Gregory Volovik
Anniversary Conference

From a Helium droplet to the Universe

Nuclear spin-lattice relaxation in UCoGe

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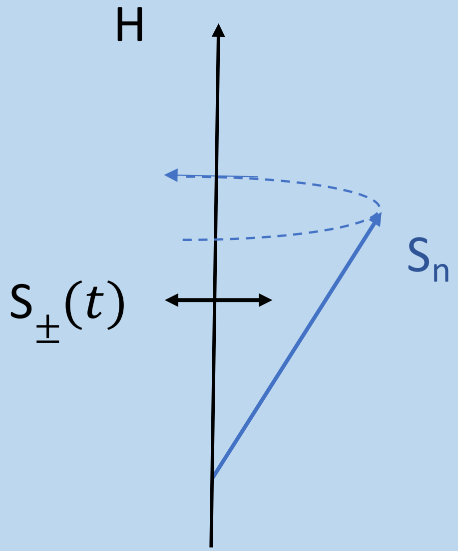
Outsite a Helium droplet but still in our Universe

NMR relaxation in metals
NMR relaxation in itinerant isotropic ferromagnets
UCoGe – orthorhombic ferromagnet
Relaxation rate in UCoGe
Three types of magnetism
Susceptibility
Curie temperature
Field-temperature dependence of relaxation in UCoGe

NMR in metals

$$\frac{1}{T_1} = \int_{-\infty}^{\infty} dt |A_{hf}|^2 \langle S_+(t)S_-(0) + S_-(0)S_+(t)\rangle = \int \frac{d^3k}{(2\pi)^3} |A_{hf}|^2 \coth\frac{\omega}{2T}\chi''_{+-}(\mathbf{k},\omega)$$

Fluctuation Dissipation Theorem



$$\frac{1}{T_1} \approx 2T \int \frac{d^3k}{(2\pi)^3} |A_{hf}|^2 \frac{\chi''_{+-}(\mathbf{k},\omega)}{\omega}$$

$$\frac{1}{T_1} \propto (\gamma_e \gamma_n N_0)^2 T$$

Korringa law

NMR in isotropic itinerant ferromagnets

H || z

$$\left(\frac{1}{T_1T}\right)_z \propto \lim_{\omega\to 0}\int \frac{d^3k}{(2\pi)^3}|A_{hf}|^2\frac{\chi''_{+-}(\mathbf{k},\omega)}{\omega}$$

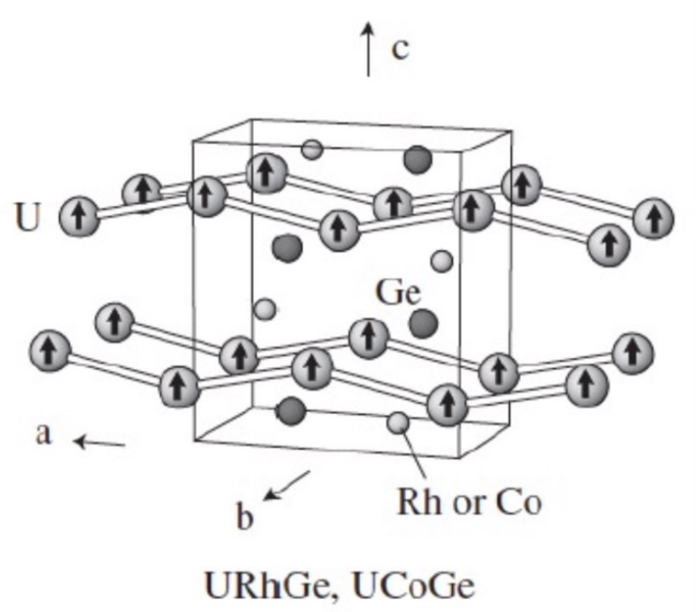
$$\left(\frac{1}{T_1T}\right)_z \propto \begin{cases} \chi_z(T) & -\text{ paramagnetic state} \\ M^{-2} & -\text{ ferromagnetic state} \end{cases}$$

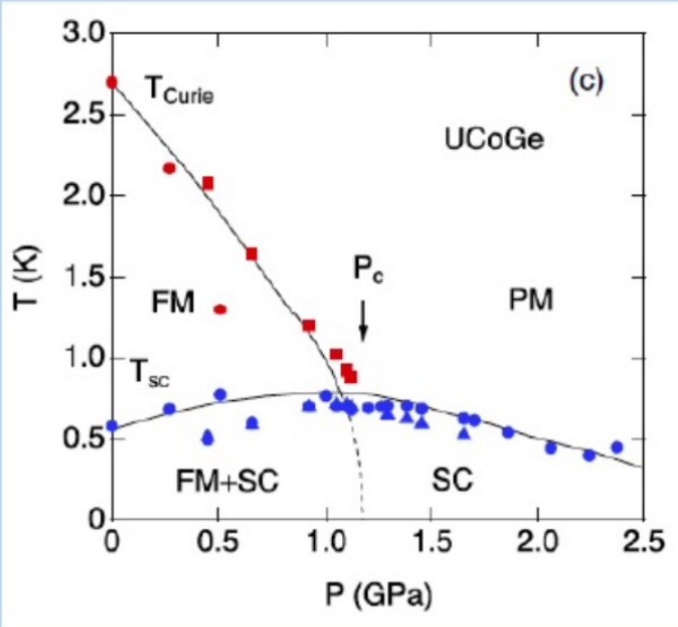
N.Moriya, K.Ueda, Sol.St.Comm. 1974

Integral from the imaginary part of transverse susceptibility is expressed through the static longitudinal susceptibility

