Energy dependence of Mu formation in insulators and semiconductors

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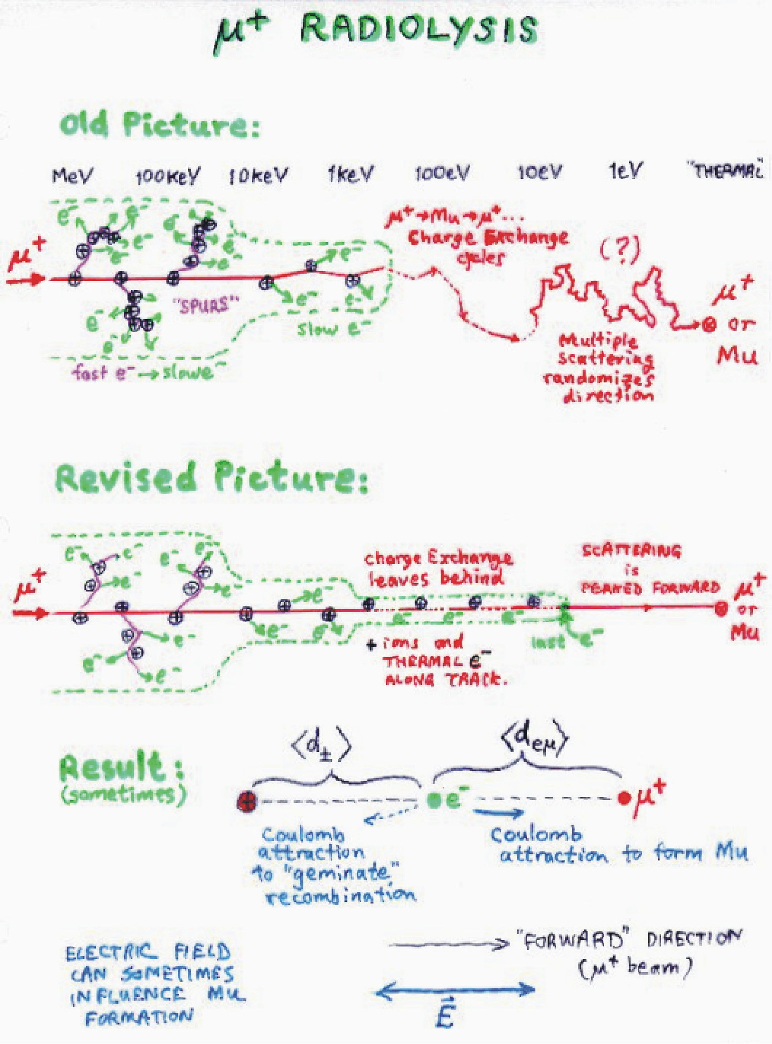
Motivation

- charge differentiation in μ^+ or Mu of fundamental interest in μSR

- moderation of μ^+ to eV energies, “prompt” fractions in solid van der Waals gases (s-Ne, s-Ar, s-N_2, s-Kr, s-Xe)

- interaction of μ^+ with track electrons, *delayed Mu formation*, LE- μ^+ beam allows to “tune” number of track electrons between $\simeq$ 20 and a few 1000 (surface μ^+: $\simeq 10^5 - 10^6$ track electrons)

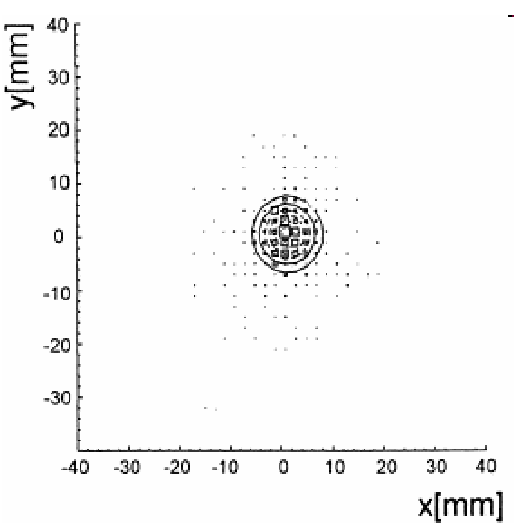
- influence of implantation energy, *i.e. number of track electrons*, on experiments in insulators and semi-conductors

