Hyperfine Spectroscopy and Characterization of Muonium Centers in $ZnGeP_2$

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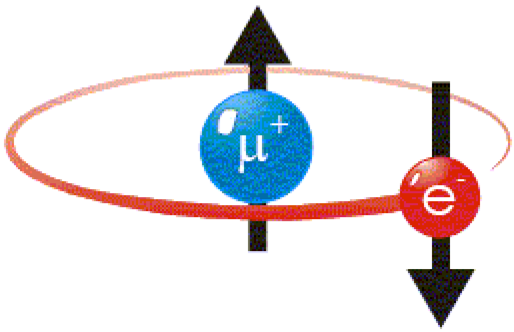
Overview of MuSR

- MuSR = Muon Spin Research (Relaxation/Rotation/Resonance)
- App: Semiconductors – exp. analog for H defects
- Implant 100% Spin-polarized Muons
- Spin vector evolves in local magnetic environment
- e^+ emitted preferentially along spin direction
- e^+ count information then analyzed

Muonium

	Muon	Proton
Mass (m_p)	$0.1126 \approx 1/9$	1
Spin	½	½
Gyro. Ratio, γ (s^{-1} T^{-1})	8.51607×10^8 $\approx 3.2 \times \gamma_P$	2.67520×10^8
Lifetime, τ (μs)	2.19709	Stable
	Muonium	**Hydrogen**
Reduced e^- mass (m_e)	0.995187	0.999456
Ground-state Radius (Å)	0.531736	0.529465
Ground-state Energy (eV)	-13.5403	-13.5984

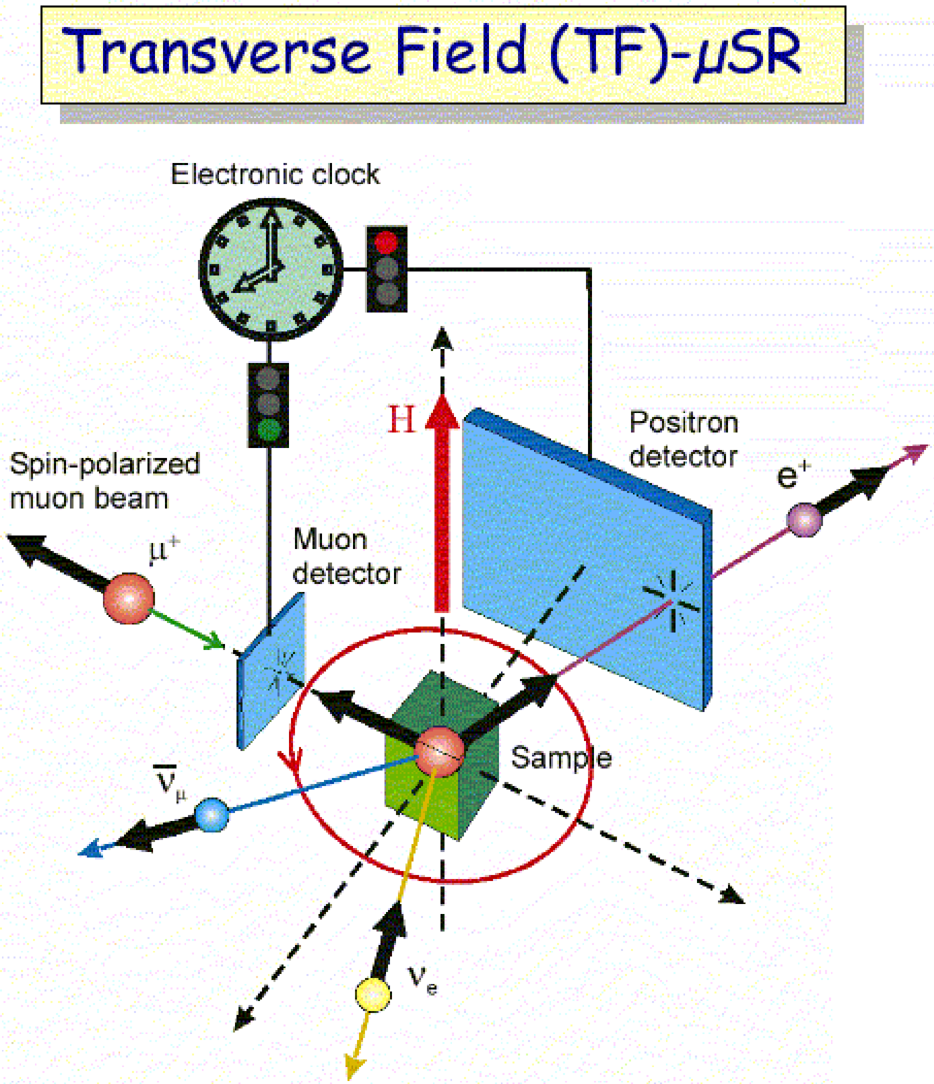
Muonium (Mu ≡ μ^+e^-)