UCoGe – orthorhombic ferromagnet

UCoGe: T_c~0.5-0.7K,
T_{curie}~2.5K, m_s~0.07μ_B





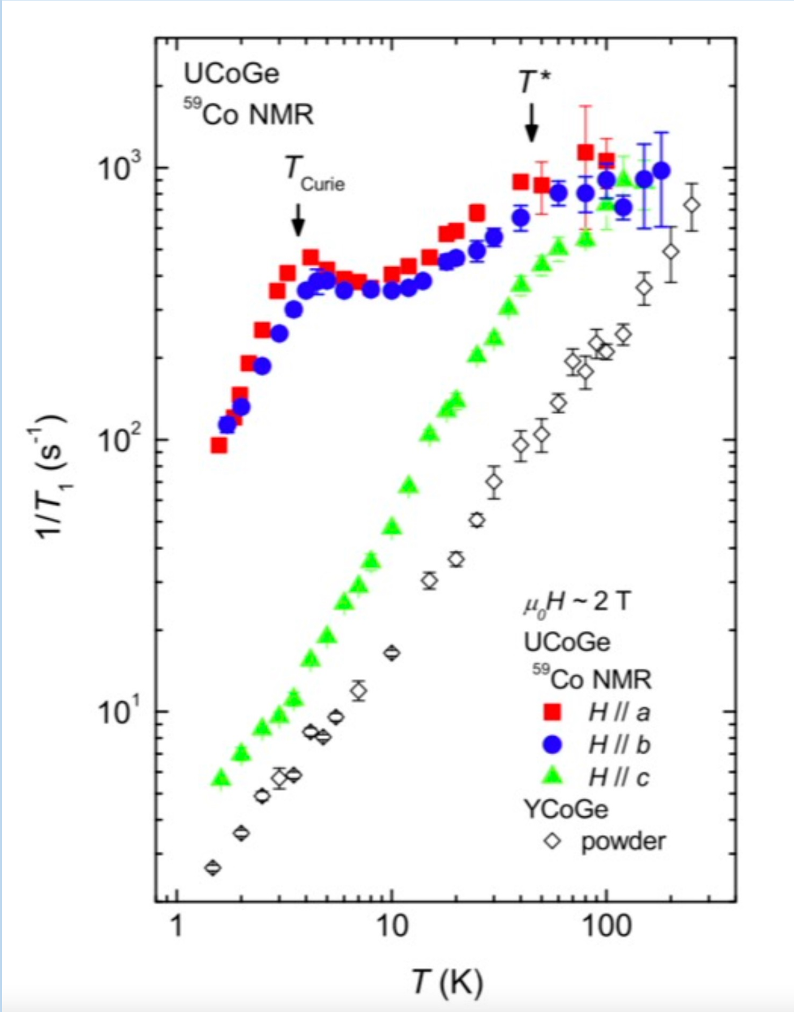
N.N.Huy et al, PRL 2007

Relaxation rates in UCoGe

$$\left(\frac{1}{T_1T}\right)_l \propto \sum_{\mathbf{k}} \left[|A^m_{hf}|^2 \frac{\chi''_m(\mathbf{k},\omega)}{\omega} + |A^n_{hf}|^2 \frac{\chi''_n(\mathbf{k},\omega)}{\omega} \right]$$

$$\left(\frac{1}{T_1T}\right)_b \propto \sum_{\mathbf{k}} |A^c_{hf}|^2 \frac{\chi''_c(\mathbf{k},\omega,H_b)}{\omega}$$

$$\left(\frac{1}{T_1T}\right)_a \propto \sum_{\mathbf{k}} |A^c_{hf}|^2 \frac{\chi''_c(\mathbf{k},\omega,H_a)}{\omega}$$



Y.Ihara et al, PRL (2010)

Three types of magnetism

(i) Localised – Magnetic moments of ions formed by the crystal field
Interacting by the Heisenberg exchange

$$-I \sum_{(ij)} \mathbf{S}_i \mathbf{S}_j$$

(ii*) Itinerant* – Stoner-Hubbard repulsion of electrons with antiparallel spins.
Magnetism is determined by the difference of the electron number in spin-up and spin-down bands

$$U \int n_\uparrow(\mathbf{r}) n_\downarrow(\mathbf{r}) d^3 r$$

(iii*) Dual* - 5f electrons form bands with finite density of states at Fermi level
The magnetic moment is furnished by electrons in spin-up and spin-down states with different orbital momentum projection filling the cellar below Fermi level.
In the real space these states are the f-type Wannier states