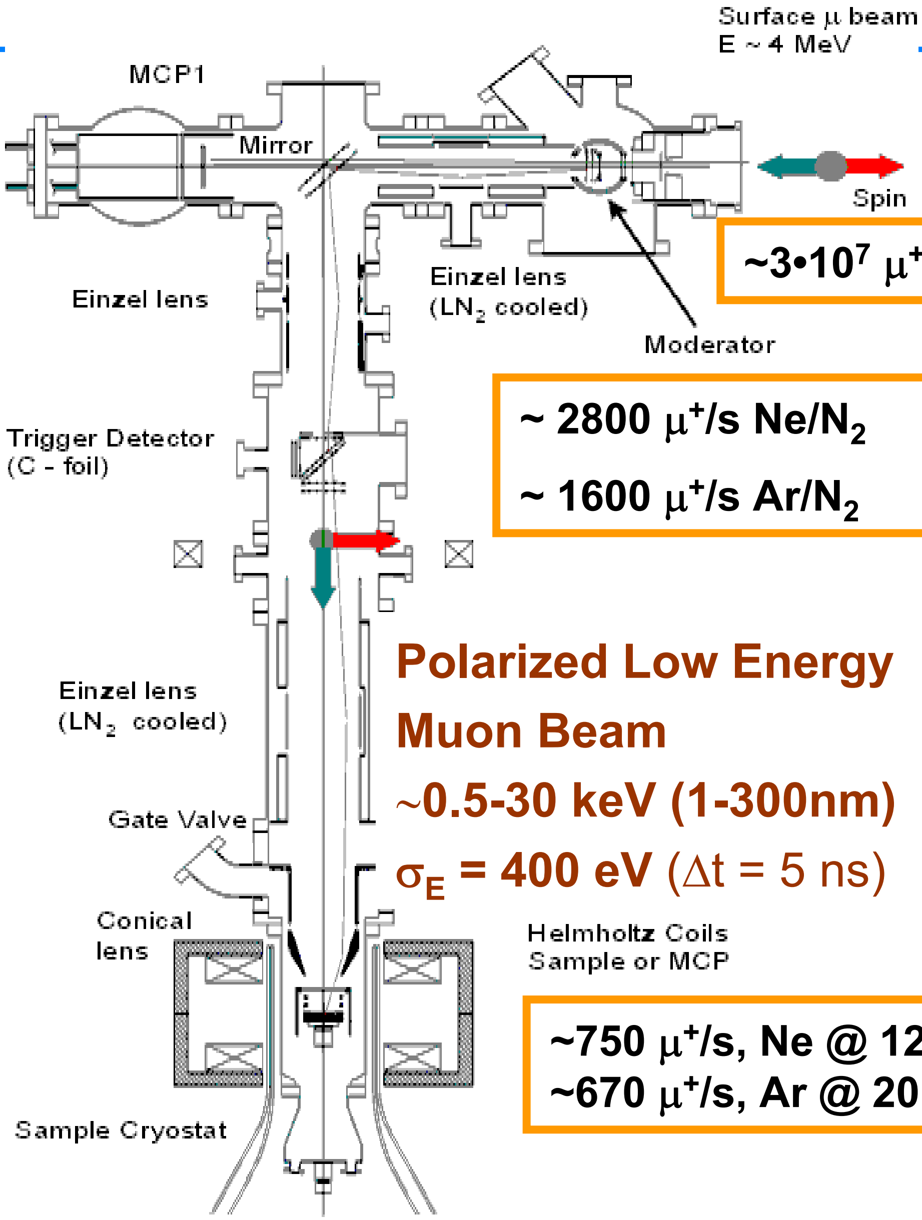


J. H. Brewer, UBC Vancouver, and Can. Inst. for Adv. Res.

LEM beam with LE-μSR spectrometer (status 12/2003)

beam spot at sample





~3•10^7 μ^+/s

~ 2800 μ^+/s Ne/N$_2$

~ 1600 μ^+/s Ar/N$_2$

Polarized Low Energy

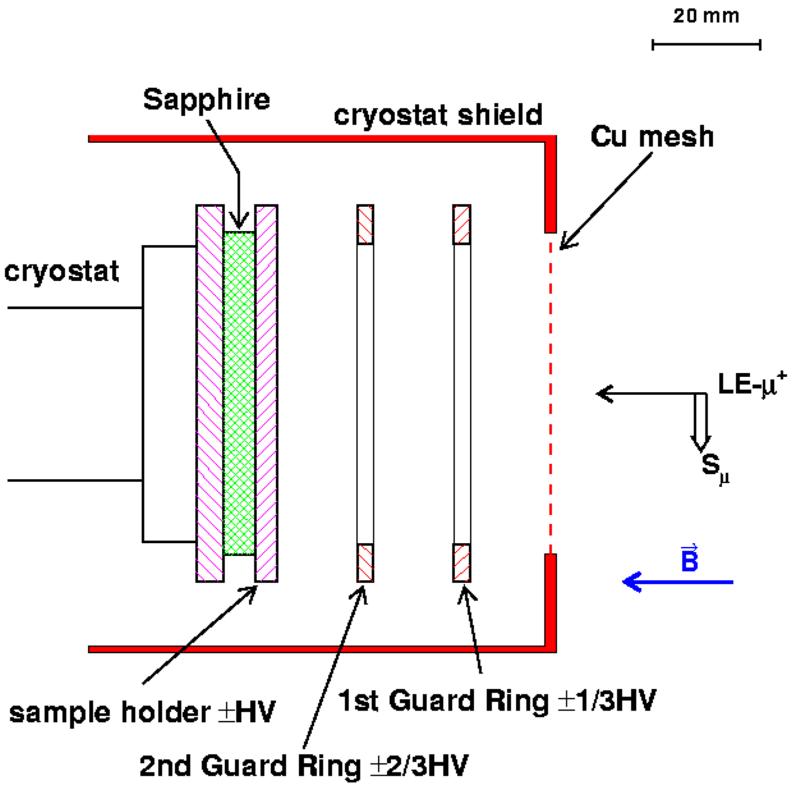
Muon Beam

~0.5-30 keV (1-300nm)

σ_E = 400 eV (Δt = 5 ns)

~750 μ^+/s, Ne @ 12kV
~670 μ^+/s, Ar @ 20 kV

Experiment



Electric fields < 1.5kV/cm

Samples:

- **SiO_2** 2mm thick, 50mm ∅, fused (**Suprasil**) and crystal
- **Al_2O_3** 0.5mm thick, 60mm ∅
- **intrinsic Si**, 0.5mm thick, <100> perp. to surface
- **s-Ne, s-Ar**, **s-Kr, s-Xe**, **s-N_2** , grown at $p_g = 1.1 \ast 10^{-6} - 5 \ast 10^{-5}$ mbar (growth rate = 1Å/s – 45Å/s), layer thicknesses □ 1000 nm, grain size of order 100 nm
- temperature 5 K (s-Ne) – 30 K (s-Xe), SiO_2 20K, 4-100K Al_2O_3, 5-250K Si
- B = 0.5 mT – 10 mT TF

