μ^+ALCR & Spin Polarons:

Search in 2 candidate materials

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Numerous semiconducting[1,2] and metallic[3] magnetic materials have been found to exhibit characteristic two-frequency μ^+SR precession signals in high transverse magnetic field (HTF-μ^+SR), but skepticism remains over the assignment of these spectra to muons associated with de Gennes' legendary magnetic polarons (MP)[4] or spin polarons (SP). This is understandable, since the SP picture is a radical departure from "conventional wisdom" about both muonium and magnetism. It is therefore incumbent upon both advocates and adversaries of this interpretation to present as much spectroscopic evidence as possible in support or contradiction of the SP picture.

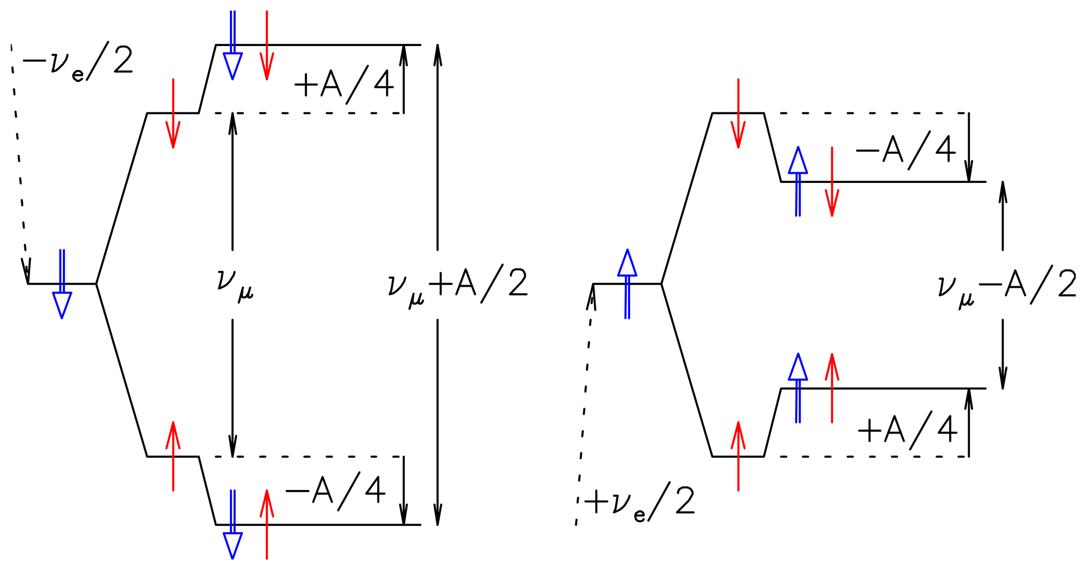

Fig. 1: Muonium energy level diagram in the limit of high magnetic field (muon Larmor frequency $\nu_\mu \gg A$, the hyperfine frequency).

Studies of muonium (Mu = μ^+e^-) in solids and muonated radicals in liquids have used muon avoided level crossing resonance (μALCR) spectroscopy[6,7,8] to yield a plethora of information about the location, structure and effective spin hamiltonian of the paramagnetic centre. It is therefore natural to explore the μALCR spectroscopy of candidate SP systems in the same way.

