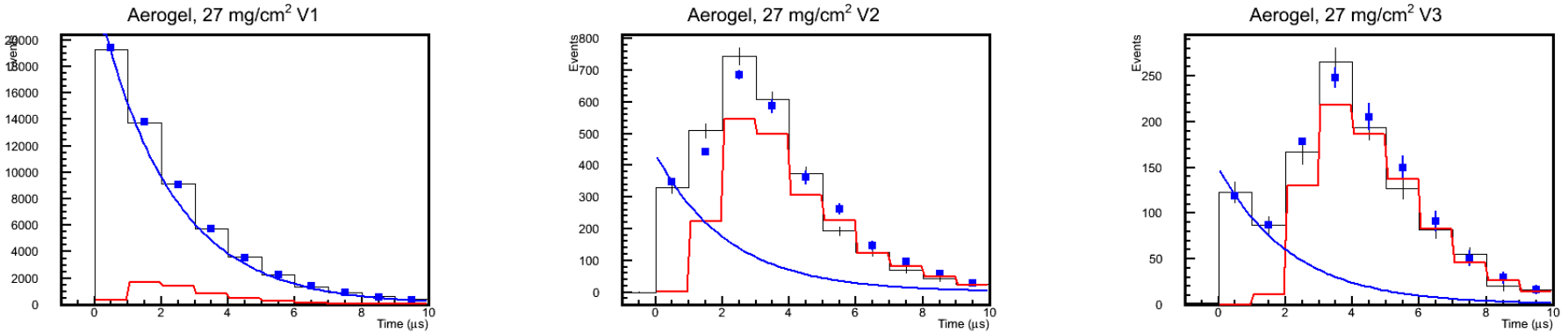




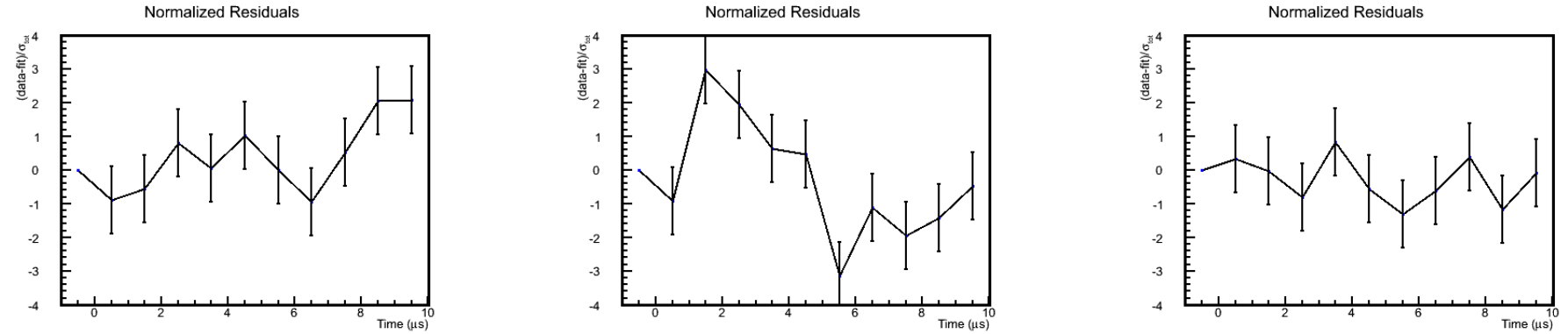
S1249 – e^+ time-position correlation

- Fit to single scale factor of simulation at T=440K (+50%), plus independent exponential backgrounds
- Diffusion constant not significantly changed
- Residuals show evidence of higher speeds; somewhat better χ^2/dof=51/26

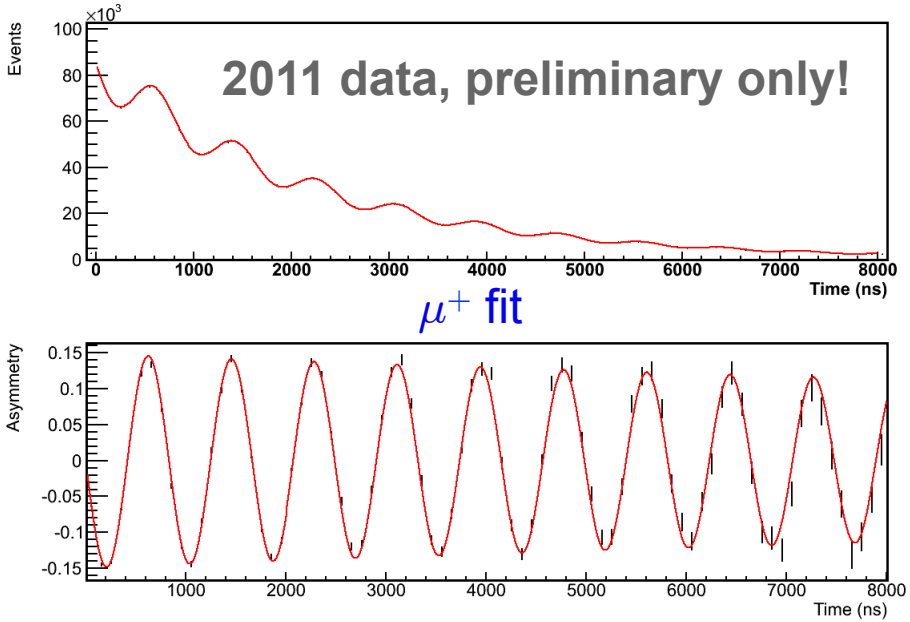
2011 data, preliminary only!