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

Brewer, http://musr.ca

Overview of MuSR: TF



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

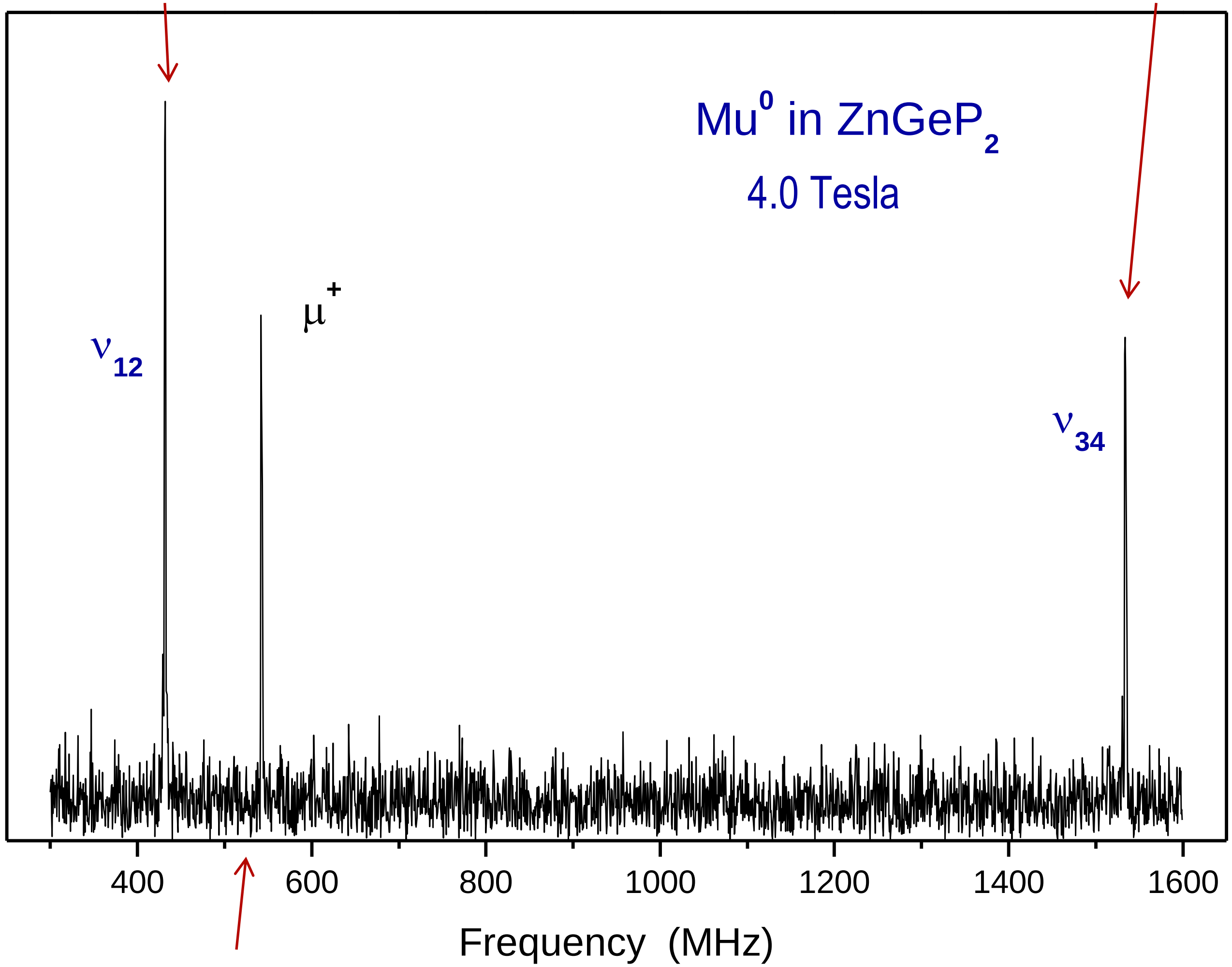
$Mu^0 = \mu^+ + e^-$
→ spin-orbit coupling
→ affects local field of μ^+
→ diff prec. Freq for:
$|\uparrow_\mu\rangle + |\uparrow_e\rangle$ & $|\uparrow_\mu\rangle + |\downarrow_e\rangle$