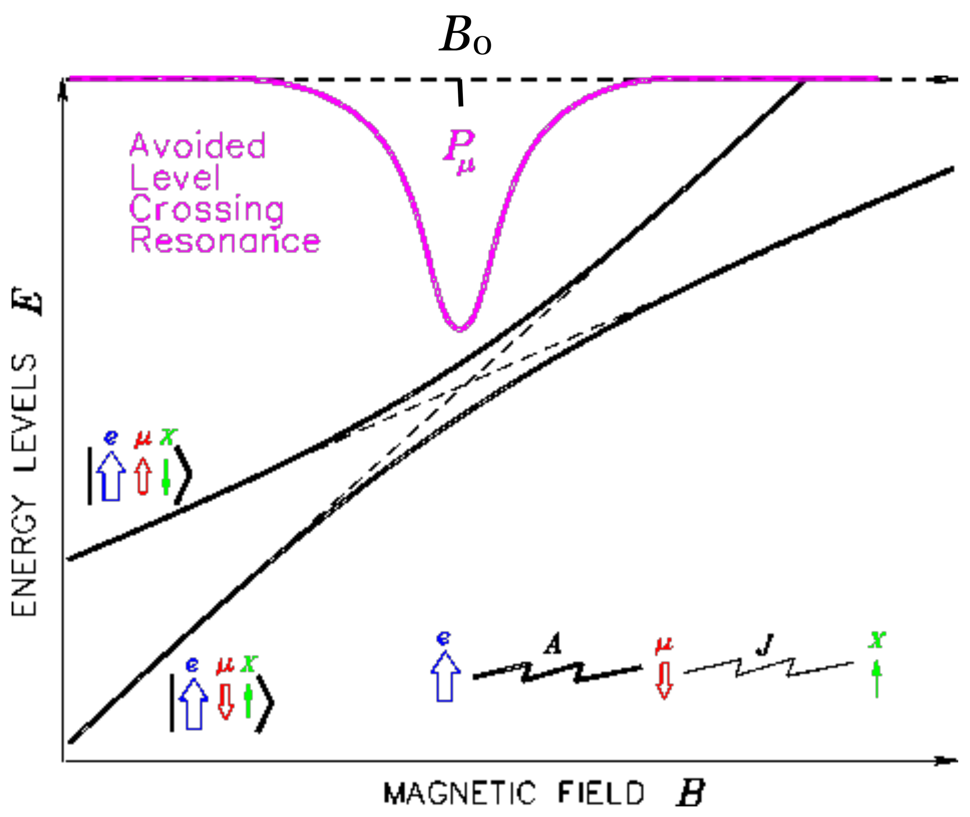

Fig. 2: Avoided level crossings occur when "flipping" a third spin $\boldsymbol{X}$ that couples to the muon and/or electron causes the same change in energy as "flopping" the muon spin at a certain applied field B_0. A resonant loss of muon polarization results at B_0. This method is widely used to identify the partner $\boldsymbol{X}$, its interaction strength J and, from that, the site and environment of the muon. Usually it is assumed that $J \ll A$. The opposite is the case in a SP, if J is the exchange interaction between the SP electron and the paramagnetic ions comprising the SP. However, if J is the *nuclear* hyperfine (NHF) coupling between the SP electron and a nearby *nuclear* spin, the same situation may apply as in ordinary semiconductors[8] or radicals.[7]

We therefore performed an initial study of several nominally dissimilar materials with nearly identical SP-like HTF-μ^+SR spectra (see middle column).

