Probing Local Features in Dilute Magnetic Semiconducting ZnGeP$_2$:Mn via $\mu$+SR

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**Project Focus**
- DMS systems gaining importance as prospects in spin-based electronics
- Mechanism responsible for connecting local magnetic features to bulk magnetic properties – not yet understood in DMS systems

**MuSR & $\mu^+$ as Local Probe [1]**
- Muon Spin Relaxation utilizes unique sensitivity of 100% spin polarized and positively charged muons to probe local magnetic and electronic environment
- Local B-field environment for $\mu$: $B_{loc} = B_{ext} + dB_{loc} = B_{ext} + B_{rep} + B_{param} + dB_{loc}$
  - $B_{ext}$ = Applied external field
  - $B_{rep}$ = dipolar field
  - $B_{param}$ = field from HI interaction
  - Short range magnetic interaction between $\mu$ and local electronic moments (ie. wavelength overlap)
  - Fermi contact interaction
  - Mag. interaction of $\mu$’s pairs (spin for $\mu$ pairs in metals)
  - BRKKY - indirect exchange between $\mu$ and unpaired $\epsilon$ via conduction $\epsilon$ [dft materials]
  - Transferred hyperfine field ($\mu$’s and $\epsilon$’s wavelength overlap in insulators)
  - $dB_{loc}$ = Contribution from fluctuation in neighboring magnetic moments → $\epsilon$

**Samples**
- BAE Systems provided high quality, p-type ZnGeP$_2$:Mn
- All samples cut from the same single crystal boule from starting melt of 1.6% Mn
- AA → lowest Mn content; FF → Highest Mn content

**The Experiment**
- LF muon spin relaxation measurements performed using the EMU MuSR spectrometer on a surface muon channel at ISIS in Didcot, UK
- 4 different ZnGeP$_2$:Mn samples, varying Mn concentration
- Temperature scans at $B_{ext}$=1kG and $B_{ext}$=3.75kG
- B-field scans at various temperatures
- P(T) fit with two Lorentzian relaxing components and one non-relaxing component

**Observed Features**
- AFM Fluctuations ($\Delta_{AFM}$): $\mu_{AFM}$ + $\mu$ $\rightarrow$ Rlx rate, $\epsilon$: Spin fluctuation rate
  - Additional measurements and modeling required to positively identify and further characterize short range correlations
- Fluctuations related to Spin Polaron ($\Delta_{SP}$):
  - Additional measurements and modeling required to positively identify and further characterize fluctuations above 400K
  - CdGeAs$_2$:Mn (3%)
  - Various properties to ZnGeP$_2$:Mn, T $> 300K$
  - Spin precession results indicate SP above 300K

**Future Work and Open Questions**
- Overall goal: Further characterize magnetic properties and further the understanding of magnetism within DMS systems
- Additional analysis and modeling to achieve better separation of relaxation rates in regions that clearly have more than 2 relaxing components: ie. 300K to 500K region in the 1Kgs measurements of sample ‘AA’ (Fig 3)
- Higher field LF measurements to slow fluctuations enough to actually be able to measure and follow fluctuations through transition regions
- Muon spin precession measurements to characterize local magnetic fields and features; ie: 1) Identify $\mu^+$ and $\mu^-$like states
  - Check for well defined internal fields in FM regime
  - Investigate spin polaron formation and properties
  - Modeling of fluctuations in DMS systems for AFM, FM, SP
  - Work is start of the large scale project of studying the local magnetic features in DMS II-IV-V$_2$ and II-VI systems
  - Link between local magnetic moments and bulk magnetism
- How is magnetism distributed throughout sample?, ie:
  - MnP$_5$ impurity phase with clustering throughout?
  - Distributed relatively uniformly throughout?
  - Something else entirely?