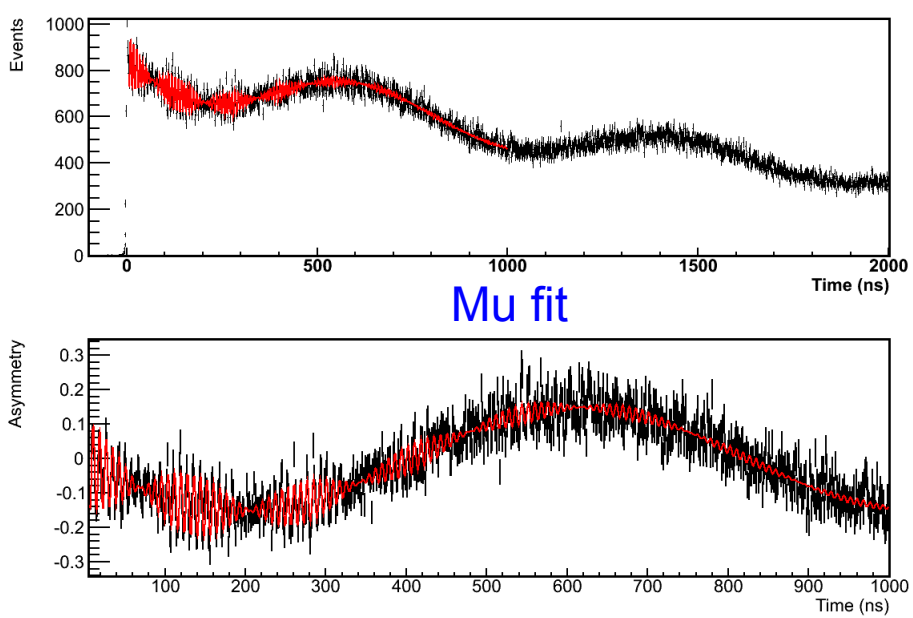


data – black histogram, fit – blue squares, simulation – red histogram, exponential background – blue curve



S1249 – Mu signal in aerogel



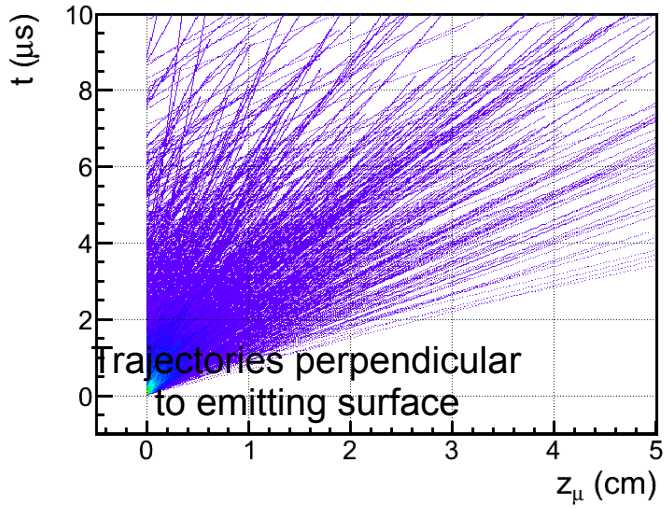


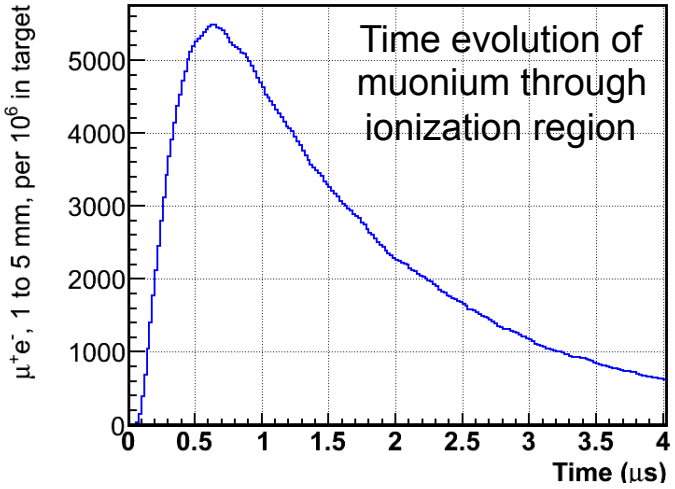
- Precession in MCP atomic e^- guide field, 88 G (not very uniform)
- $A_{\mu+} = 0.148 \pm 0.002$, $A_{Mu} = 0.131 \pm 0.007 \rightarrow F_{Mu} = 0.64$, assuming all polarization is observed

