Hyperfine Spectroscopy and Characterization of Muonium in ZnGeP$_2$

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The Experiment

- Transverse field (TF) hyperfine (HF) spectroscopy (Fig. 1) performed using HiTime high frequency spectrometer in the M15 beamline at TRIUMF, Vancouver, Canada.
- Longitudinal field (LF) $T_{1\text{-}}^1$ depolarization measurements (Fig. 2) using EMU spectrometer at STFC ISIS Facility, UK.

Introduction

The purpose of this study is to extend the investigation of muonium defect centers as an experimentally accessible analog of isolated hydrogen defect states in semiconductors into the chalcopyrite structured II-V$_2$ compounds. Also, we aspire to increase the understanding of probe dynamics associated with using positive muons to characterize the atomic-scale magnetism in Mn-doped II-V$_2$ compounds.

Results and Interpretation

- $\nu = \gamma_B$ where $\gamma = 135.54$ MHz/T which is the diamagnetic frequency [4].
- $\nu_{12}$ and $\nu_{34}$ show behavior characteristic of hyperfine splitting from a muonium atom, Mu$^0$ with varying temperature and applied field [5].
- HF interaction for promptly formed Mu$^0$ state (visible in TF) is isotropic since variations in sample orientation produced identical results.
- $T_{1\text{-}}^1$ depolarization data in LF, Fig. 2, showed state with anisotropic hyperfine interaction [6].
- $T_{1\text{-}}^1$ depolarization rates as a function of field using single state model assuming dipolar fluctuating piece of the hyperfine parameter responsible for depolarization yields hop rates (Fig. 4), shown in Fig. 4, extracted from [7].

$$T_{1\text{-}}^1 = \left(1 - x\sqrt{1 + x} \right) \frac{D^2 \tau}{1 + x \delta^2 \tau^2}$$
where $x = B/\nu_B$ and $\nu_B = 0.1131$ GHz (decoupling field).

Further Discussion

- Sites where Mu$^0$ may reside:
  - T-site with phosphorous near neighbors; where isotropic Mu$^0$ formed.
  - T-site associated with II-IV sublattice; where anisotropic Mu$^0$ formed.
- Variation in HF parameter, Fig. 1 inset, as function of temperature fits local-mode vibrational model (Einstein model) [8,9] ie.

$$A(T) = A_0 \exp \left[ \frac{h \nu}{k_B T} \right] + C_2 \exp \left[ \frac{h \nu}{k_B T} \right]$$
$$A_0 = \text{isotropic zero-temperature HF parameter}$$
$$C_1, C_2 = \text{coupling constants (temperature independent)}$$
$$\nu = \text{single vibrational frequency}$$

- For this particular experiment, $h \nu = 7.20$ meV, similar to Mu$_0$ in structurally similar ZnSe [10].
- Hop rates and 2$\Delta \nu$ having similar order of magnitude confirm the isotropic characteristic of the 1962 MHz HF term in TF-site and exclude the possibility of motional averaging.

Conclusions

- Upon muon implantation, Mu$^0$, with isotropic hyperfine parameter of 1962 MHz, promptly formed in a phosphorous T-site.
- Mu$^0$ rapidly hops, visiting other sites with different hyperfine parameters where there is an abrupt change in isotropic to anisotropic hyperfine parameter occurring at each subsequent hop.
- While occupying the T-site associated with the II-IV sublattice, Mu$^0$ has anisotropic hyperfine parameter (with axial symmetry) of $A_1 = 3185$ MHz and $D = 374$ MHz.
- Since hop rates increase with decreasing temperature, motion below 80 K can be assigned to quantum tunneling; however, the slower decrease at lowest temperatures is commonly assigned to interactions with defects or impurities.
- Motion between 100 K and 200 K is commonly assigned to thermally activated hopping.
- Rapid increase in the relaxation rate (Fig. 3) above 200 K yields an ionization energy near 200 meV.
- Further study necessary to develop a model for the relaxation due to motion involving two distinct Mu$^0$ centers.

References:


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