s-Ar data

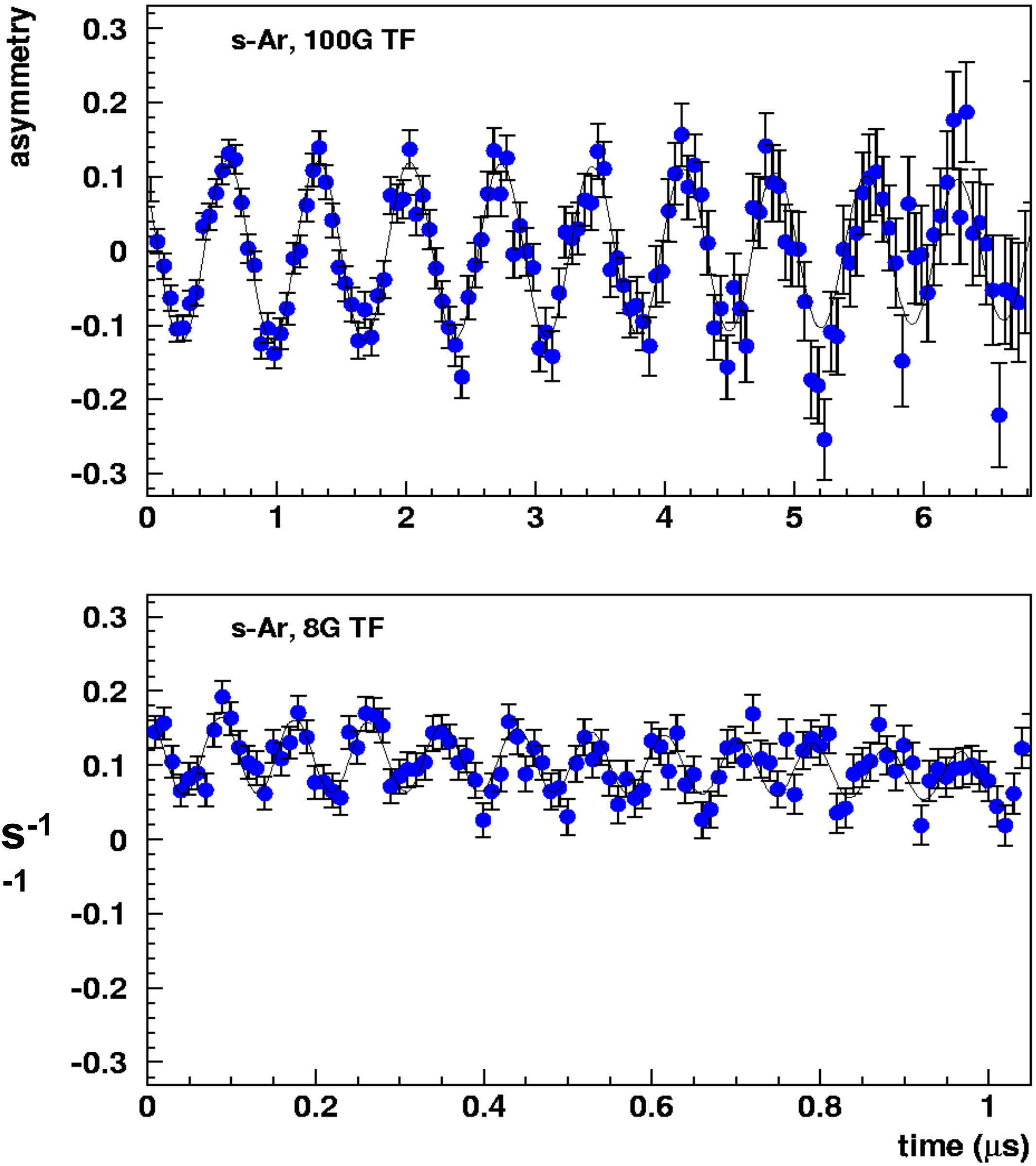
E_{μ} = 16.4 keV

T = 10 K

p_g = 6.5 $\ast 10^{-6}$ mbar

max. asymmetry = 0.26

A_{μ} = 0.124(3), σ_{μ} = 0.08μs^{-1}
A_{Mu} = 0.057(4), λ_{Mu} = 0.5μs^{-1}

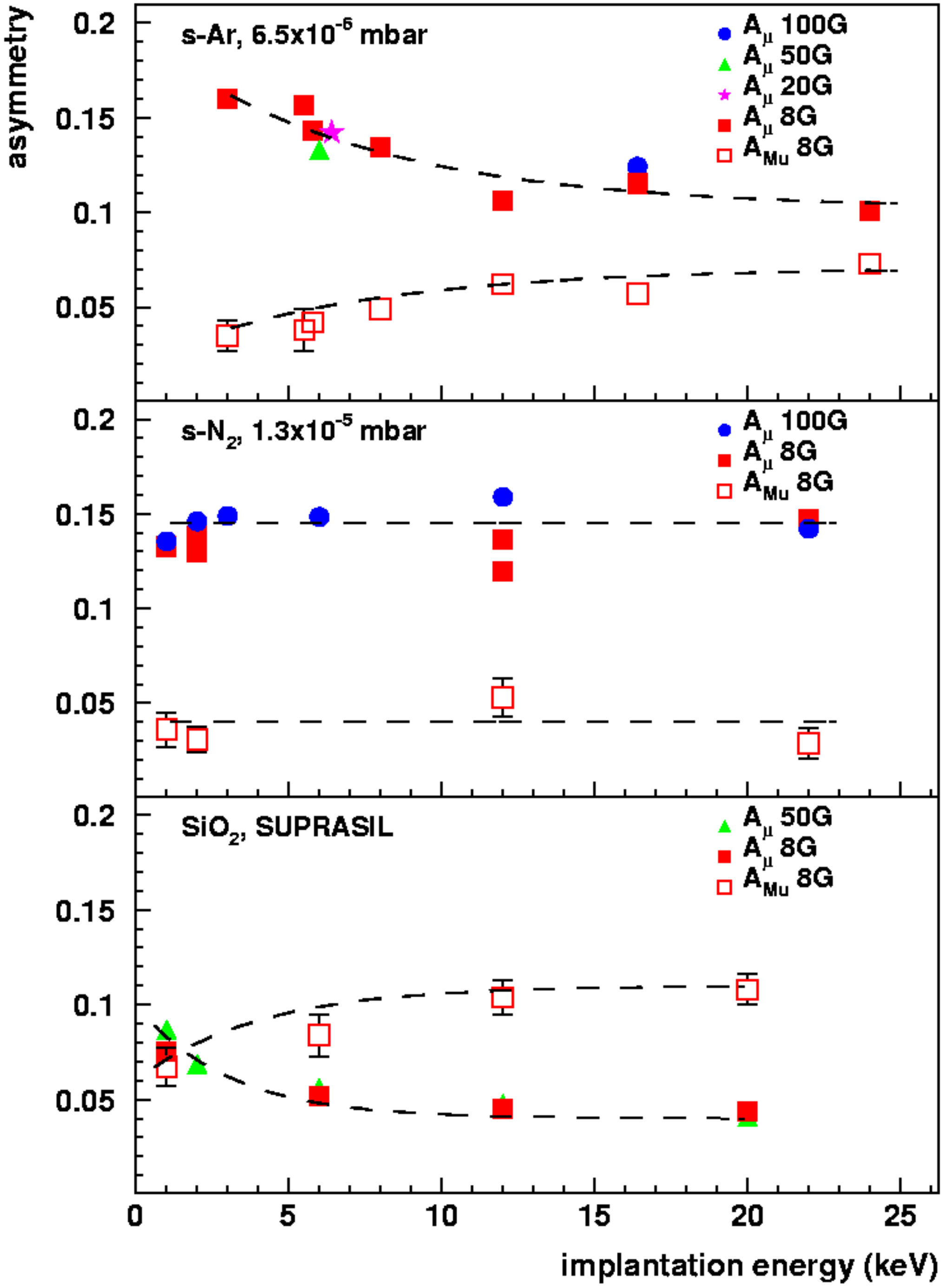


