Muonium Transitions in Ge-rich SiGe Alloys

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Experimental Facility:
M20 Beamline at
TRIUMF (Vancouver, BC, Canada)

ICDS-26: 20/July/2011

Project Focus: $Si_{1-x}Ge_x$

Mu defect in bulk Czochralski-grown SiGe alloys

Measure and investigate compositional trends in:

- Donor & Acceptor energies
- Paramagnetic Mu hyperfine frequencies
- Charge-state cycles
- Site change-cycles

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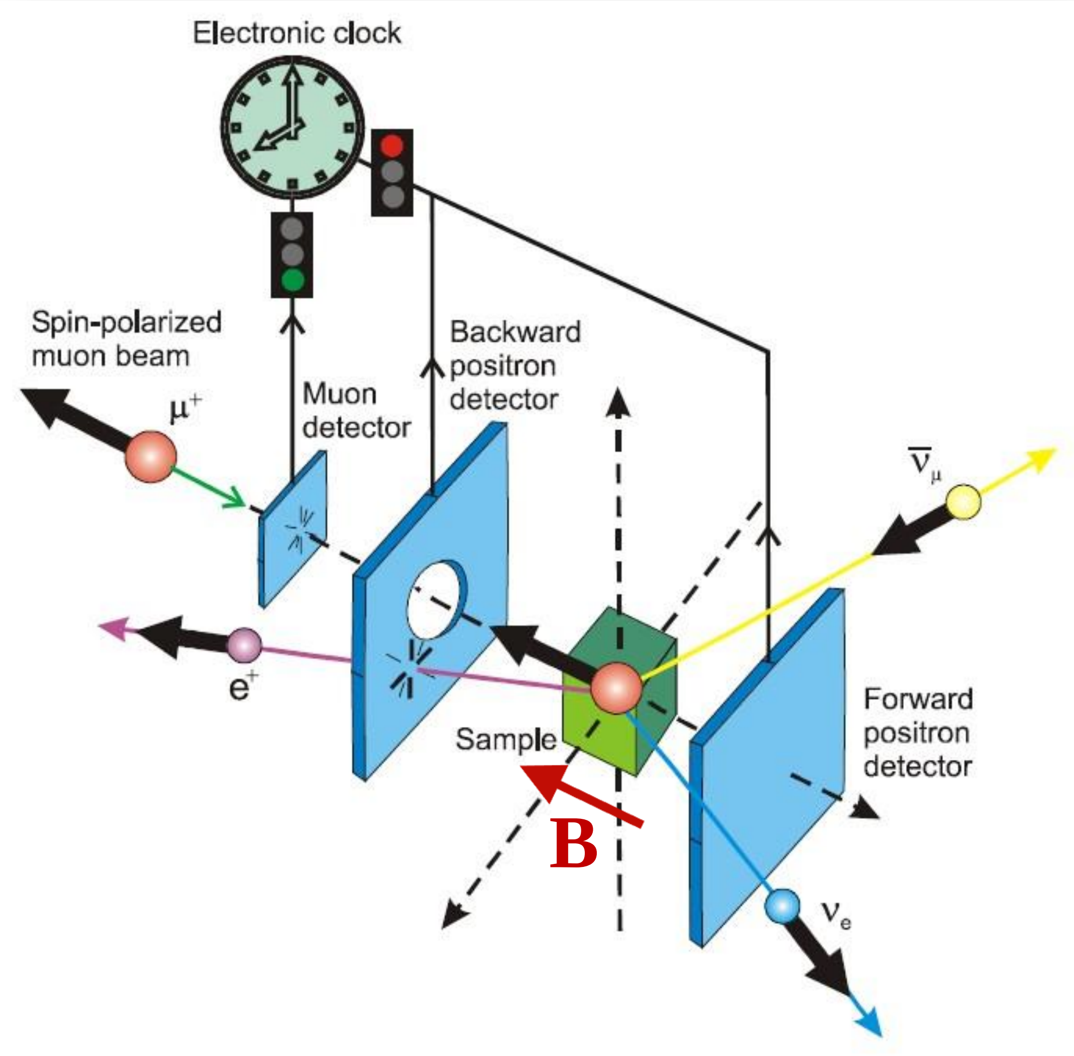
LF-μSR

- Implant 100% spin polarized muons
- **B** applied || to initial spin direction
- Spin evolves in local environment
- Evolution of polarization tracked



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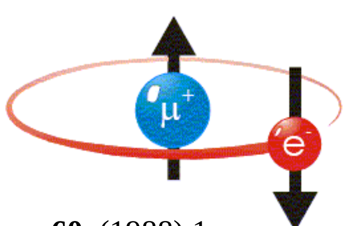
Experimentally Accessible Analog to Hydrogen

	Muon	Proton
Mass (m_p)	0.1126 ≈ 1/9	1
Spin	½	½
Gyro. Ratio, γ (s^{-1} T^{-1})	8.51607 x 10^8 ≈3.2 x γ_P	2.67520 x 10^8
Lifetime, τ (μs)	2.19709	Stable
	Muonium	**Hydrogen**
Red. e^- mass (m_e)	0.995187	0.999456
G. S. Radius (Å)	0.531736	0.529465
G. S. Energy (eV)	-13.5403	-13.5984

Muonium (Mu ≡ μ^+e^-)



$\mu^+ \sim p^+$

$m_\mu \approx 1/9\ m_p$
$m_\mu \approx 207 m_e$; **S**=1/2

$Mu^0 = \mu^+ + e^-$

Mu^0~light isotope H
(see table)

i.e.: Early history of H impurities

Brewer, http://musr.ca →
B.D. Patterson, *Rev. Mod. Phys.*, **60**, (1988) 1

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Samples relevant to today’s presentation

Single crystal, Cz-grown,
$Si_{1-x}Ge_x$: x=0.94,0.91,0.81 (Yonenaga)

Slightly p-type (not intentionally doped) 10^{14}-10^{15} cm^{-3}

Mu^+_{BC} is equilibrium state

On implantation, μ^+ captures e^-, forms
highly mobile Mu^0_T (~75% initial state in pure Ge)

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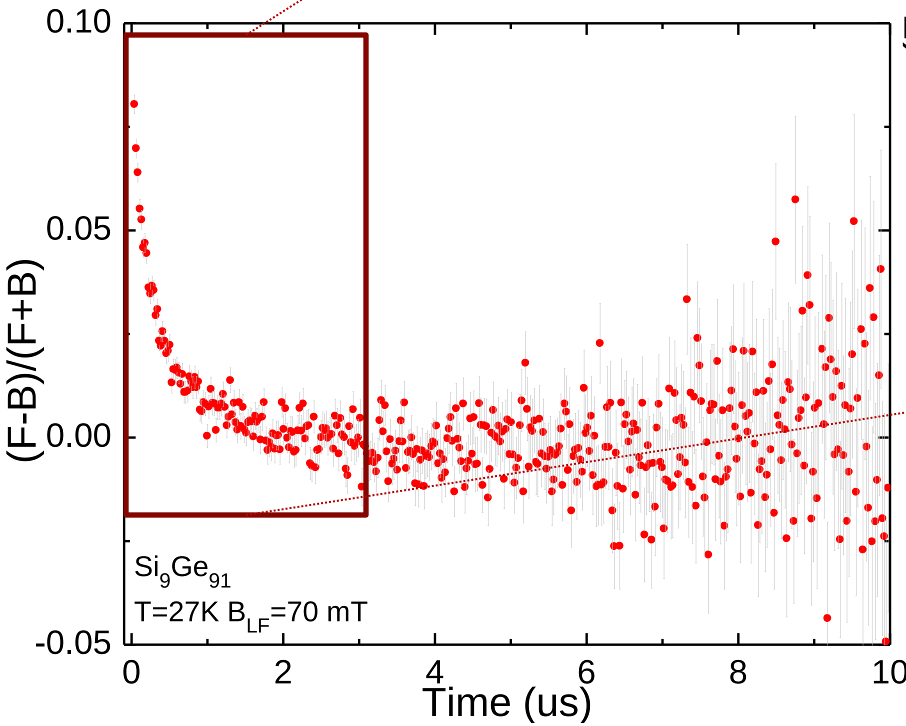
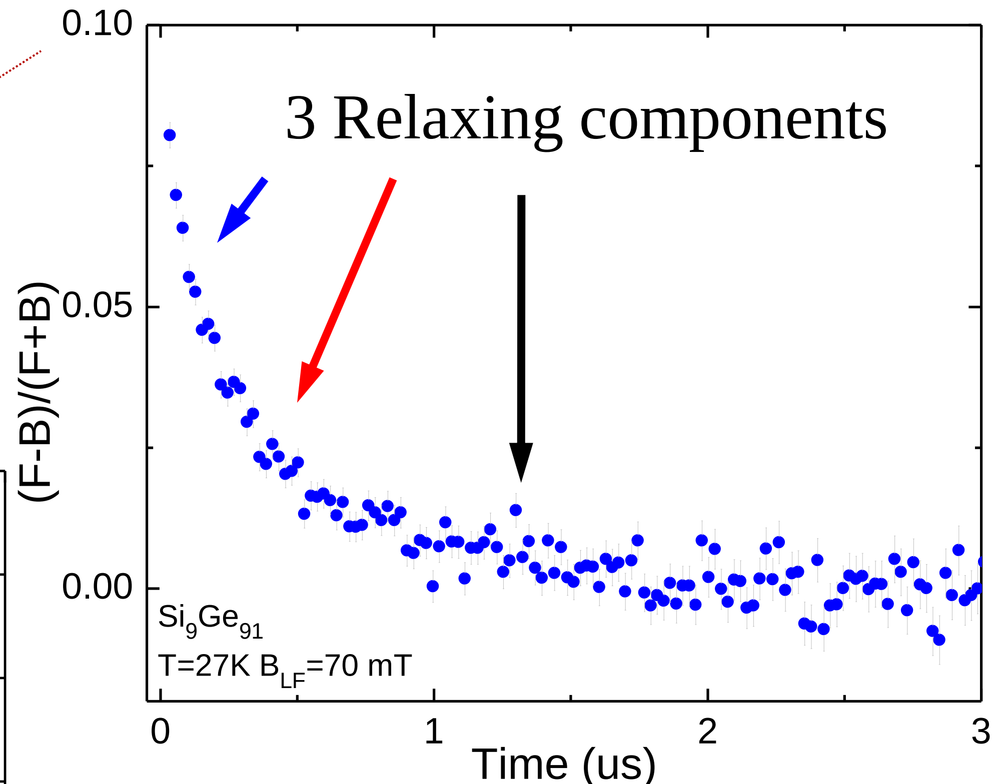
LF-μSR on Si_9Ge_{91}: T=27K with B_{LF}=70mT