Hyperfine Spectroscopy of $ZnGeP_2$

(from TF-μSR)

- 431.55 MHz (+/- 0.004)

1534.07 MHz (+/- 0.06)



542.16 MHz

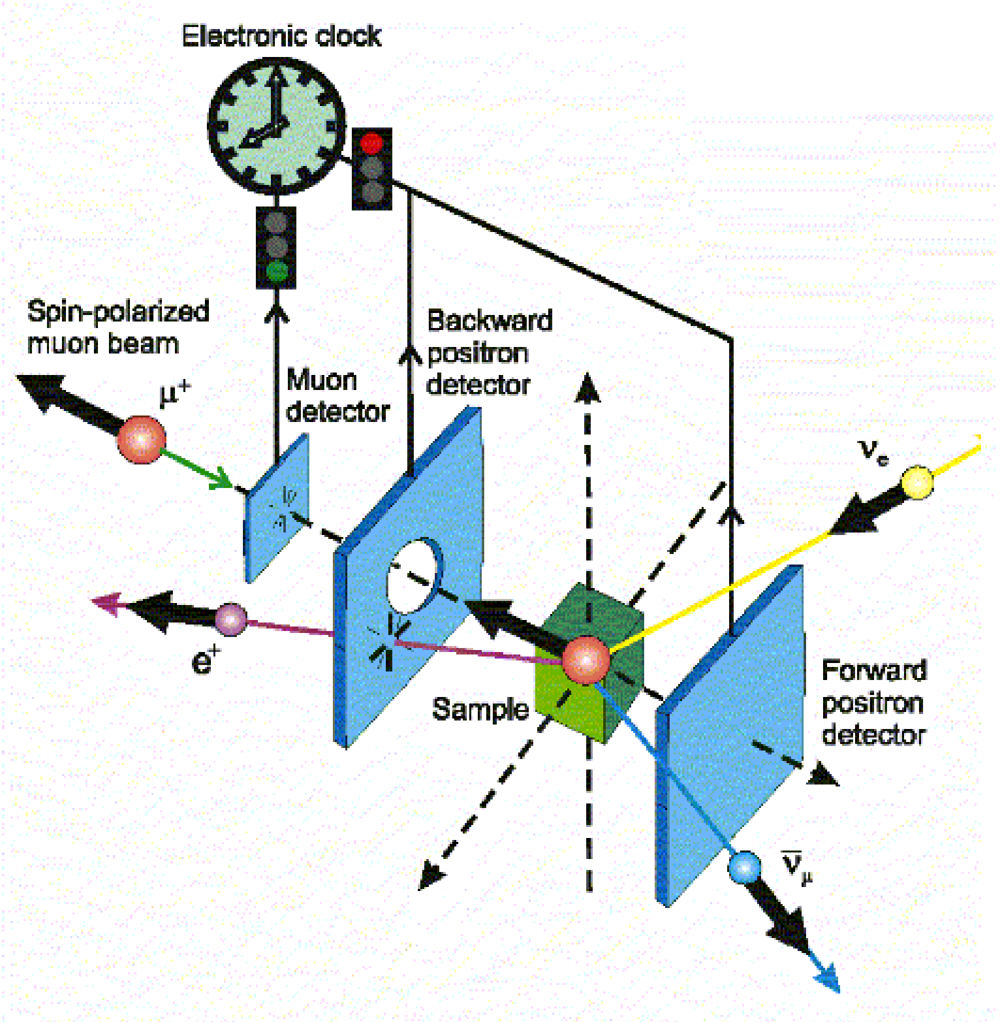
$$A_1 = \nu_{34} - \nu_{12}$$
$$= 1965.6 \text{ MHz}$$

P.W. Mengyan, et. Al., Physica B (2009), doi: 10.1016/j.physb.2009.08.212

Overview of MuSR: LF

B applied || to μ^+ spin pol.
→ breaks HF interaction

=> 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

Brewer, http://musr.ca

From LF-μSR

*HF info from T_1^{-1} depolarization curves
(field dep. of Amp.)