Mu and diamagnetic asymmetries for

s-Ar film 1000nm, 10K
(σ_μ = 0.08, λ_{Mu} = 0.5μs^{-1})

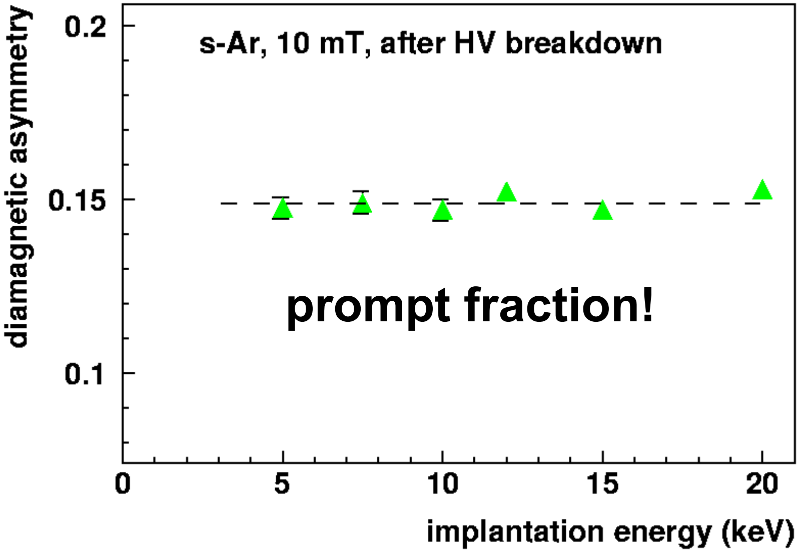
s-N_2 film 1000nm, 13K
(σ_μ = 0.14, λ_{Mu} = 7μs^{-1})

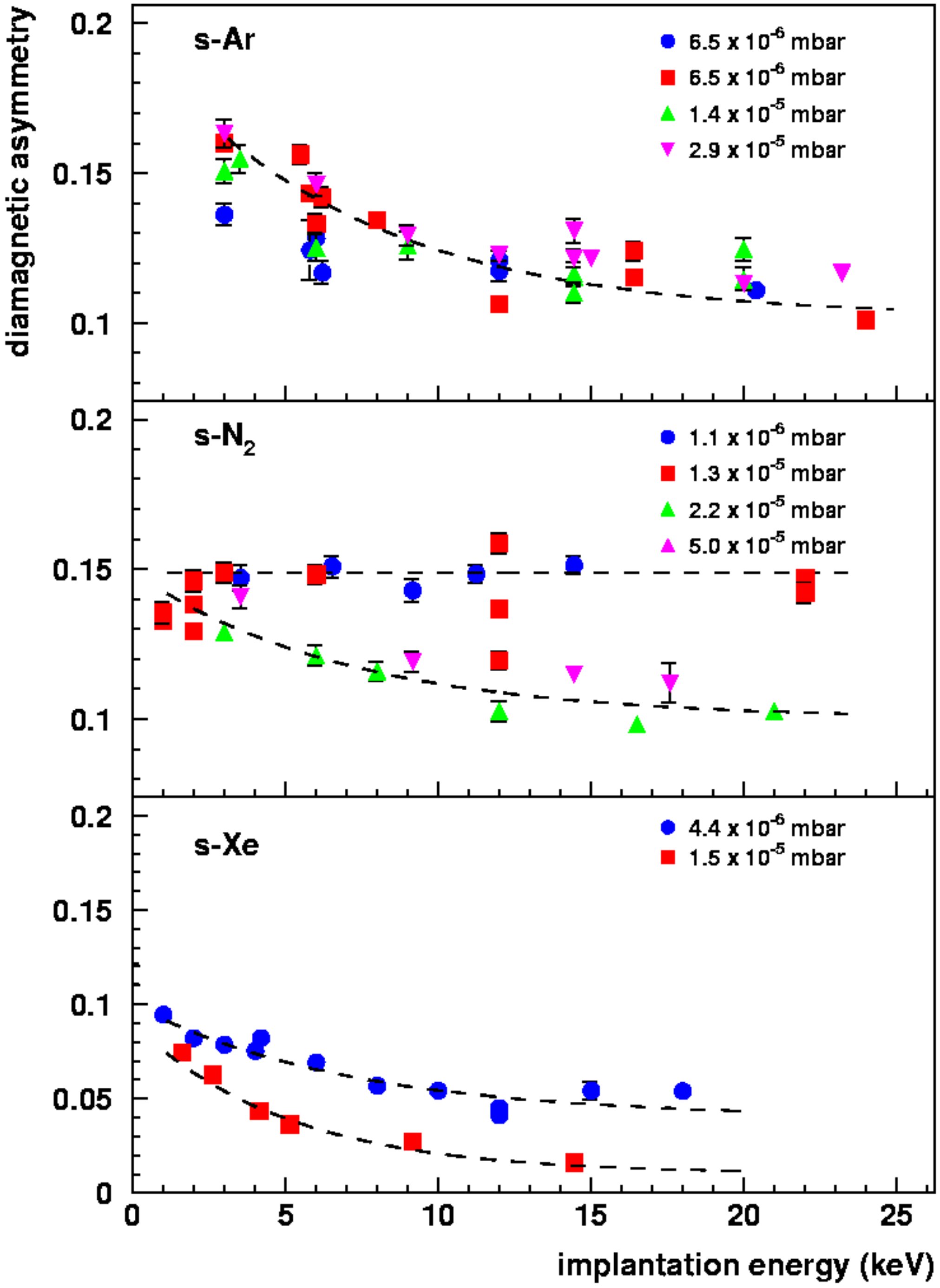
SiO_2 glass, 20K
(σ_μ = 0.17, λ_{Mu} = 3.2μs^{-1})