Asymmetry: 'corrected' average of counts

$$A(t) = \frac{N_F(t) - \alpha N_B(t)}{N_F(t) + \alpha N_B(t)}$$

Data: Shown





Fast: 5 $\rightarrow$75+ us^{-1}

Moderate: ~1 $\rightarrow$ 10 us^{-1}

Slow: < 0.05 us^{-1}

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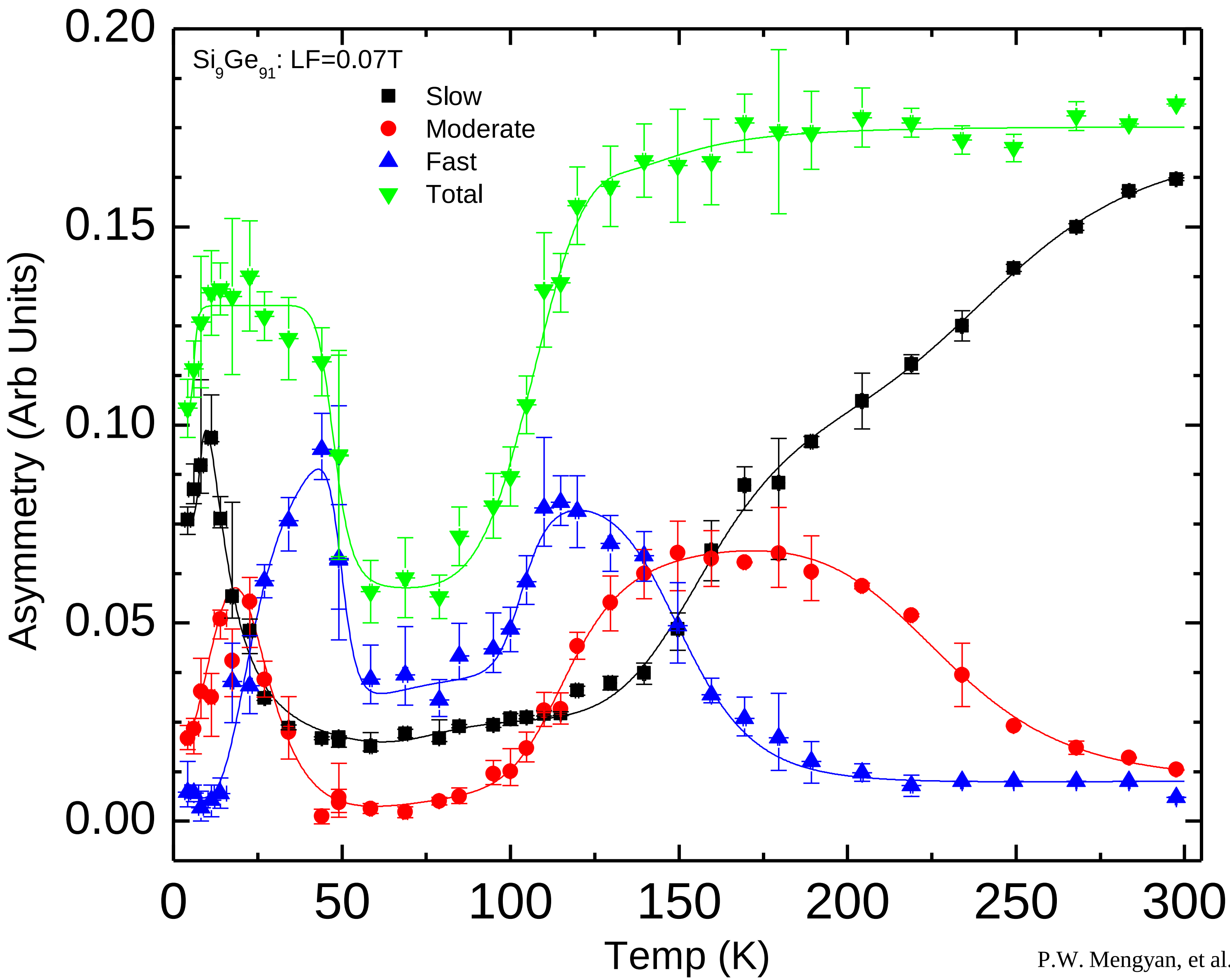
LF-μSR on Si_9Ge_{91}: Results



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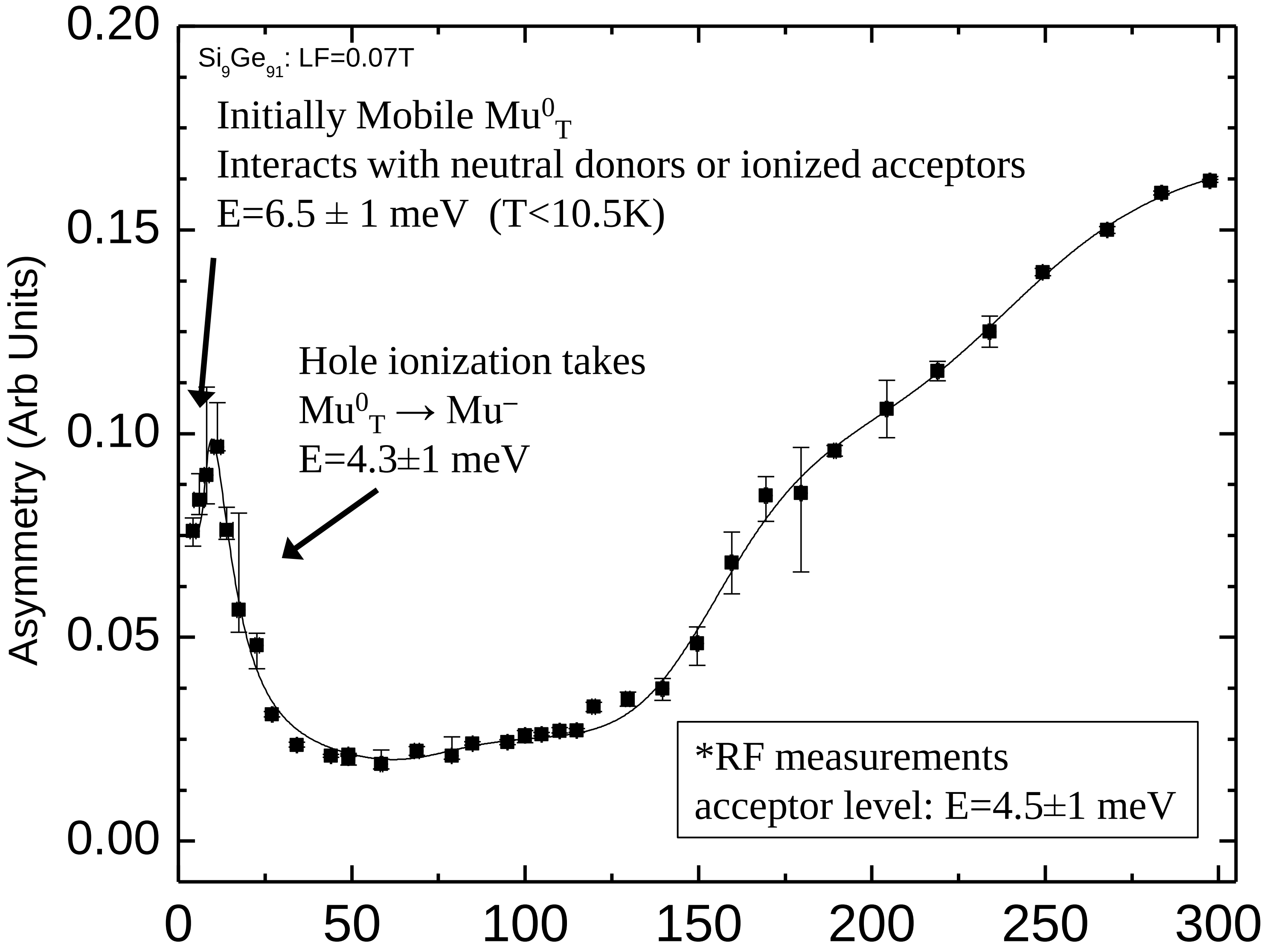
Si_9Ge_{91}: Slowly Relaxing Piece



*B.R. Carroll, et al., *Phys Rev B.* **82 (2010) 205205**;
*P.J.C. King, et al, *Physica B* **401-402** (2007) 617-620

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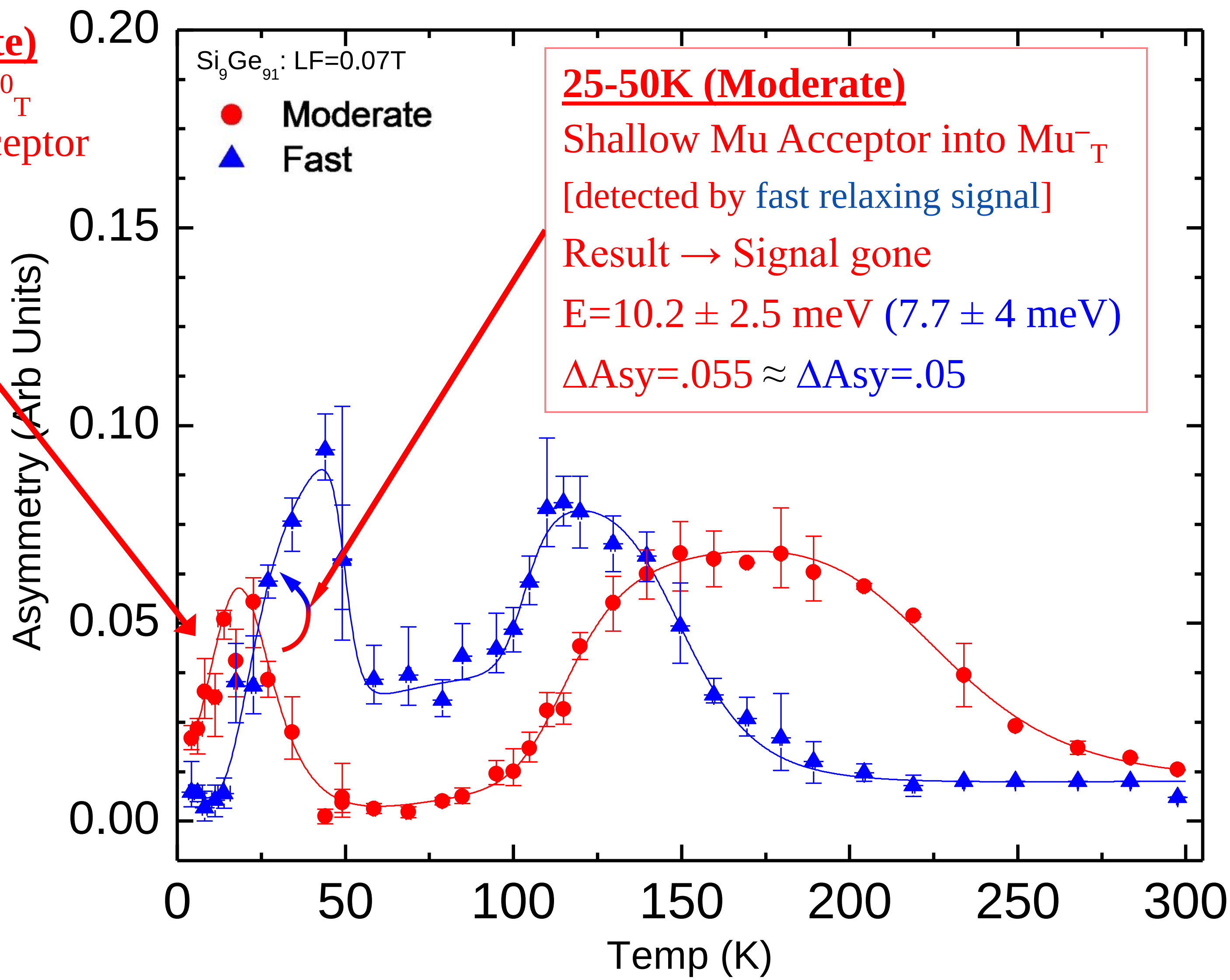
Si_9Ge_{91}: Moderate Relaxing Piece