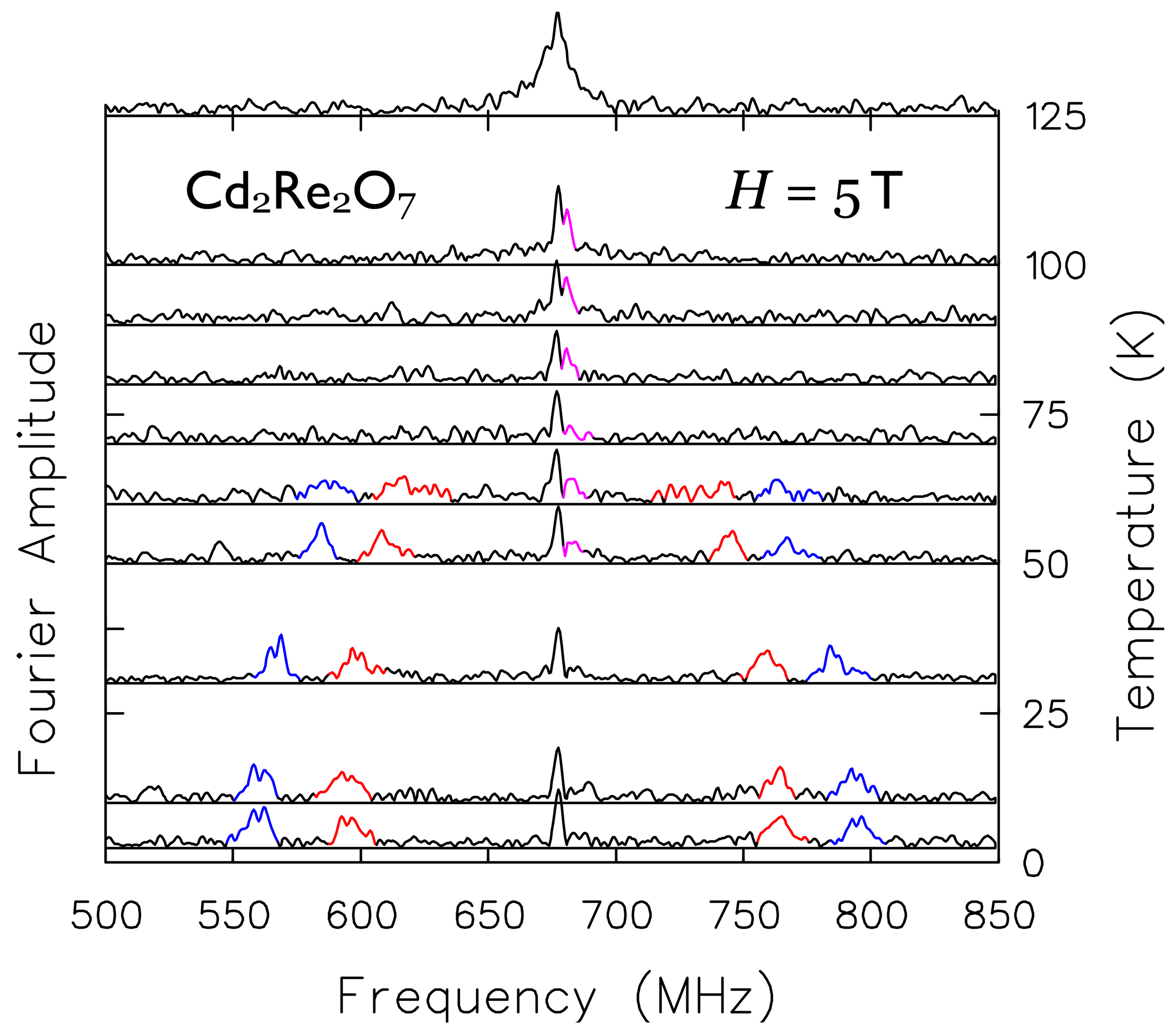

Fig. 3: $Cd_2Re_2O_7$ is a weakly *metallic* pyrochlore with geometrically frustrated magnetism, heavy electron effective mass and a superconducting transition at 1 K. In the region below 60 K, where its resistivity follows a T^2 dependence (characteristic of a Fermi liquid regime), the HTF-μ^+SR frequency spectrum at H = 5 T shows the splittings characteristic of a SP with a large hyperfine coupling.[3]