- 4 densities of silica aerogel used in 2011; 27, 49, 99, and 180 mg/cm^3
- No significant density dependence observed for emission probability

Prediction for muonium ionization

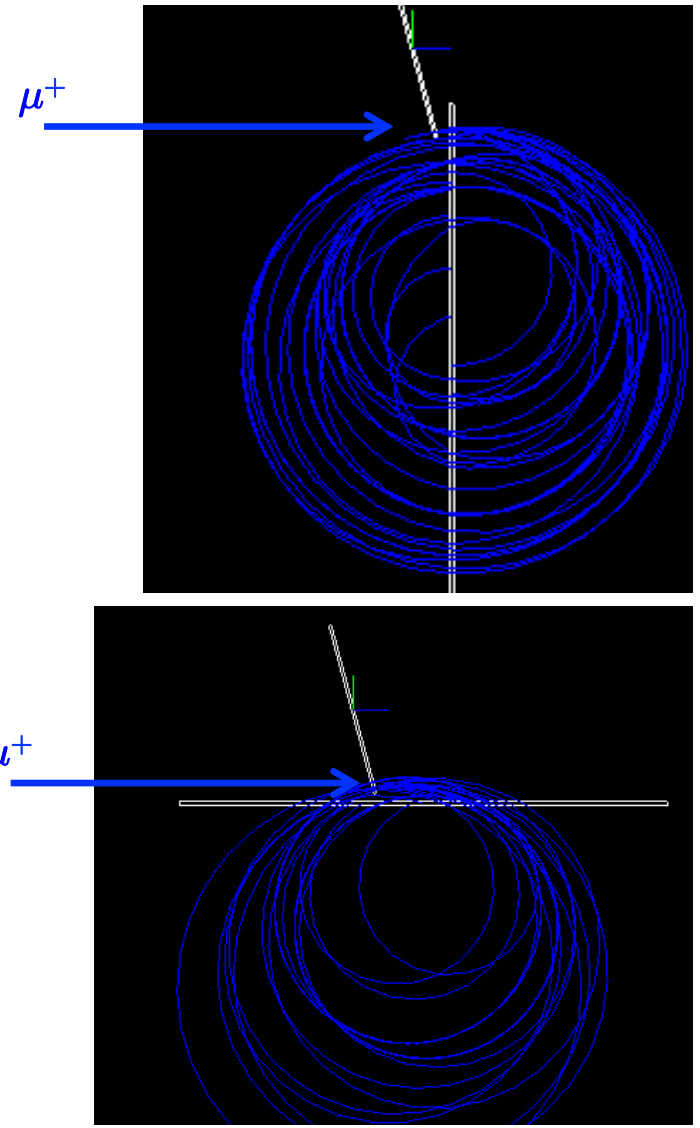
- Use diffusion simulation to predict muonium emission into laser ionization region.
- For a narrow pulsed beam with TRIUMF beam properties (22 MeV/c, $\Delta p/p \sim 6\%$ FWHM):
  - For region from 0.1 to 0.5 cm from emitting surface, yield of S1249 target is shown per 10^6 initial muonium atoms formed in the silica.
  - Correct for 60% muonium formation probability in aerogel; also only half of the incident muons stop in the layer ⇒ 0.15% of incident muon beam is muonium in ionization region.





Problems

- Muon polarization in Mu is only 50%.
  - in longitudinal field, this increases to ~90% at 0.3 T
- Diffusion distance $(D\tau_\mu)^{1/2}$ is much smaller than muon range spread for conventional surface beams.
  - the number of passages through a layer could be increased by the "anticyclotron" method
- Is there a common solution?
  - transversely-polarized μ^+ is degraded, then passes multiple times through a layer
  - ionization in B field, extraction of μ^+ by E field parallel to B axis
- G4 simulations by D. Contreras (TRIUMF co-op student)
  - total yield into vacuum can be increased substantially using 1.2 T
  - beam spreads due to multiple scattering in direction parallel to B field (out of page)
  - only 50% increase in yield in 1 cm^2 area of layer surface
  - real field shapes? getting 4 MeV μ^+ into field? getting keV μ^+ out of field?
  - More effort needed to make more realistic simulation.



Summary

- Silica powder has so far been the main material for production of muonium in vacuum for research applications.
- Aerogel is a potential alternative to silica powder for muonium production in vacuum.
  - more convenient, more vacuum-friendly, self-supporting
  - yields are no better than 50% of powder yields
    - note wide discrepancies in powder yield
- Diffusion model reproduces the main features.
  - is the inconsistency with room-temperature thermal emission real?
    - if so, what modifications are necessary?
- Problems to be solved:
  - diffusion distance is much smaller than surface muon beam spreads
  - polarization loss in muonium formation

The S1249 group, 2011

- G. Beer, D. Contreras, Y. Fujiwara, Y. Fukao, S. Hirota, H. Iinuma, K. Ishida, M. Iwasaki, T. Kakurai, S. Kanda, G. Marshall, T. Mibe, H. Onishi, A. Olin, N. Saito, D. Tomono, K. Ueno.