T < 25K (Moderate)
Initially Mobile Mu^0_T
To Shallow Mu Acceptor
E=1.8 ± 0.7 meV



25-50K (Moderate)
Shallow Mu Acceptor into Mu^-_T
[detected by fast relaxing signal]
Result → Signal gone
E=10.2 ± 2.5 meV (7.7 ± 4 meV)
ΔAsy=.055 ≈ ΔAsy=.05

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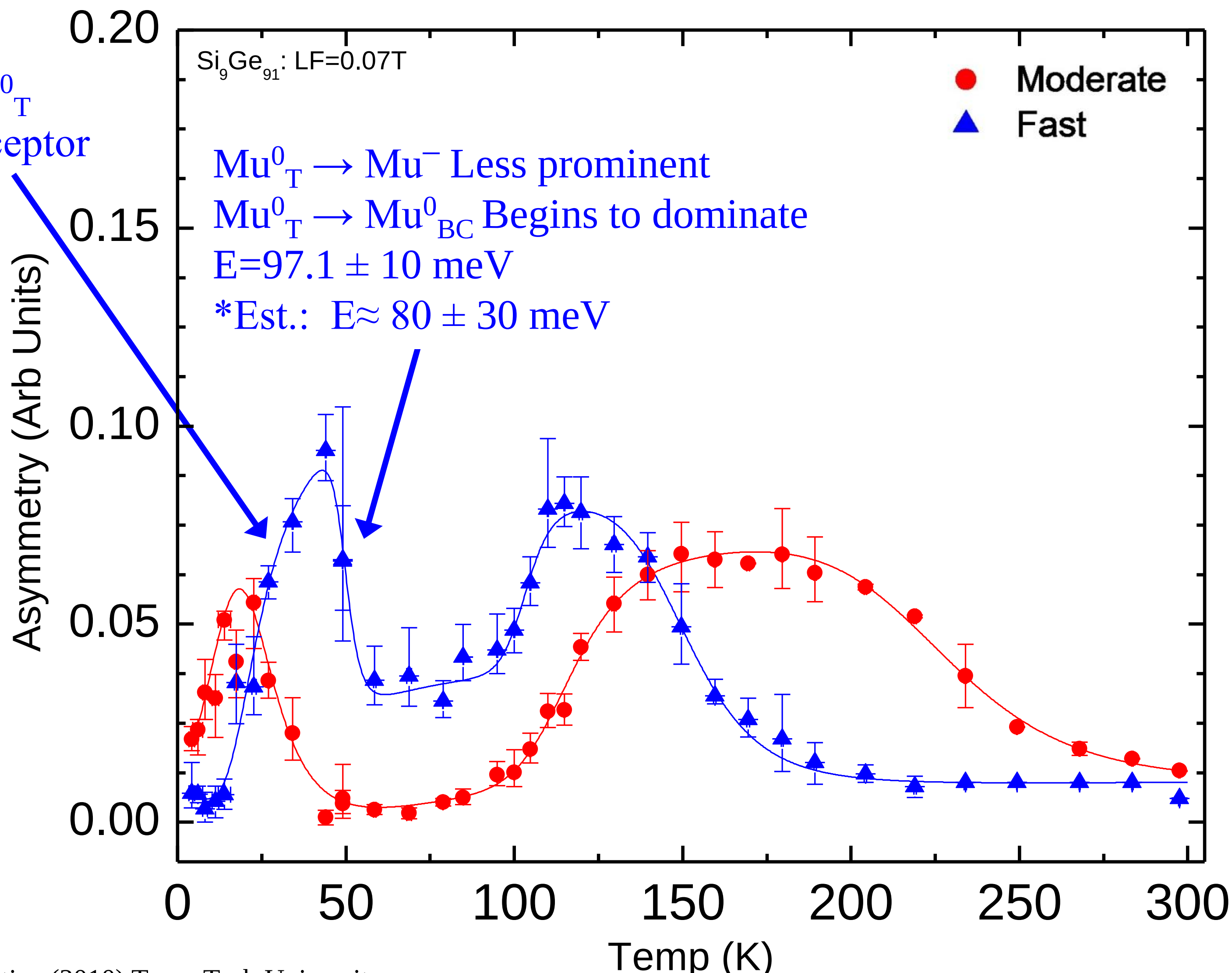
Si_9Ge_{91}: Fast Relaxing Piece

T < 45K (Fast)
Initially Mobile Mu^0_T
→ Shallow Mu Acceptor
→ Mu^-
E=7.7 ± 1.4 meV



$Mu^0_T \rightarrow Mu^-$ Less prominent
$Mu^0_T \rightarrow Mu^0_{BC}$ Begins to dominate
E=97.1 ± 10 meV
*Est.: E≈ 80 ± 30 meV

*B.R. Carroll, *Ph.D. Dissertation* (2010) Texas Tech University
*R.L. Lichti, et al., *Phys Rev B.* **60** (1999) 1734-1745

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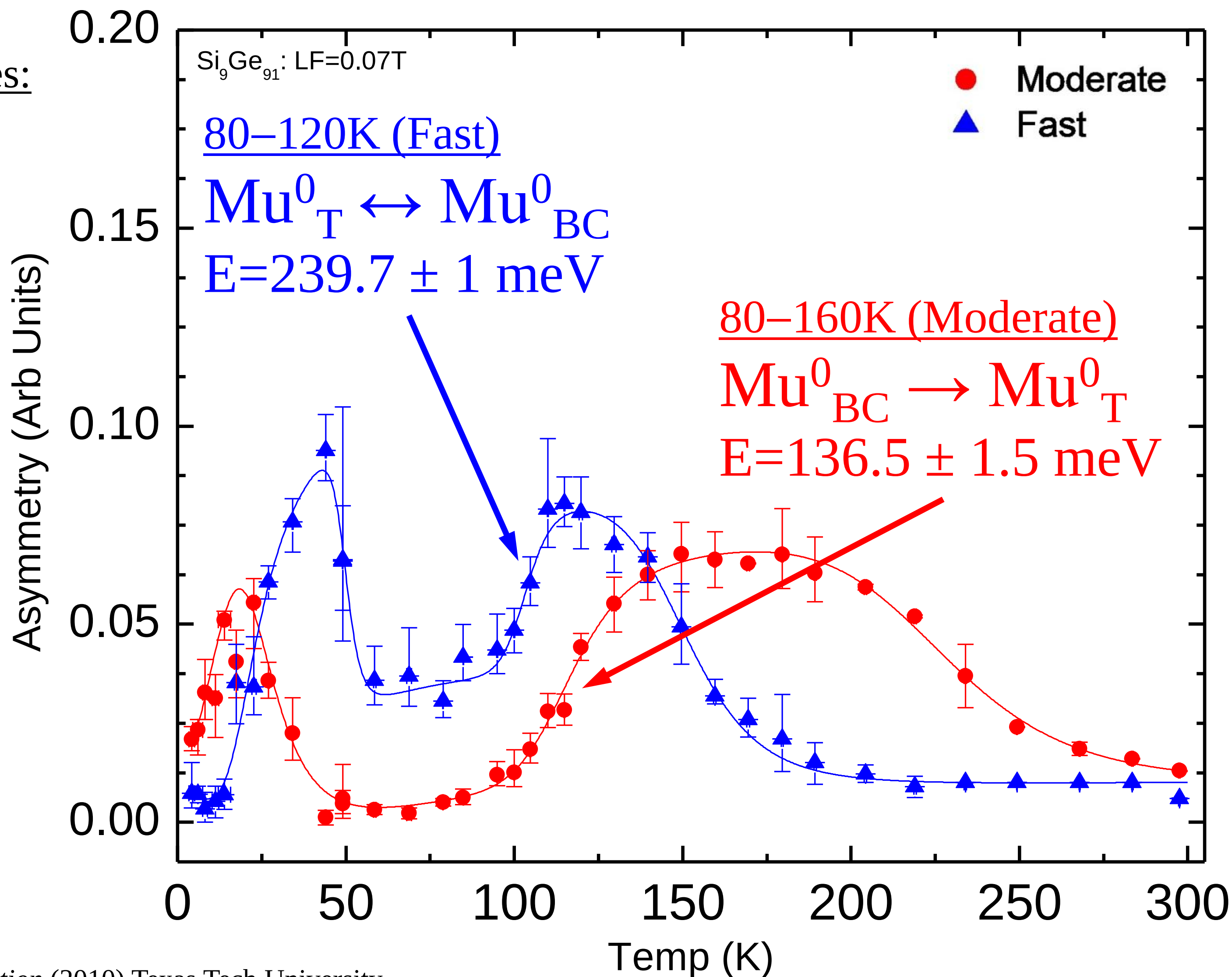
Si_9Ge_{91}: Cycles

*<u>Net energy of cycles:</u>

$Mu^0_T \rightarrow Mu^0_{BC}$
$E \approx 100$ meV

$Mu^0_{BC} \rightarrow Mu^0_T$
$E \approx 140$ meV



*B.R. Carroll, *Ph.D. Dissertation* (2010) Texas Tech University
*R.L. Lichti, et al., *Phys Rev B.* **60** (1999) 1734-1745