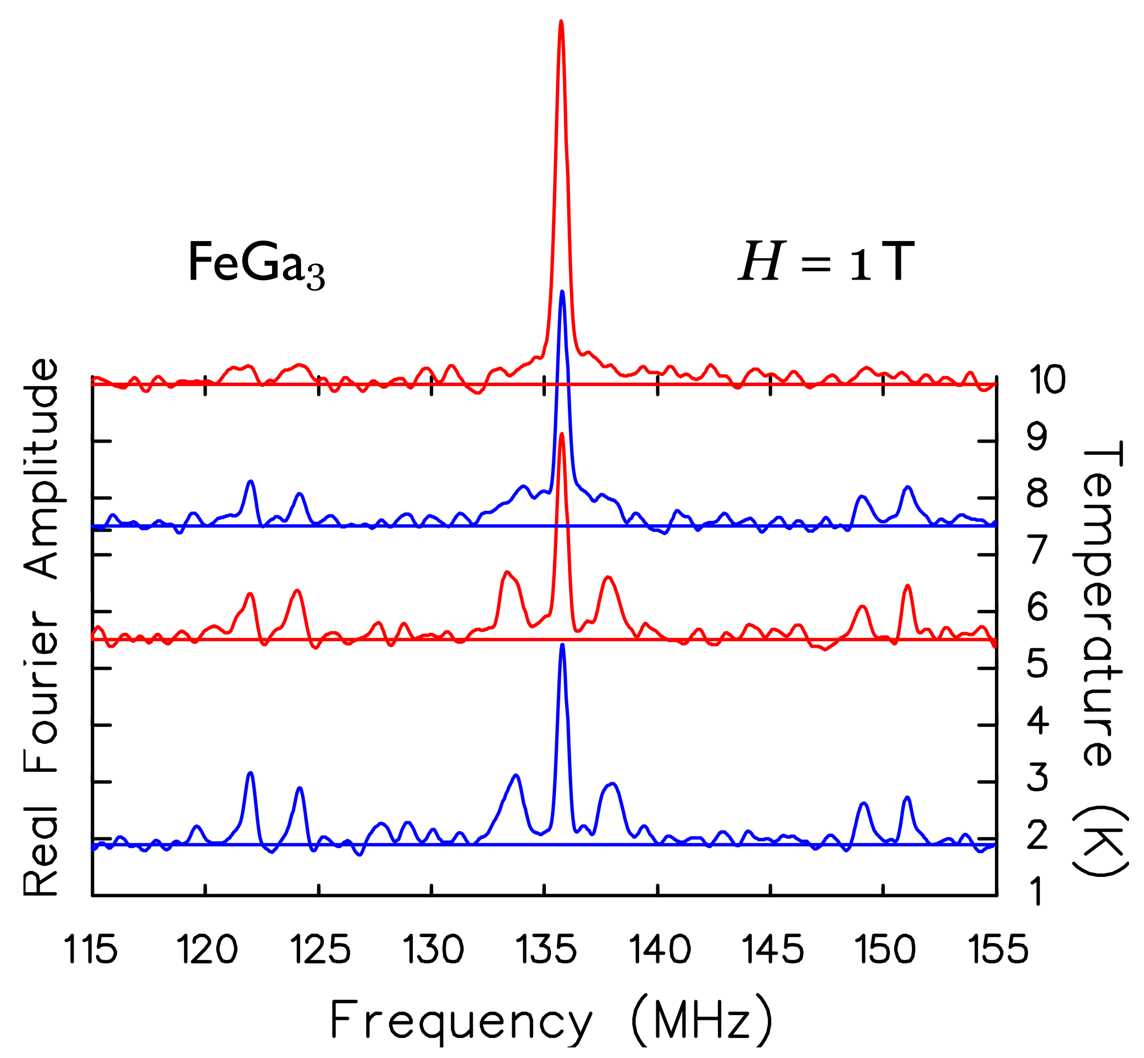

Fig. 4: $FeGa_3$ is a narrow-gap diamagnetic *semiconductor* for which the gap formation is attributed to strong electron correlations within a narrow $3d$ band. Below about 10 K an extremely narrow SP band is thought to form; in the same range, characteristic SP splittings are observed in the HTF-μ^+SR frequency spectra, with splittings independent of field up to 5 T.

Both materials have plentiful nuclear spins which might couple to the SP electron, possibly producing a rich μALCR spectrum.