**Current analysis suggests axially symmetric anisotropic HF interaction with:

$\rightarrow A_2 = 3185$ MHz & D = 374 MHz

*F.L. Pratt, *Philos. Mag. Lett.* **75** (1997) 371.

**P.W. Mengyan, et. Al., Physica B (2009), doi: 10.1016/j.physb.2009.08.212

Note: TF vs LF results for HF term(s)

TF data:

A_1 = 1961.8 (+/- 2.3) MHz

(isotropic – experimental determination)

LF data:

A_2 = 3185 MHz

D = 374 MHz

Why the different HF?

P.W. Mengyan, et. Al., Physica B (2009), doi: 10.1016/j.physb.2009.08.212

$ZnGeP_2$: Structure

Chalcopyrite structured
II-IV-V_2 material

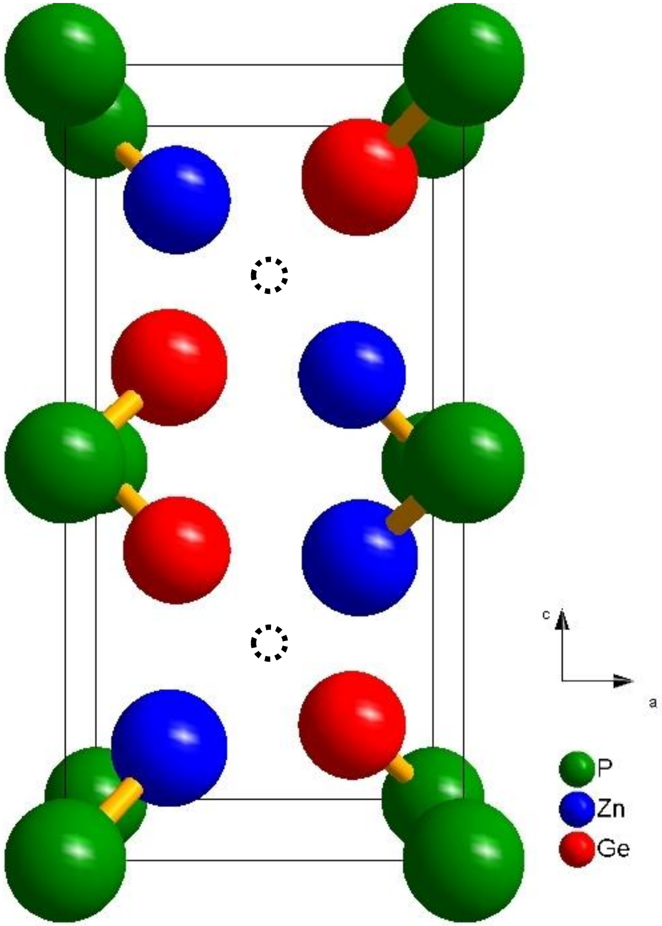
Zincblende structure (c.f. III-V), doubled unit-cell

III-Sublattice replaced by II-IV atoms, 1:1

V replaced by V_2

2 T-sites: T_V & T_{II-IV}

$ZnGeP_2$: II-IV pseudo-T-site



*Unequal charge on Zn (+1.2q_e) & Ge (+1.8q_e)
→distorted 1s Ψ
→ anisotropy with [110] axial symmetry

$$\vec{E} = \mp \frac{1}{4\pi\varepsilon_0} \frac{32\sqrt{3}}{9} \left(q_{Zn} - q_{Ge} \right) [110]$$

Seen in LF but not TF
=> not promptly formed, but visited throughout lifetime

* P. Zapol, et. al. J. Appl. Phys. **79** (1996) 671

The Sample

Single Crystal

Nominally undoped

7.1x8.5x1.1 mm^3

Orientation: [001]

Summary: Mu0 Centers in $ZnGeP_2$

1) Implantation
2) Formation of Mu^0 in T_V
   with isotropic: A_1 = 1961.8 (+/- 2.3) MHz
   (Visible in TF)
3) Mu^0 hops w/ ID change ea. hop (not discussed)
4) Mu^0 in $T_{II\text{-}IV}$ with anisotropic:
   A_2 = 3185 MHz D = 374 MHz (+/- 10%)
   (Visible in LF Repolarization data)