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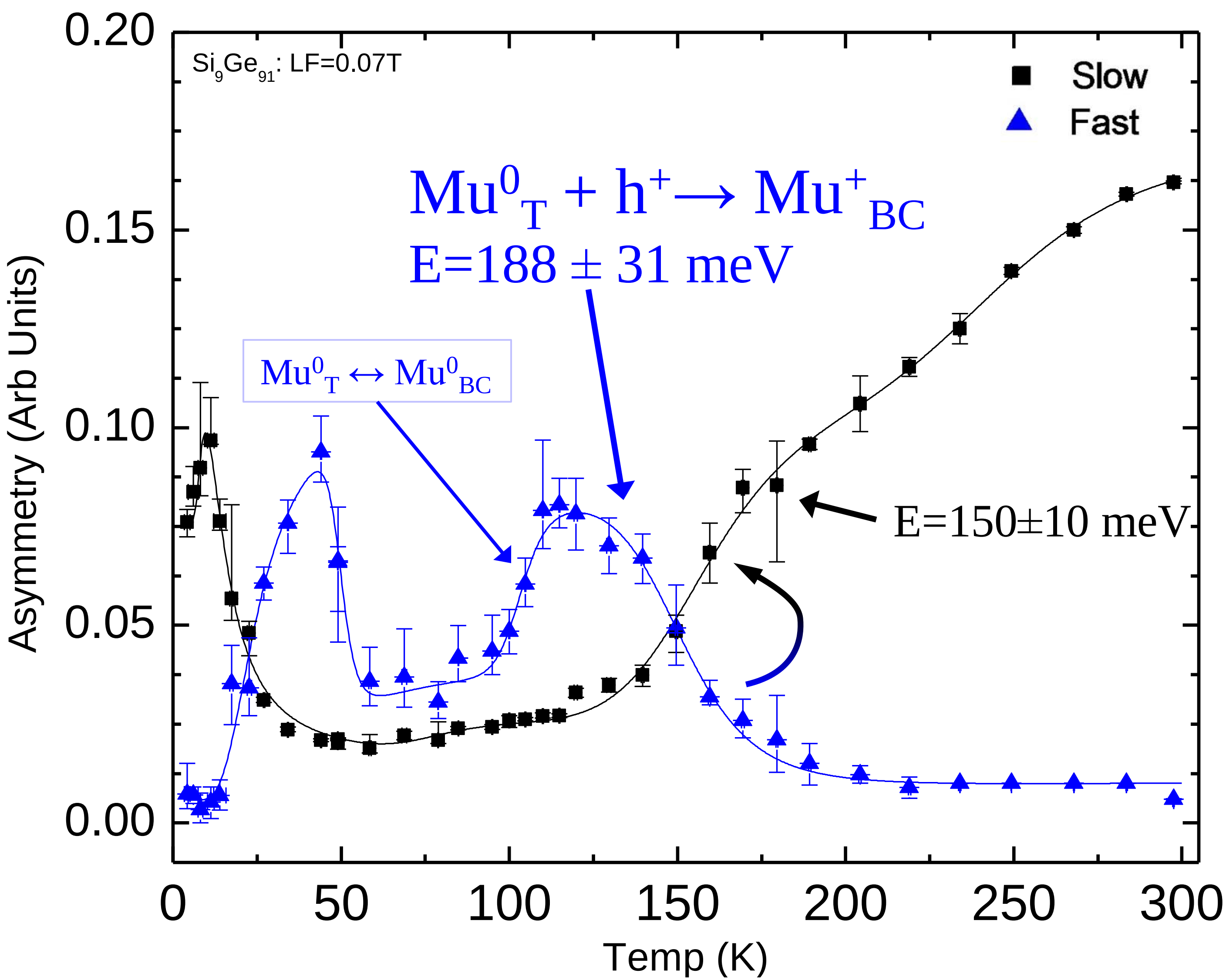
Si_9Ge_{91}: Cycles

<u>120–200K (Fast)</u>
$Mu^0_T \leftrightarrow Mu^0_{BC}$ cycle
Ending by hole capture
$(Mu^0_T + h^+ \rightarrow Mu^+_{BC})$
h^+ Ionization $\rightarrow Mu^-$

Continues until h^+ capture dominates and drives:
$Mu^0_T \rightarrow Mu^+_{BC}$
as long lived final state



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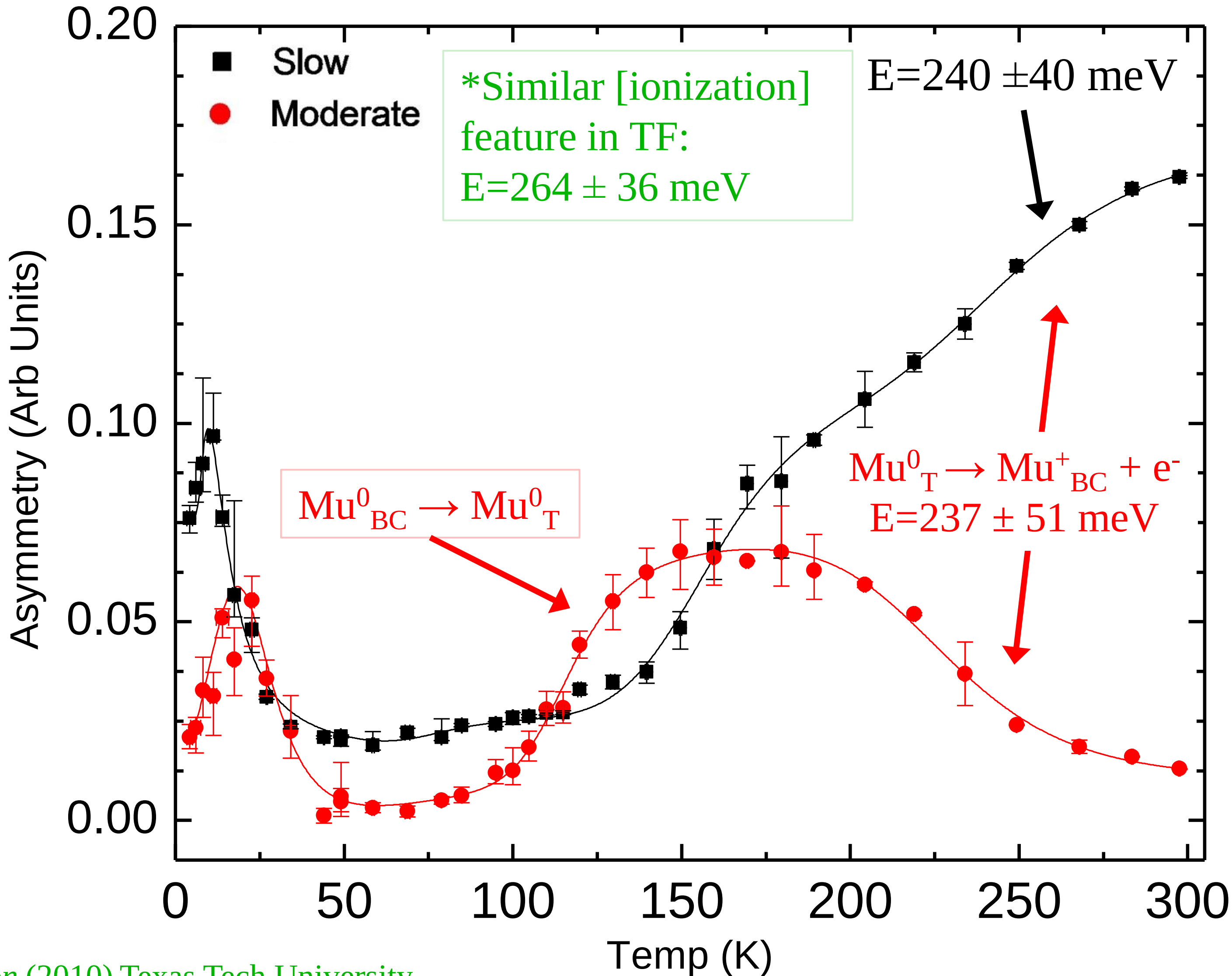
Si_9Ge_{91}: Cycles

<u>160–300K (Moderate)</u>
$Mu^0_{BC} \rightarrow Mu^0_T$ Process
Ending by hole capture
$(Mu^0_T + h^+ \rightarrow Mu^+_{BC})$
h^+ Ionization $\rightarrow Mu^-$

Continues until BC ionization takes:
$Mu^0_T \rightarrow Mu^+_{BC}$
as long lived final state



*B.R. Carroll, *Ph.D. Dissertation* (2010) Texas Tech University

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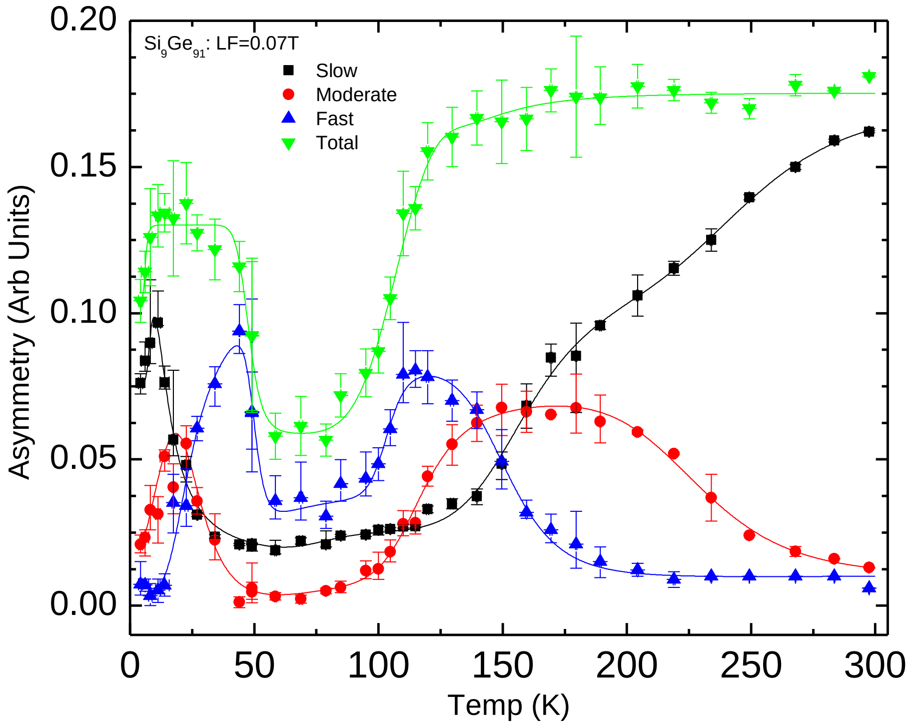
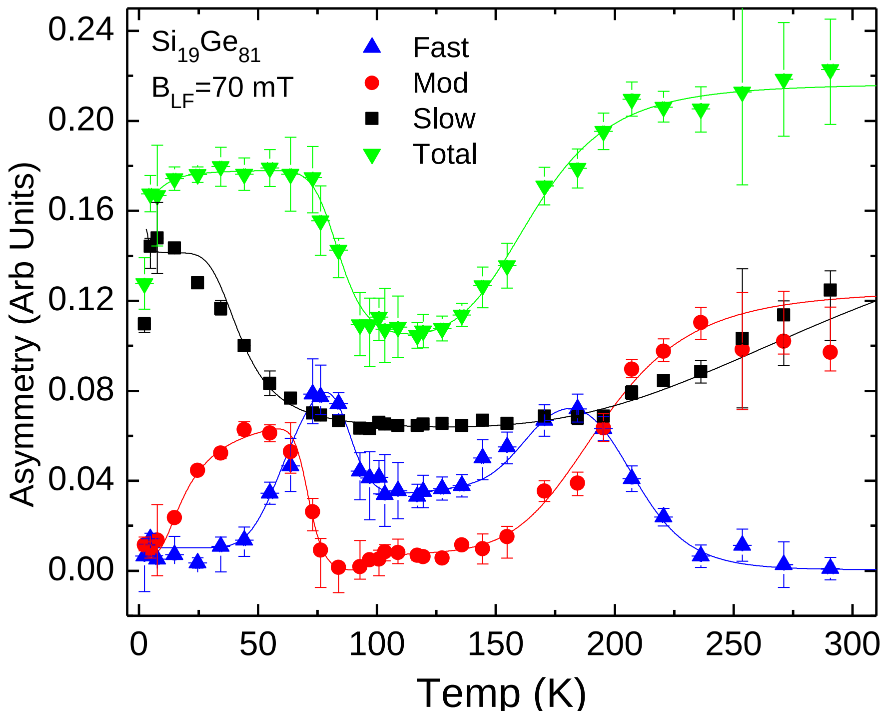
Si_9Ge_{91} vs. $Si_{19}Ge_{81}$