Different growing conditions of the van-der-Waals films

Charging of layer may hinder the recombination of e-h pairs, *Grosjean et al, NIMB 157 (1999)*

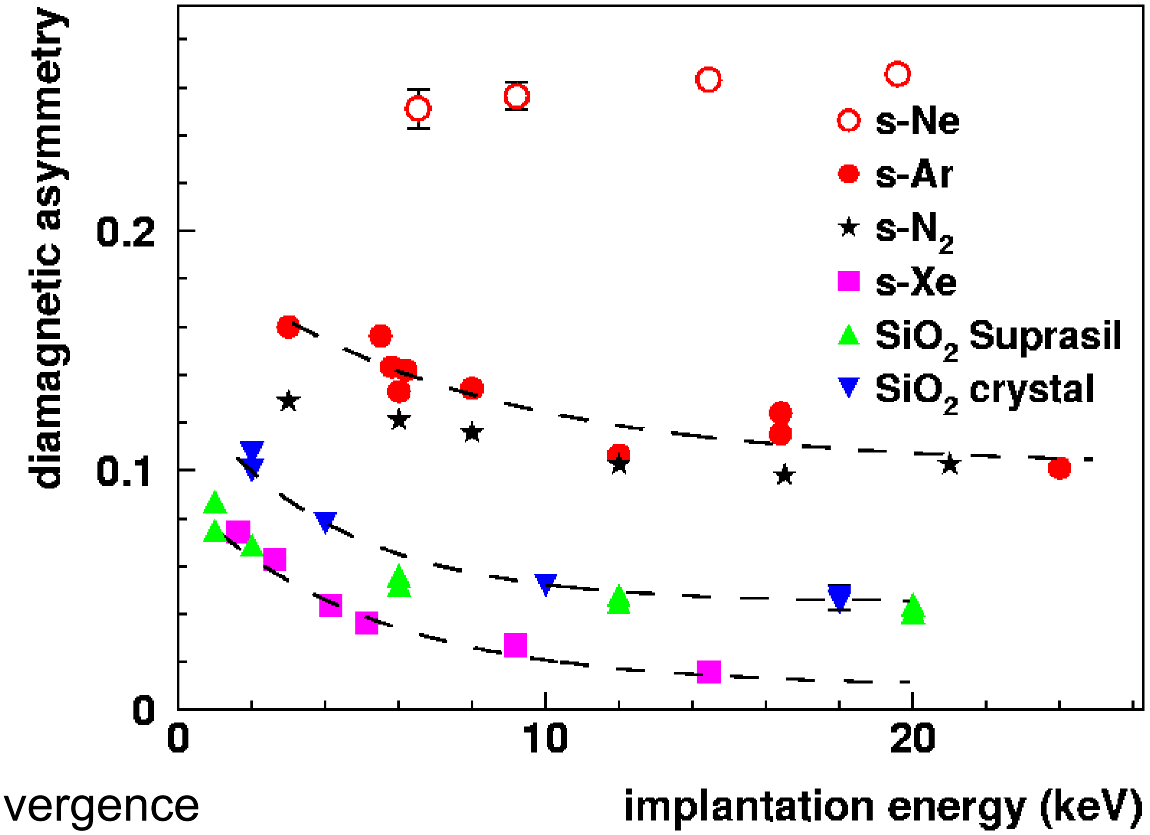




Comparison of different insulators

no delayed Mu in s-Ne films
lower delayed Mu yield in s-Ar, $s\text{-}N_2$ than in bulk polycrystals

⇨ possibly caused by the large escape depths of epithermal μ^+ and grain size of order 100nm (trapping of excess electrons)
$d_{e\text{-}\mu}$ = 50-100nm (Storchak, Eshchenko et al)