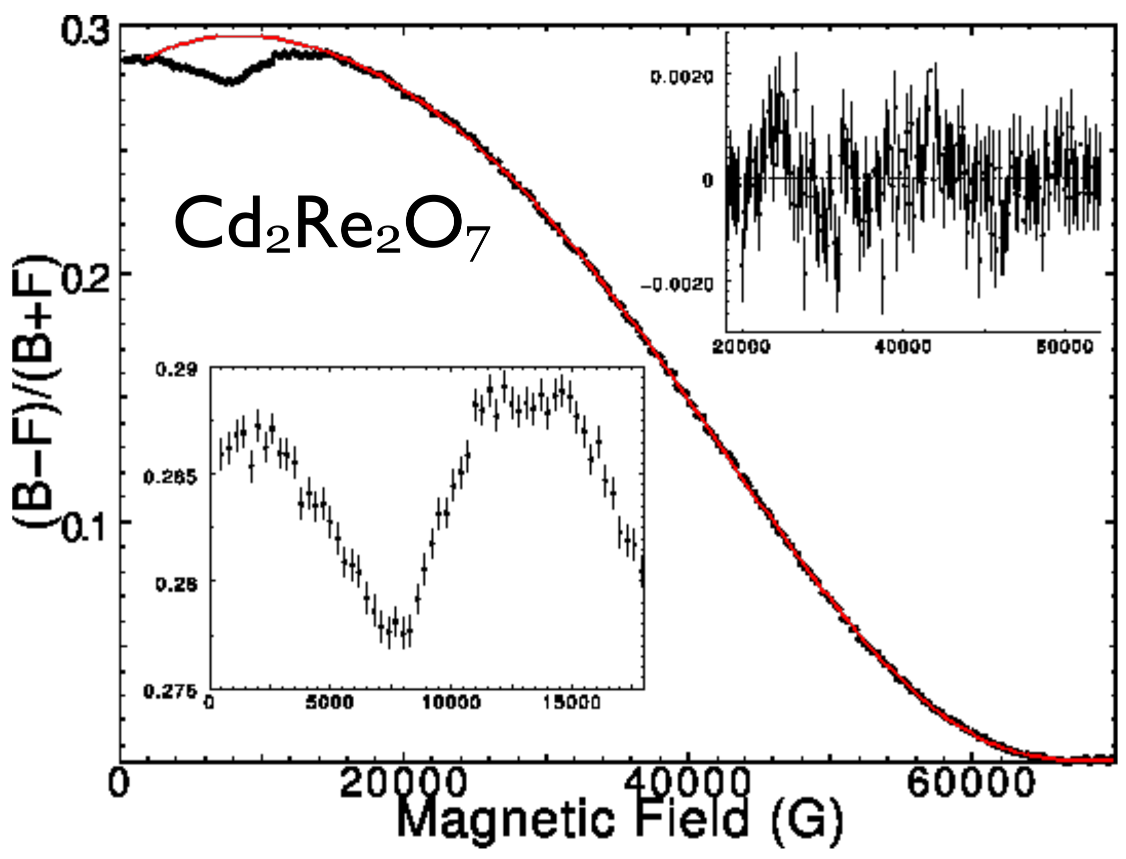

Fig. 5: $Cd_2Re_2O_7$ μALCR spectrum from 0 to 7 T at 30 K, taken on M15 with *HiTime*. *Upper right inset*: residuals from a polynomial fit (red line) to the systematic decrease at high field due to curling up of electron orbits. *Lower left inset*: a broad resonance at ~0.75 T ($\nu_\mu \approx$ 100 MHz $\approx A_{SP}/2$) is presumably some sort of zero-crossing resonance; hints of other resonances are too faint to be conclusive.