Si_9Ge_{91}



$Si_{19}Ge_{81}$



Similar features

Not enough high temp data to see full ionization
ie. Only 1 step in slow signal towards ionization in x=0.81

Shift with composition

Poor component separation: 25-100K & >200K

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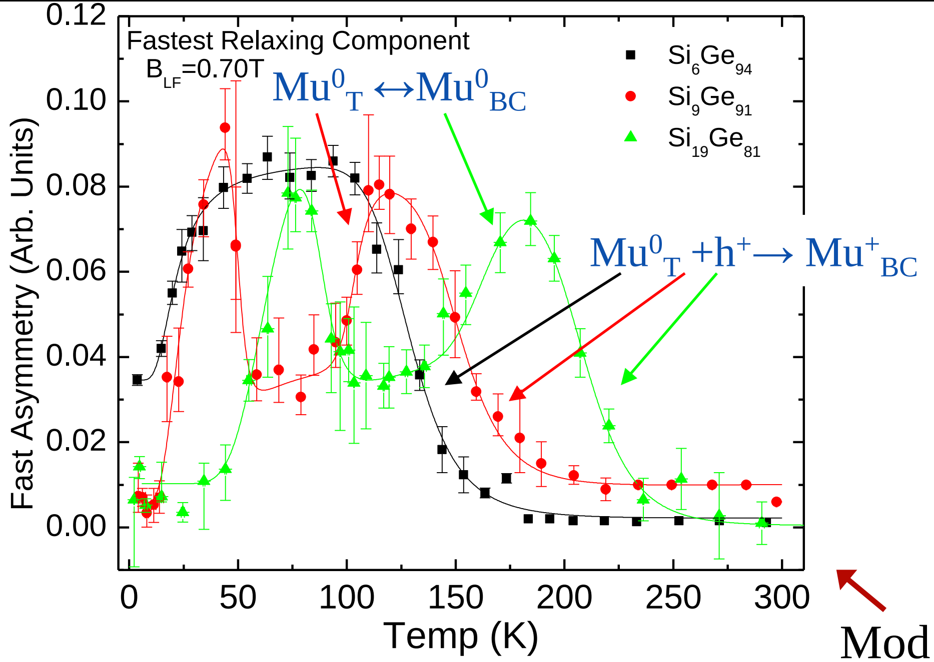
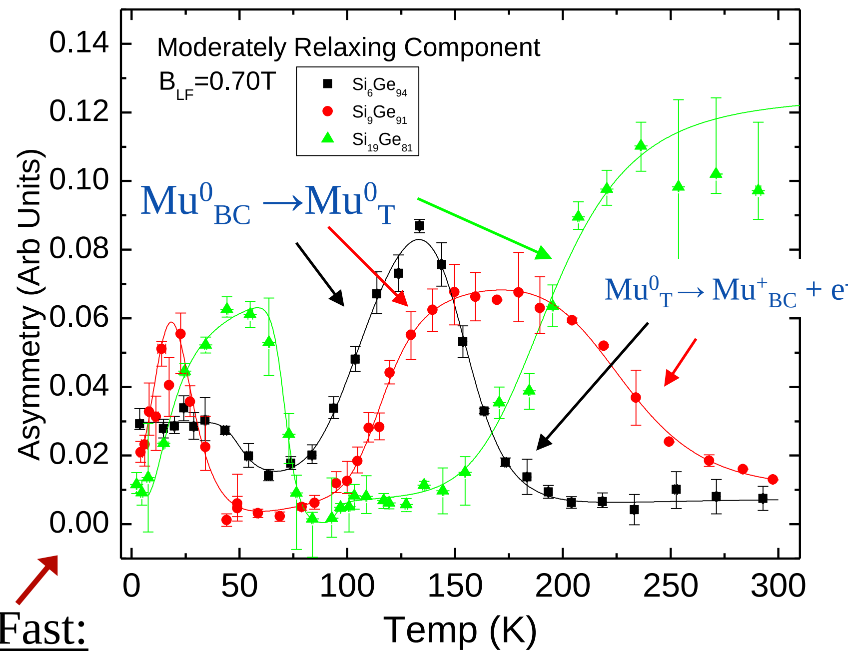
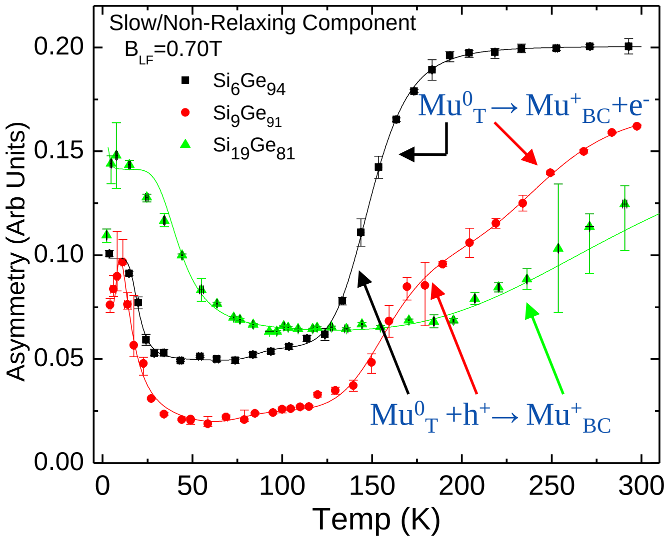
Si_6Ge_{94}







Mod & Fast:

- Peak shift with composition
- Energies consistent with estimated cycle energies
- Hole ionization & $Mu^0_T \rightarrow Mu^0_{BC}$ process

Slow:

- Increase in ionization energy w.r.t. composition
- $Si_{19}Ge_{81}$ minimum does not follow trend
- Si_6Ge_{94} Only one resolved step in higher temp

All:

Cyclic transition involving $Mu^0_T \leftrightarrow Mu^0_{BC}$ end in Mu^+_{BC}

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Future Work

Overall goal includes determining how cyclic processes evolve w.r.t. alloy content throughout full range

Additional data fitting & theoretical modeling
→ ensure accurate assignments for the processes
→ extend appropriately to the other Ge-rich compositions

Continue to develop comprehensive description of the Mu/H defect characteristics

Summary of Energies

	$Si_{19}Ge_{81}$	$Si_{9}Ge_{91}$	$Si_{6}Ge_{94}$
$Mu^0_T \rightarrow Mu^-_T$	**4 ± 3 meV**	**5.5 ± 2 meV**	V.B. Resonant
$Mu^0_T \rightarrow Mu^0_{BC}$	**106 ± 28 meV**	**97.1 ± 10 meV**	**71 ± 14 meV**
$Mu^0_T \leftrightarrow Mu^0_{BC}$	247 ± 12 meV	239.7 ± 1 meV	Unable to Resolve
$Mu^0_{BC} \rightarrow Mu^0_T$ $(\rightarrow Mu^-_T + h^+)$	138 ± 37 meV	136.5 ± 1.5 meV	137 ± 15 meV
$Mu^0_T + h^+ \rightarrow Mu^+_{BC}$	325 ± 84 meV*	**188 ± 31 meV**	**133 ± 23 meV**
$Mu^0_{BC} \rightarrow Mu^+_{BC} + e^-$	*	237 ± 51 meV	210 ± 45 meV

Red: 'New' information

* Not enough data to determine with *reasonable* accuracy

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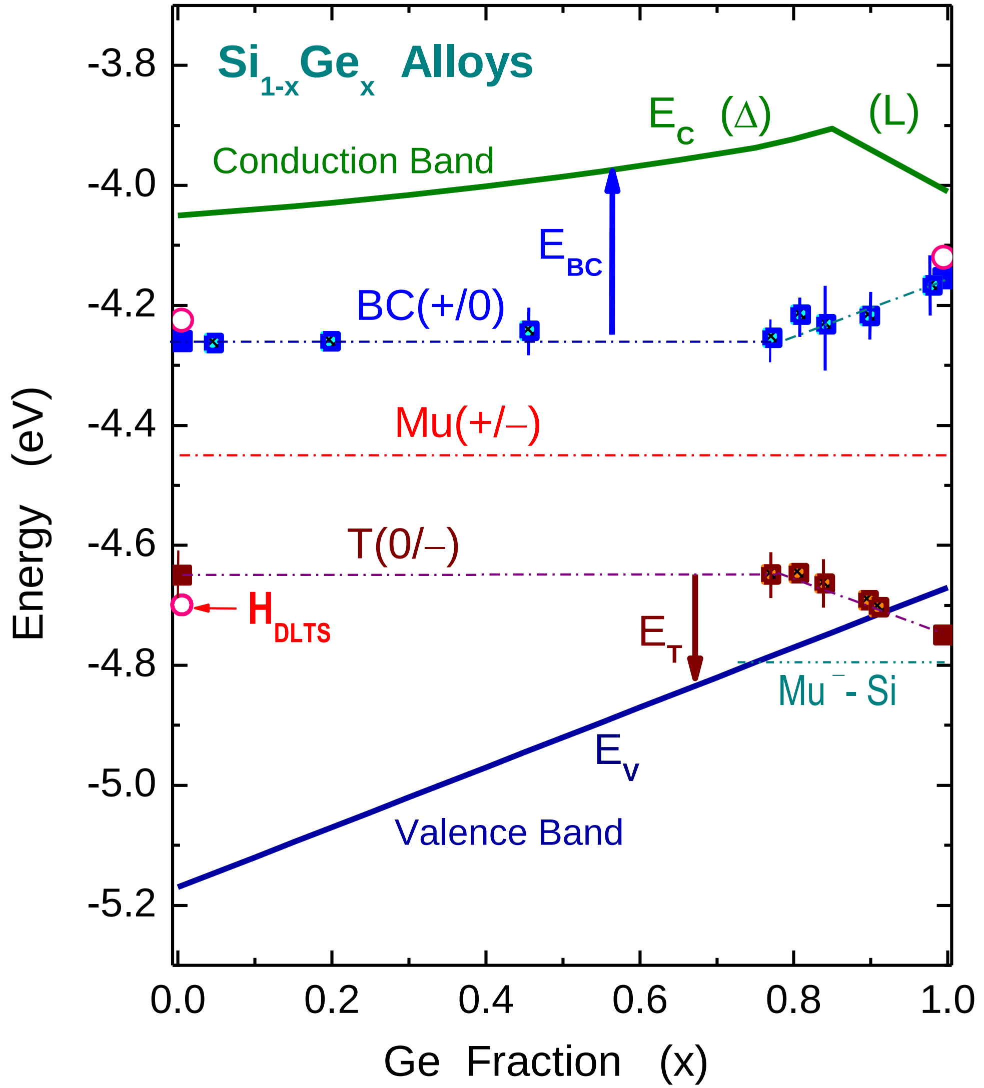
Thank you