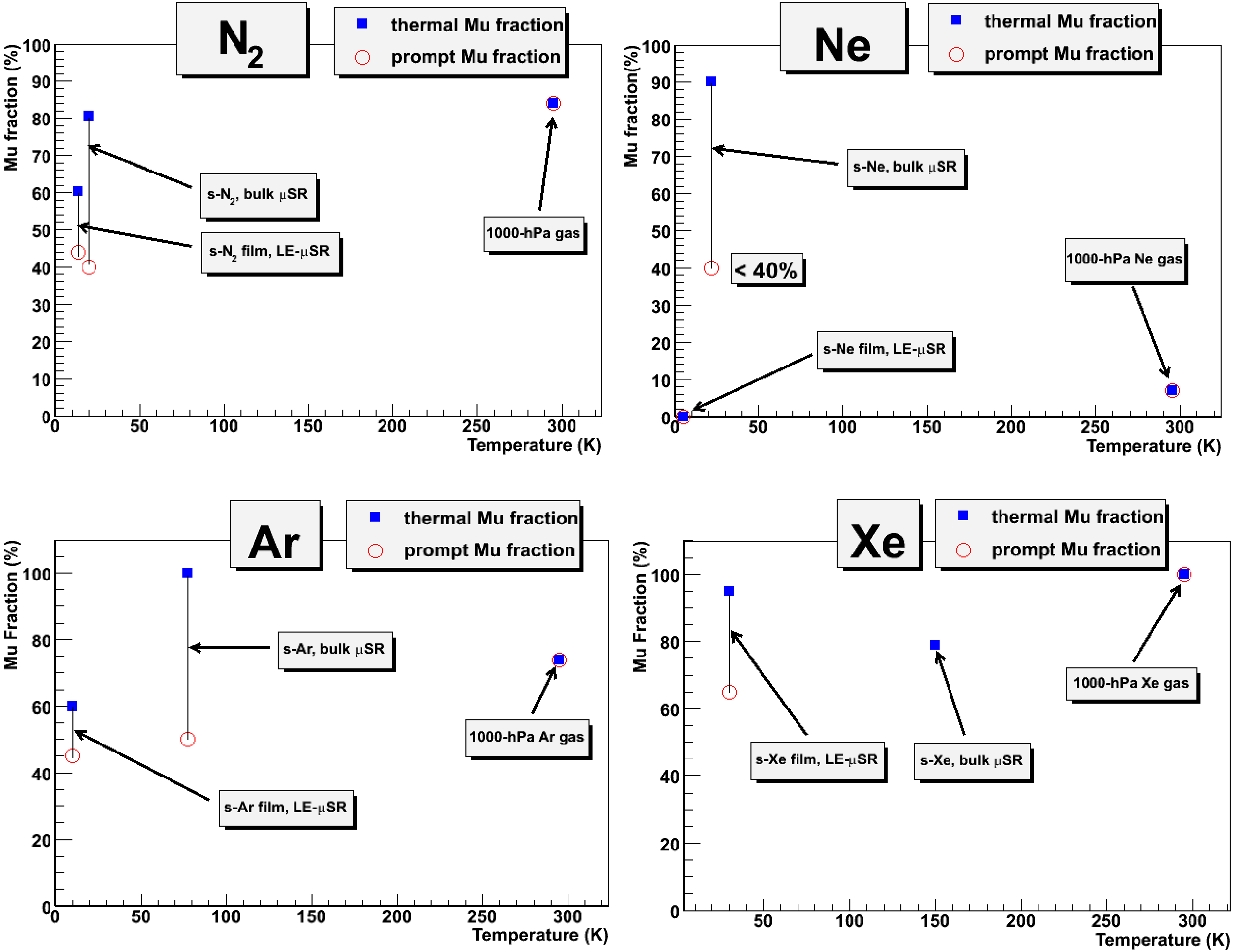


General feature:
decrease of A_μ accompanied by an increase of A_{Mu}
This is attributed to 'delayed' convergence of a track electron with the thermalized μ^+, *i.e. delayed Mu formation*

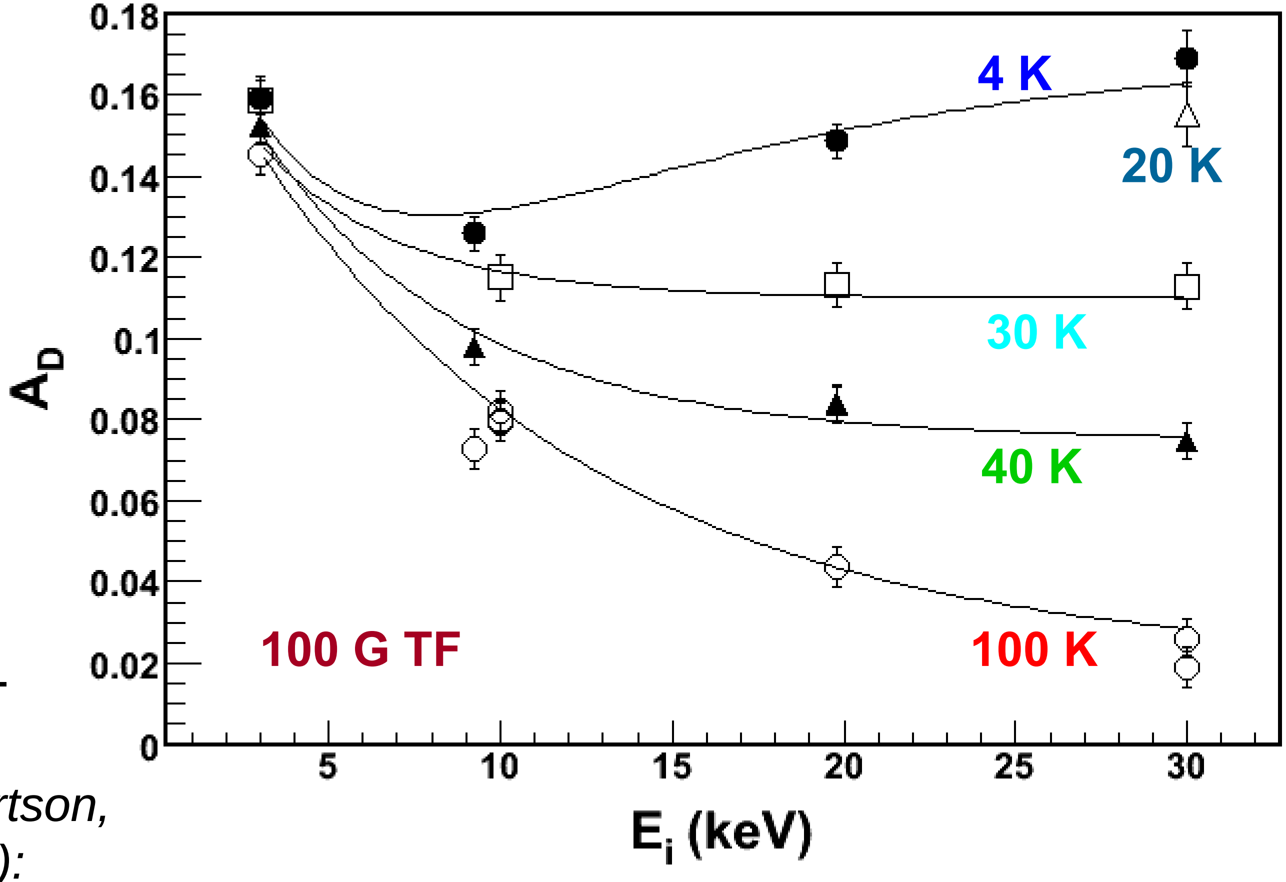
T. Prokscha et al, Physica B 326 (2003)
T. Prokscha et al, in preparation