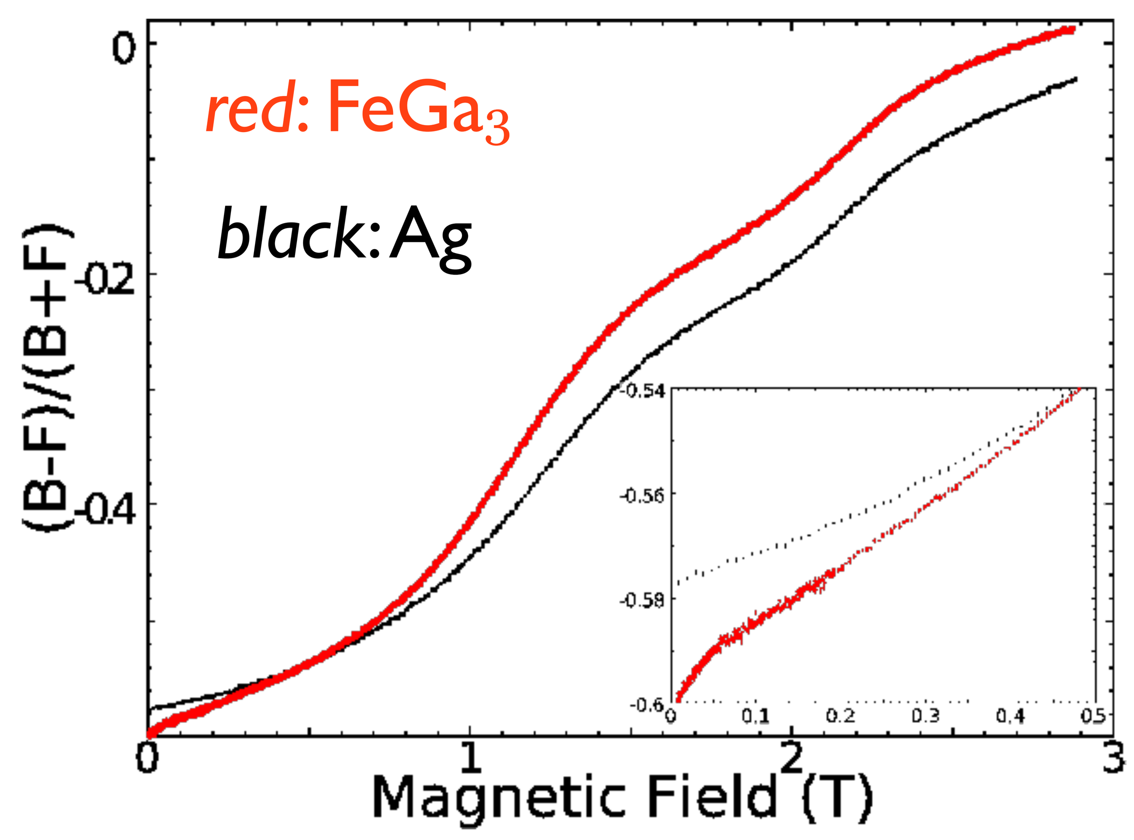

Fig. 6: μALCR spectra of $FeGa_3$ at 5 K and Ag (for systematic calibration) from 0 to 3 T, taken on M20 with *Helios*. If there is a resonant "dip" in the $FeGa_3$ polarization curve, it is either extremely broad or extremely narrow. The decrease at very low field (inset) is presumably just decoupling from local dipolar fields.

Conclusions

Our search for μALCR in these SP candidate materials has been unsuccessful. The NHF couplings between the SP electron and neighboring nuclei may be either too weak or too anisotropic to engender resonances. There might be extremely *narrow* resonances that would require scanning the appropriate field range with much smaller step sizes. (We used steps of 4, 10, 50 and 100 G in low, medium and high field regions.) Such a survey would benefit enormously from a good guess of where such resonances might be expected to appear.

References

[1] Storchak V G *et al.* 2009 Phys Rev. B **80** 235203-235209
[2] Storchak V G *et al.* 2009 Phys. Rev. B **79** 193205-193208
[3] Storchak V G *et al.* 2010 Phys. Rev. Lett. **105** 76402-76405
[4] de Gennes P G 1960 Phys. Rev. B **118** 141
[5] Nagaev E L 2002 *Colossal Magnetoresistance and Phase Separation in Magnetic Semiconductors* (London: Imperial College Press).
[6] Kreitzman S R *et al.* 1986 Phys. Rev. Lett. **56** 181
[7] Kiefl R F *et al.* 1986 Phys. Rev. A **34** 681
[8] Kiefl R F *et al.* 1987 Phys. Rev. Lett. **58** 1780