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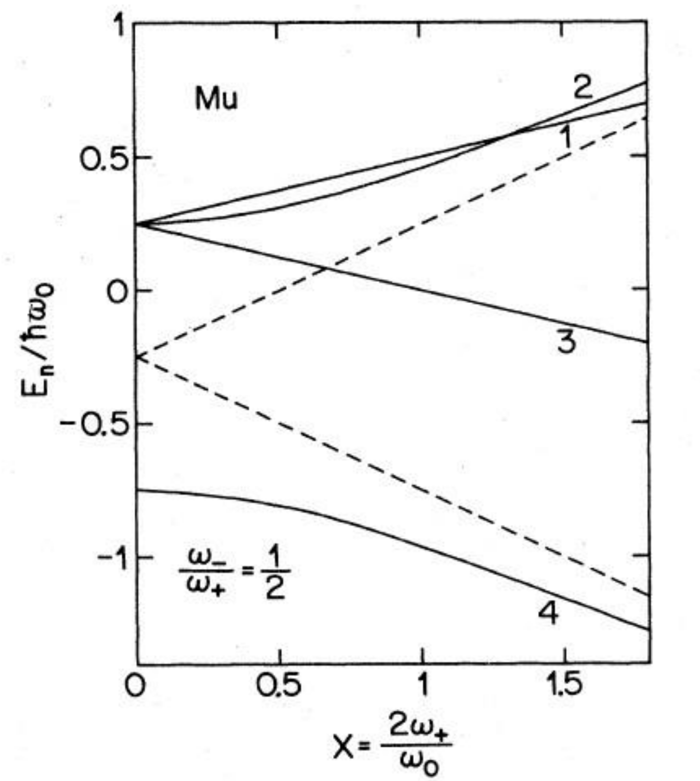
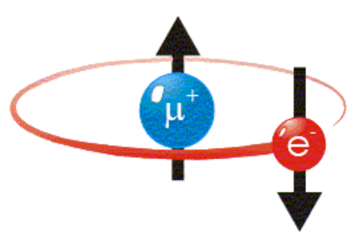


FIG. 1. The hyperfine energy-level (Breit-Rabi) diagram for isotropic 1s-Mu as a function of the dimensionless magnetic field $x = B(g_\mu \mu_\mu - g_e \mu_B)/(hA)$. A fictitious value for the quantity ω_-/ω_+ has been used for clarity; its true value is 0.9904. The dashed lines are the high-field asymptotes for levels 2 and 4.

B.D. Patterson, *Rev. Mod. Phys.*, **60**, (1988) 1

Muonium (Mu ≡ $\mu^+ e^-$)



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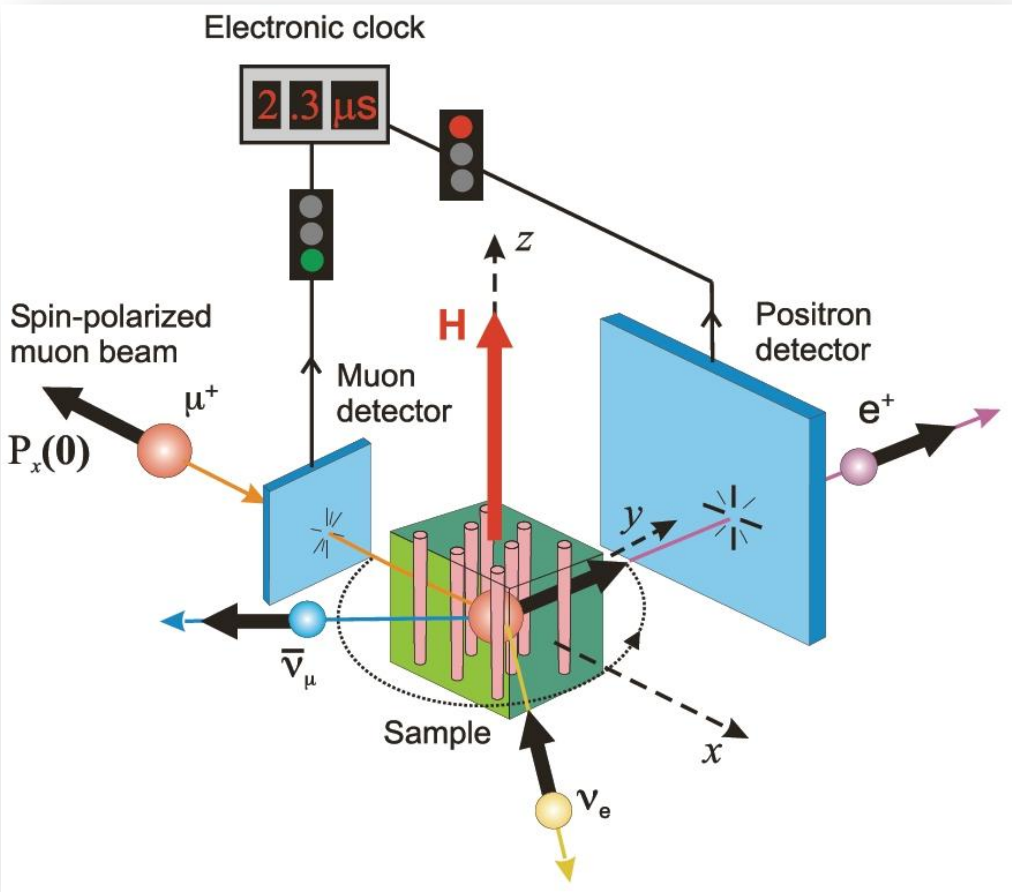
TF-μSR



Field applied ⊥ to initial spin polarization
→ μ^+ spin precession about applied field at:

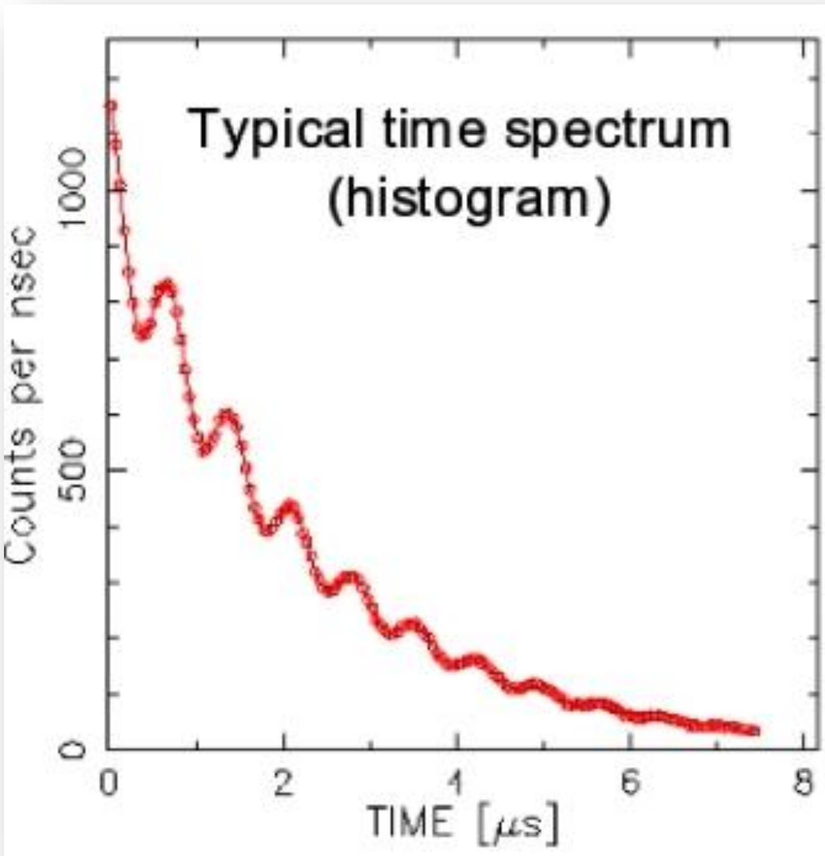
$\nu_{\mu+} = \gamma_\mu \times |\mathbf{B}|$ $|\gamma_\mu = 135.54\text{MHz/T}$

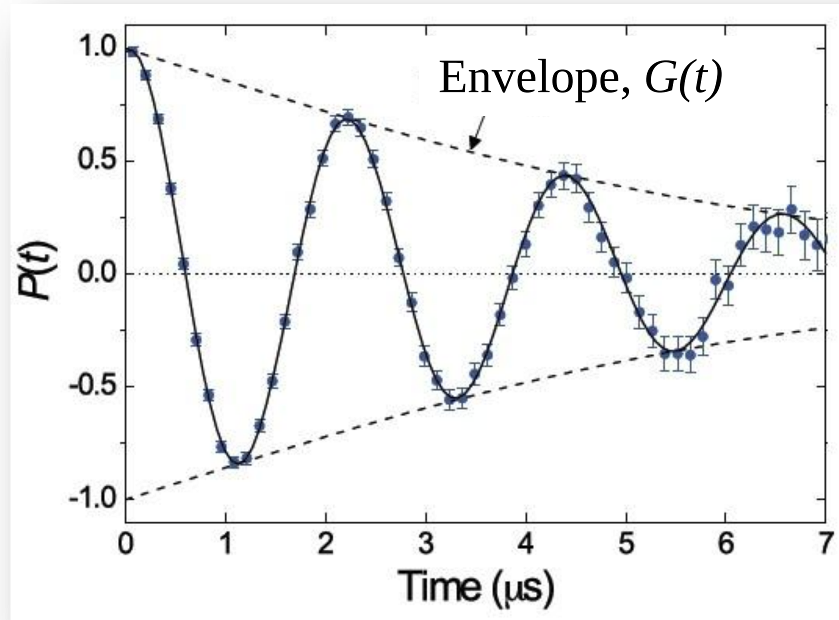
$Mu^0 = \mu^+ + e^-$
→ spin-orbit coupling
→ affects local field of μ^+
→ diff prec. Freq for:
$|\uparrow_\mu> + |\uparrow_e>$ & $|\uparrow_\mu> + |\downarrow_e>$