Thermal and prompt Diamagnetic and Mu fractions

	T [K]	thermal fractions [%]		prompt fractions [%]		Ref.
		dia	Mu	dia	Mu	
s-N_2	20	19	81	60	40	Storchak, 1999
film	13.5	40	60	56	44	this work
gas		16	84	16	84	Fleming, 1982
s-Ne	22	10	90	>60	<40	Eshchenko, 2002
film	5	100	0	100	0	this work
gas		93	7	93	7	Fleming, 1982
s-Ar	78	0	100	50	50	Eshchenko, 2002
film	10	40	60	55	45	this work
gas		26	74	26	74	Fleming, 1982
s-Xe	150	5(3)	79(25)	-	-	Kiefl, 1981
film	30	5	95	35	65	this work
gas		0	100	0	100	Fleming, 1982
SiO_2	20	17	83	40	60	this work
	298	15	85	40	60	Brewer, 2000


N2
thermal Mu fraction
prompt Mu fraction
Mu fraction (%)
s-N2, bulk µSR
s-N2 film, LE-µSR
1000-hPa gas
Temperature (K)
Ne
thermal Mu fraction
prompt Mu fraction
Mu fraction(%)
s-Ne, bulk µSR
< 40%
1000-hPa Ne gas
s-Ne film, LE-µSR
Temperature (K)
Ar
thermal Mu fraction
prompt Mu fraction
Mu Fraction (%)
s-Ar, bulk µSR
1000-hPa Ar gas
s-Ar film, LE-µSR
Temperature (K)
Xe
thermal Mu fraction
prompt Mu fraction
Mu Fraction (%)
1000-hPa Xe gas
s-Xe film, LE-µSR
s-Xe, bulk µSR
Temperature (K)
0
50
100
150
200
250
300