P.W. Mengyan, et. Al., Physica B (2009), doi: 10.1016/j.physb.2009.08.212

Summary

This completes our discussion of the Muonium centers in $ZnGeP_2$

P.W. Mengyan, et. Al., Physica B (2009), doi: 10.1016/j.physb.2009.08.212

Thank You

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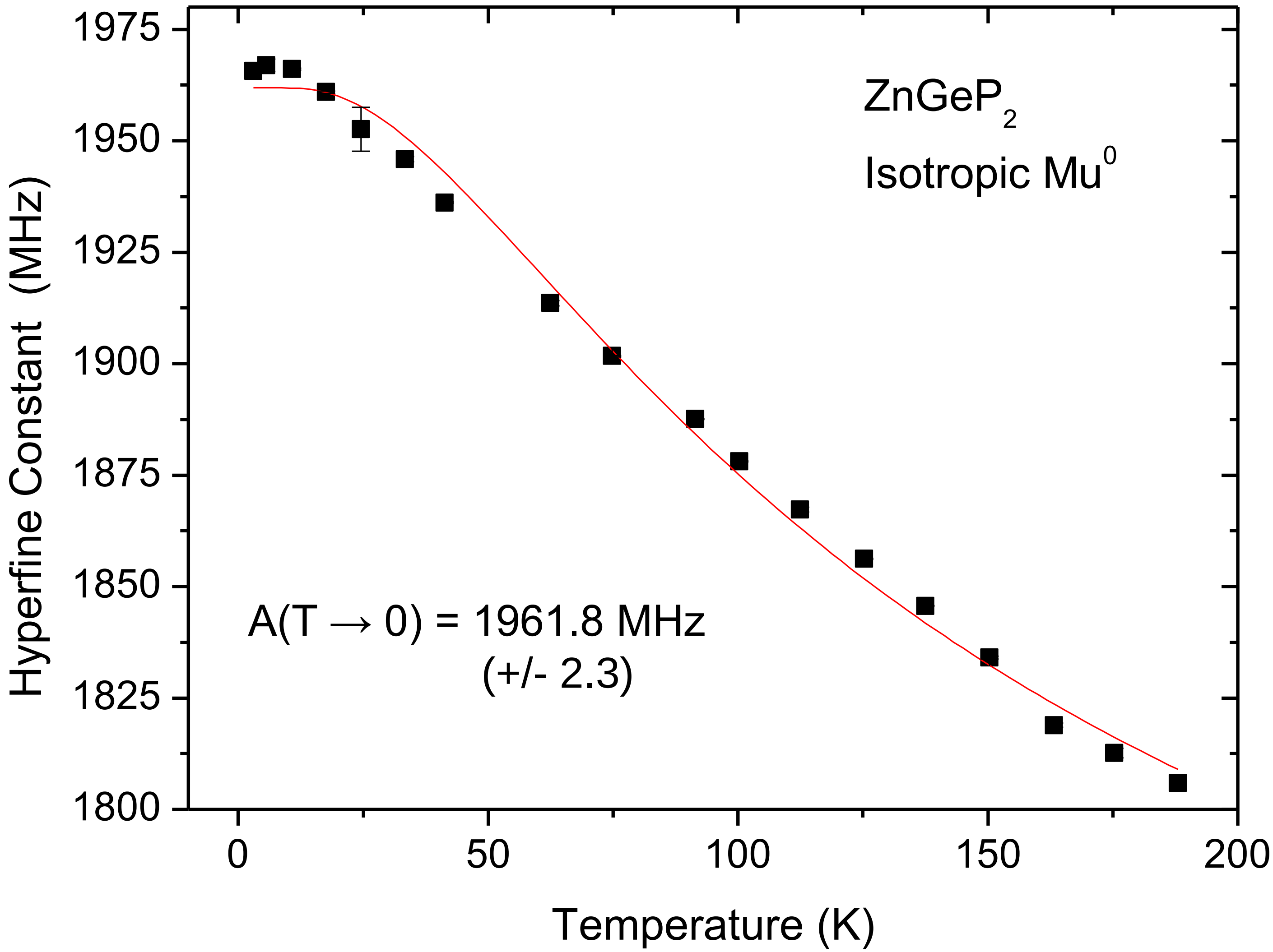
Hyperfine Spectroscopy of $ZnGeP_2$
(from TF-μSR)



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ZnGeP$_2$: Structure

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Zincblende structure, doubled unit-cell

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