Brewer, http://musr.ca

B.D. Patterson, *Rev. Mod. Phys.*, **60**, (1988) 1

TF-μSR: Sample signal from relaxing μ^+





$$P(t) = G(t)\cos\left(\gamma_{\mu^+}\left|\mathbf{B}_{\mu^+}\right| + \delta\right)$$

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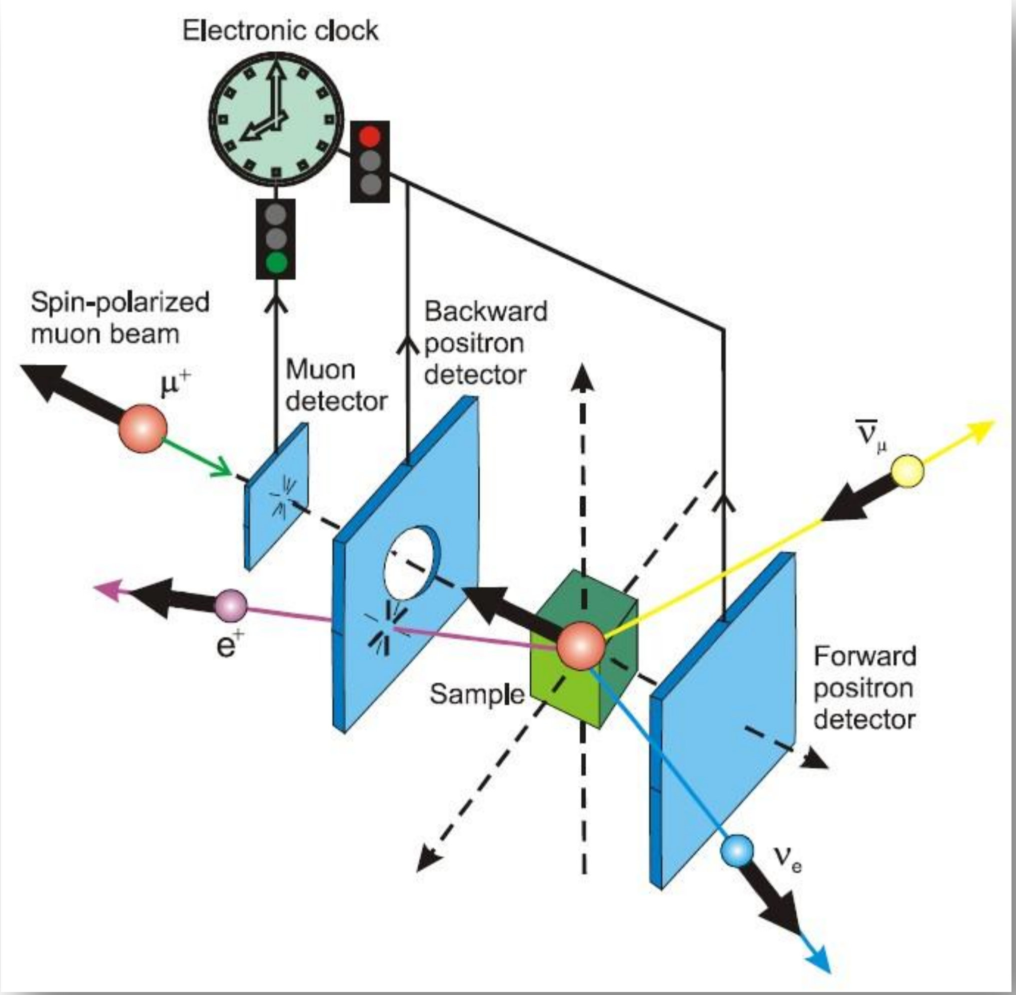
LF-μSR

B applied || to μ^+ spin pol.
See time evolution of P(t) along original direction

=> Change in Spin P(t) from:
1) local environment (nearby nuclear moments)
2) muonium motion
(e^- spin-flip w/ each site change, transferring back to μ^+ contributing to Δ P(t))



R.F. Kiefl, R. Kadono, et al., *Phys Rev Lett*, **62** (1989) 7

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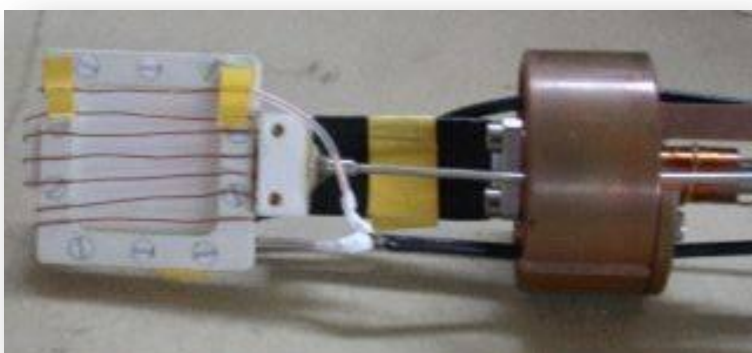
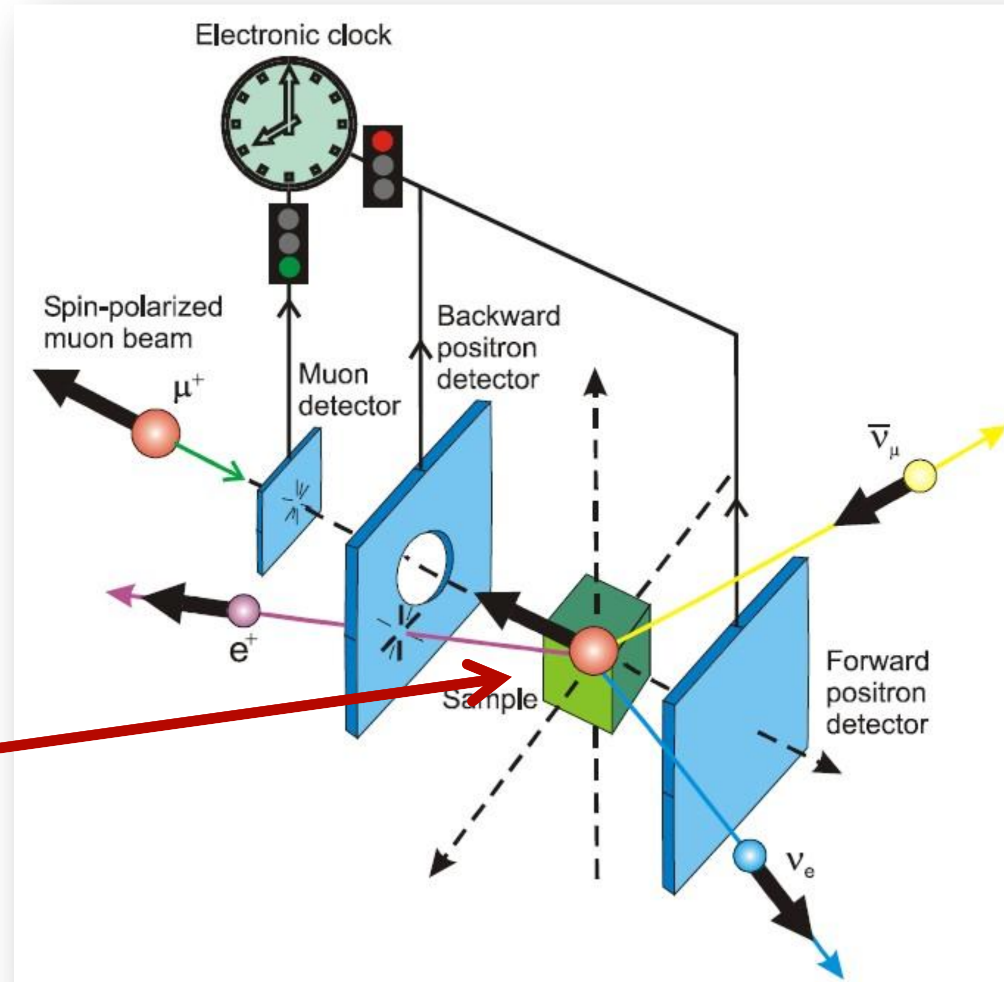
RF-μSR

Start with LF setup

Oscillating field applied to drive transitions between Zeeman level(s)





Picture: J. Lord, RF-μSR and Pulsed Techniques, http://www.isis.stfc.ac.uk/groups/muons/muon-training-school