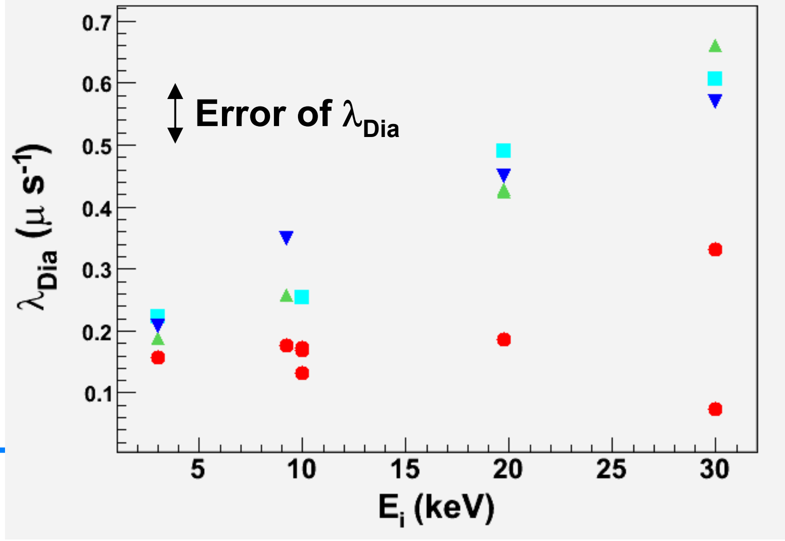
Sapphire



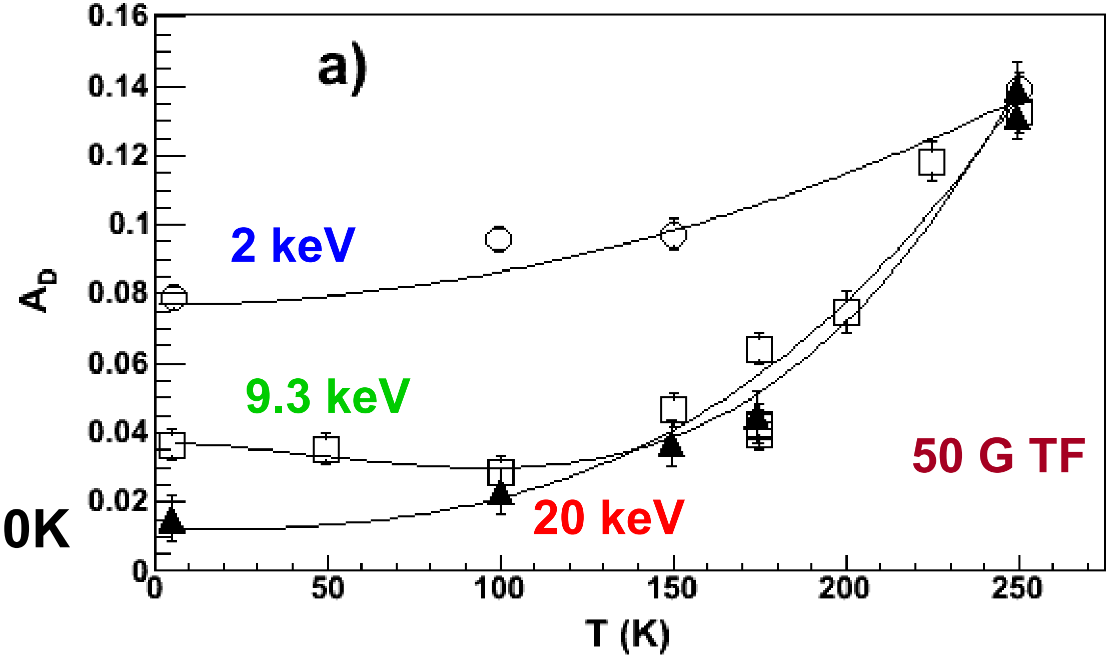
J.D.Brewer et al, Physica B 289(2000):
thermal ionization of Mu^-

P.W.Peacock and J.Robertson, Appl. Phys. Lett. 83 (2003):
H^- is the ground state in Al_2O_3 (CASTEP calculation)

This data suggests **the delayed formation of Mu above 100K, and of Mu^- at lower temperatures**



Intrinsic Si (10kΩcm)

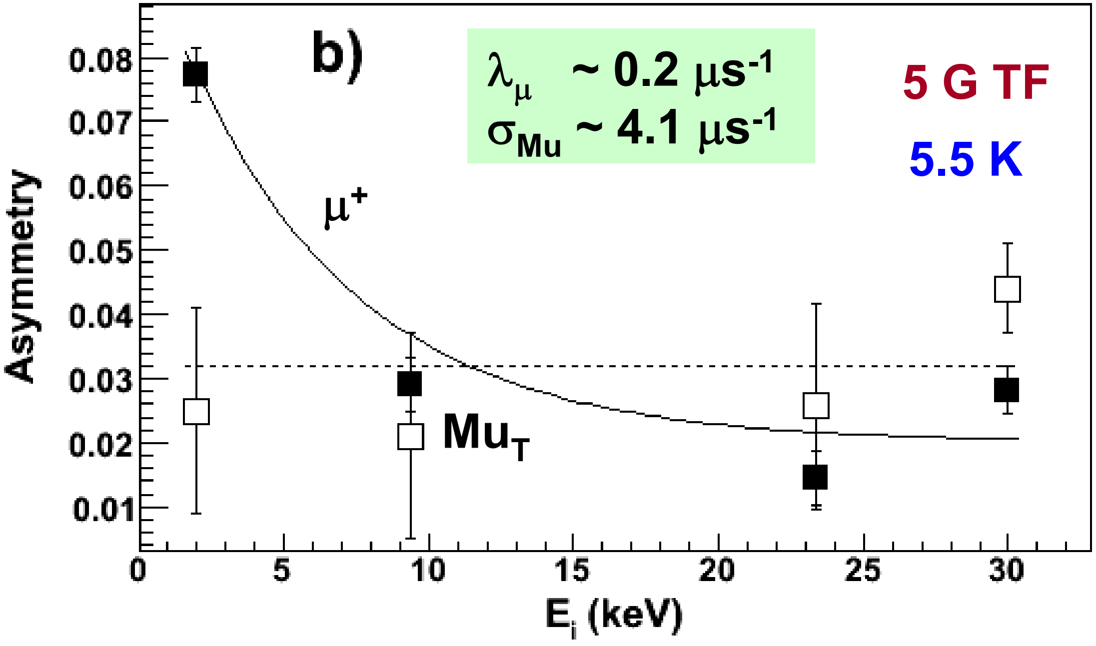


λ_μ = 0.05-0.3 μs^{-1}, max at 100K

Decrease of μ^+ corresponds to increase of Mu_{BC}

Mu_{BC} at 35 and 42 MHz not observed due to limited statistics and time resolution of 5 ns

Mu_{BC} formed delayed, in agreement with *Storchak et al, Phys.Rev.Lett. 78 (1997*)



Summary 1:

➢ efficient delayed Mu formation requires of the order of 1000 electrons generated in the ionisation track → Siebbeles et al (J.Chem.Phys. 111 (1999)): "… *delayed Mu formation cannot be described by considering only the last ionisation or the final spur of the muon track."*

➢ delayed Mu formation is suppressed in thin films of s-Ne, s-Ar, s-N_2, possibly due to trapping of electrons at grain boundaries

➢ the prompt Mu fractions are significantly smaller in the solid vdW-gases than in the low-pressure gases → the picture of treating the vdW-solid as a dense gas is too simple due to breakdown of randomness of charge changing collisions at about 100 eV

Summary 2:

- ➢ Mu_{BC} in Si is mainly due to delayed Mu formation conforming with E-field μSR investigations

- ➢ weakly bound (E_A=130K) Mu^- is possibly the ground state in Al_2O_3, supporting the idea of delayed Mu^- formation

- ➢ LE-μSR complementary to E-field bulk-μSR studies

- ➢ energy dependence of delayed Mu formation in the keV range appears to be a general property

- ➢ Mu_{BC}, possibly shallow Mu difficult to investigate at $E < 5$ keV

What to do next

- intrinsic Ge, Mu_{BC} fraction should be smaller than for Si
- try to observe Mu_{BC} in Si directly
- intrinsic GaAs
- try to observe shallow Mu in CdS and ZnO, according to recent E-field measurements in CdS (Eshchenko et al, PRB68 (2003)) shallow Mu is formed by capture of a radiolysis electron

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