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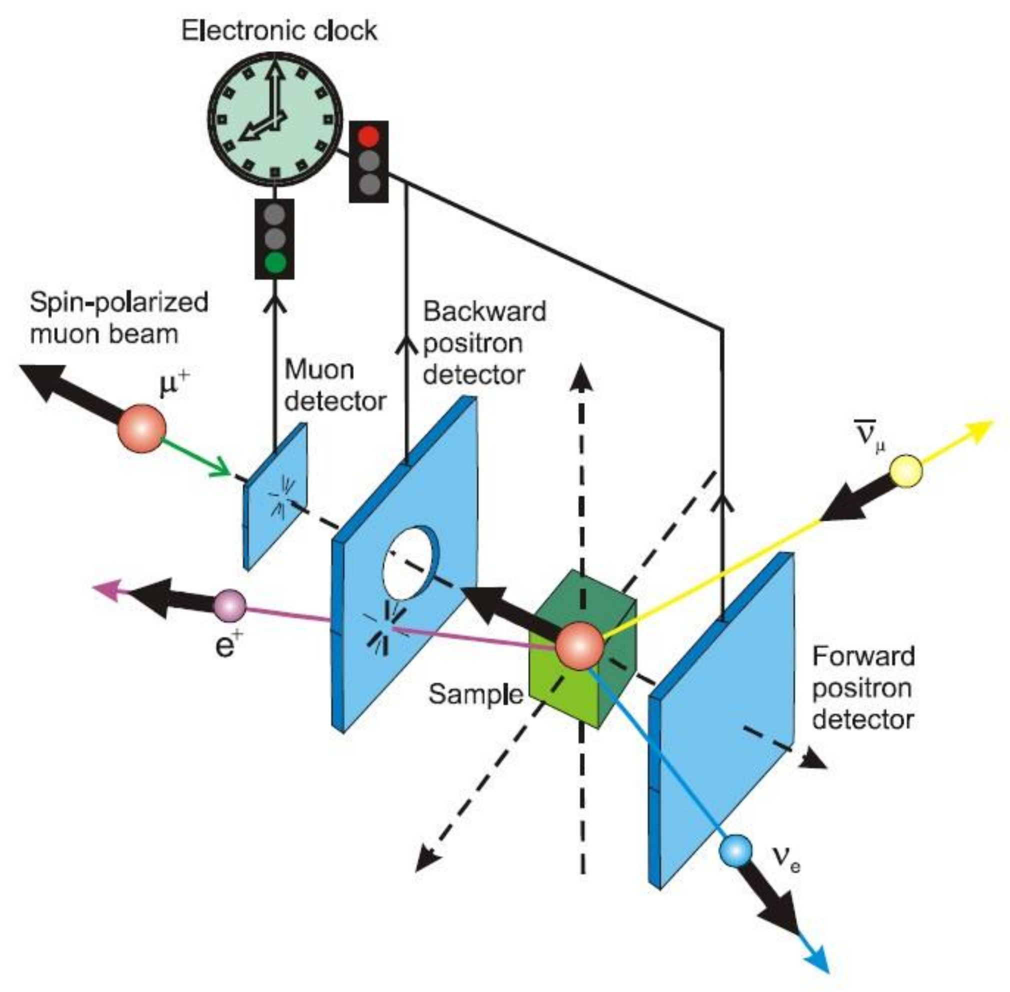
ZF-μSR



Brewer, http://musr.ca

No net B applied
See time evolution of P(t) in natural environment

=> Change in Spin P(t) from:
1) local environment (nearby nuclear moments)
2) μ^+ motion

R.F. Kiefl, R. Kadono, et al., *Phys Rev Lett*, **62** (1989) 7
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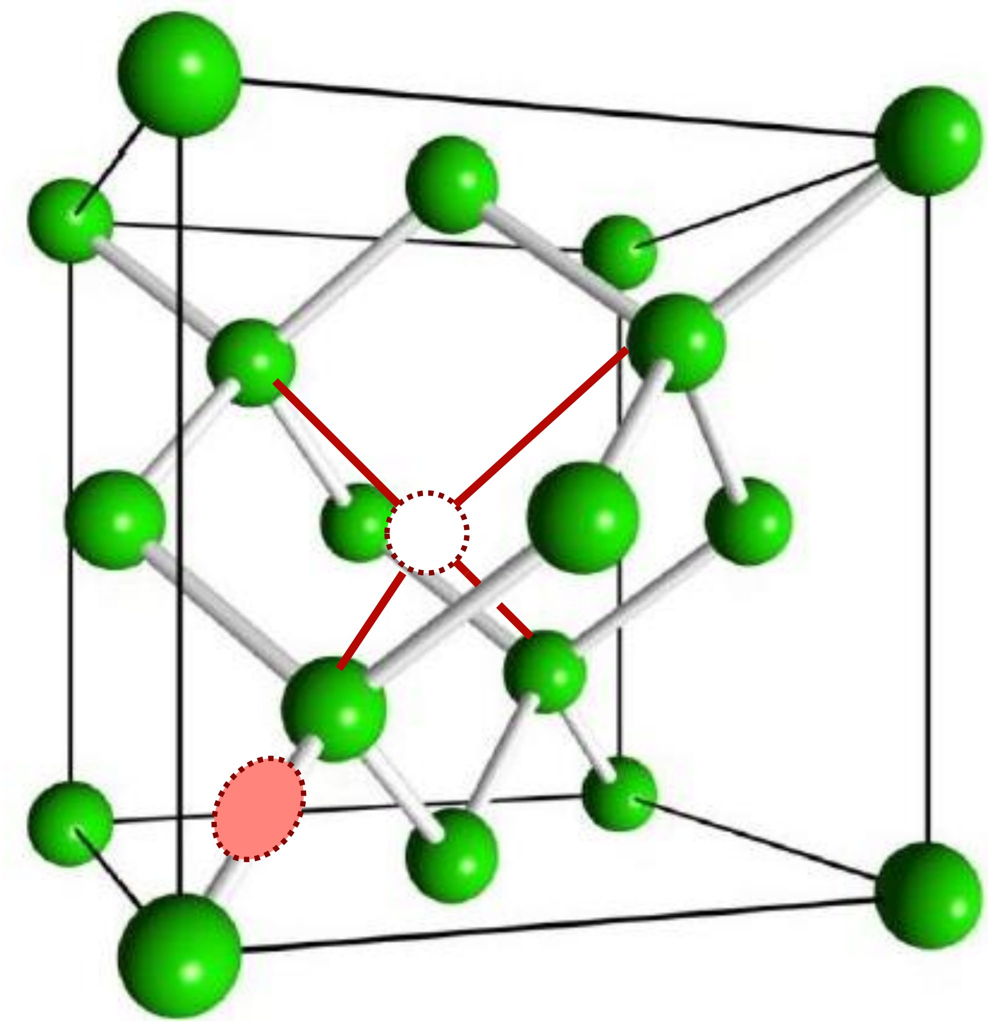
Mu T and BC Sites in Diamond Structure



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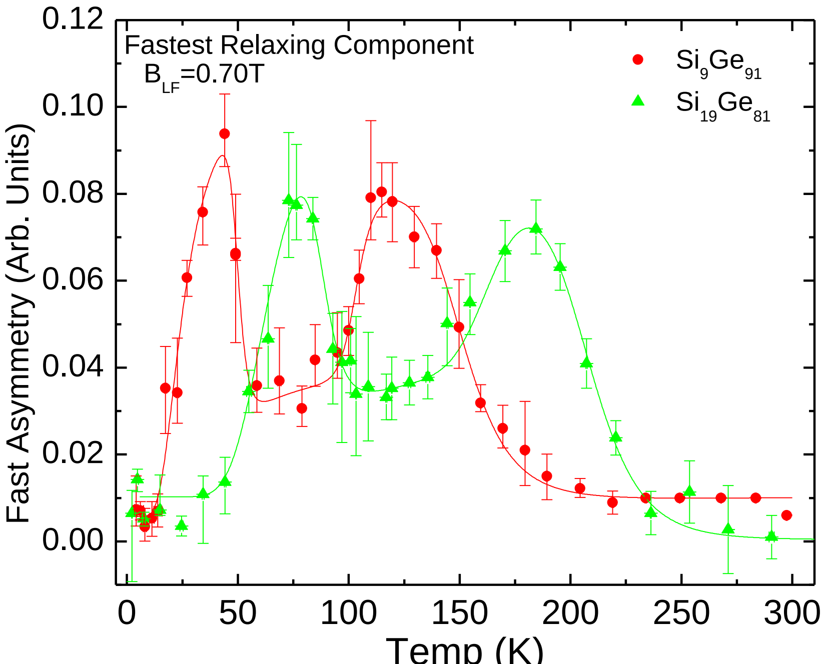
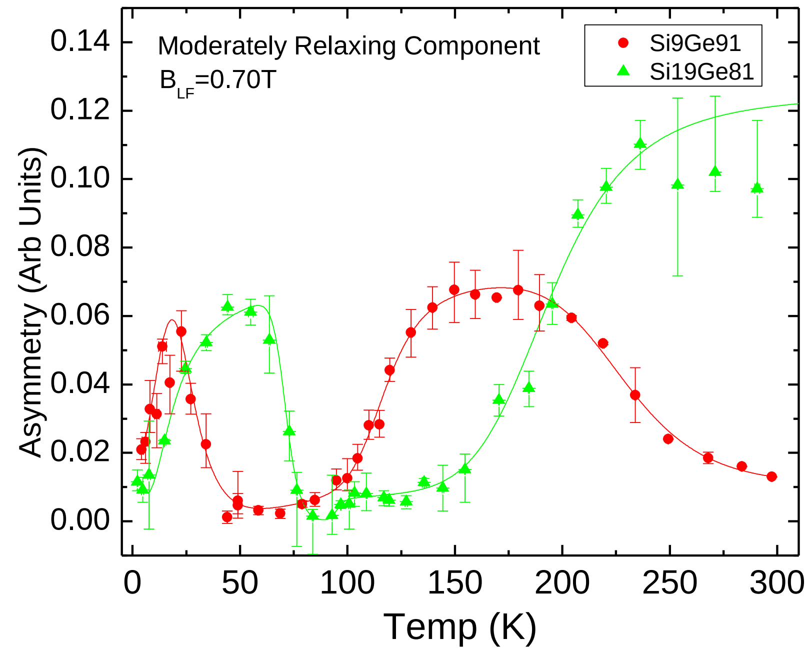
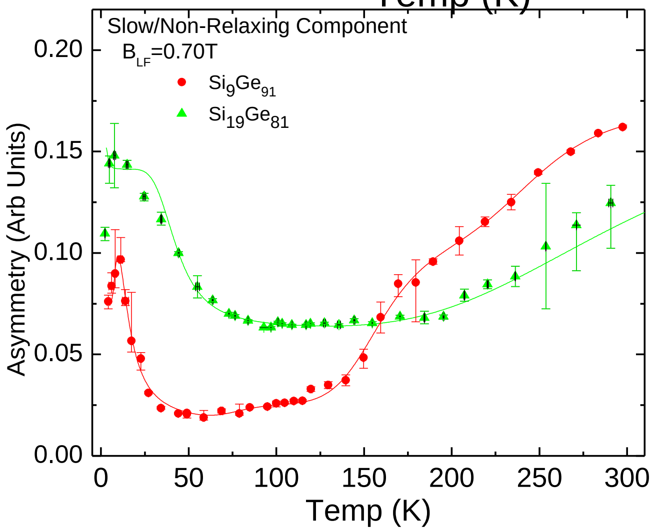
Si_9Ge_{91} vs $Si_{19}Ge_{81}$







Comparison of Si_9Ge_{91} to $Si_{19}Ge_{81}$

Mod & Fast: peak shift with composition

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Summary

<u>Using LF-MuSR we have observed:</u>

• Hole ionization & $Mu^0_T \rightarrow Mu^0_{BC}$ Transition
Both associated with shallow acceptor (base to ~50K)

• Two cyclic transitions involving: $Mu^0_T \leftrightarrow Mu^0_{BC}$
Followed by hole ionization: $Mu^0_T \rightarrow Mu^-_T$
Continues until h^+ capture drives final state to stable Mu^+_{BC}
or terminated by BC ionization causing $Mu^0_{BC} \rightarrow Mu^+_{BC}$

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