Magnetism in UCoGe

The magnetic moment
Is almost completely
Concentrated near U ions .
Magnetic moment of Co ions
and itinerant electrons is
negligibly small

	$H(T)$	μ_{tot} (μ_B/atom)	$\mu_L^U(5f)$ (μ_B/atom)	$\mu_S^U(5f)$ (μ_B/atom)	$\mu_{tot}^U(5f)$ (μ_B/atom)
H∥**c**	17	0.44	0.695	−0.297	0.398
	1	0.09	0.135	−0.059	0.076

Magnetic circular dichroism *M.Taupin et al, PRB 2015*
Band structure calculations *M.Samsel-Szekala et al, J.Phys. Cond.Mat 2010*

Susceptibility

$$\left(\frac{1}{T_1 T}\right)_b \propto \sum_{\mathbf{k}} |A^c_{hf}|^2 \frac{\chi''_c(\mathbf{k},\omega,H_b)}{\omega}$$

Static susceptibility along spontaneous magnetisation at fixed value of magnetic field in perpendicular direction

$$\chi_c(H_b) = \left(\frac{\partial M_c}{\partial H_c}\right)_{H_b}$$

$$\chi_c(\mathbf{k}) = \frac{1}{(\chi_c(H_b))^{-1} + 2\gamma^c_{ij} k_i k_j}$$

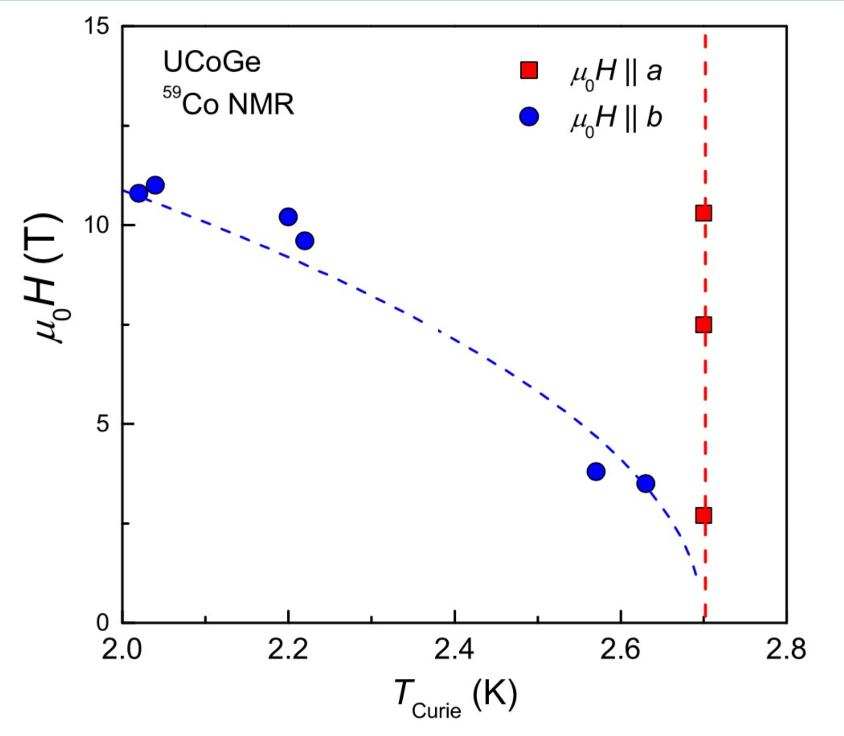
$$\chi_c(\mathbf{k}) = \frac{1}{\pi} \int \frac{\chi''_c(\mathbf{k},\omega)}{\omega} d\omega$$

$$\chi_c(\mathbf{k},\omega) = \frac{1}{-\frac{i\omega}{A} + (\chi_c(H_b))^{-1} + 2\gamma^c_{ij} k_i k_j}$$

$$\frac{\chi''_c(\mathbf{k},\omega,H_b)}{\omega} = \frac{A}{\omega^2 + A^2\left[(\chi_c(H_b))^{-1} + 2\gamma_{ij} k_i k_j\right]^2}$$

Curie temperature

$$F = \alpha_c M_c^2 + \beta_c M_c^2 + \alpha_a M_a^2 + \alpha_b M_b^2 + \beta_{ac} M_a^2 M_c^2 + \beta_{bc} M_b^2 M_c^2 - \mathbf{HM}$$



$$\alpha_c = \alpha_{c0}(T - Tc0) \quad \alpha_a > 0 \quad \alpha_b > 0$$

$$M_b \approx \frac{H_b}{2(\alpha_b + \beta_{bc} M_c^2)}$$

$$F = \alpha_c M_c^2 + \beta_c M_c^4 - \frac{1}{4}\frac{H_b^2}{\alpha_b + \beta_{bc} M_c^2}$$

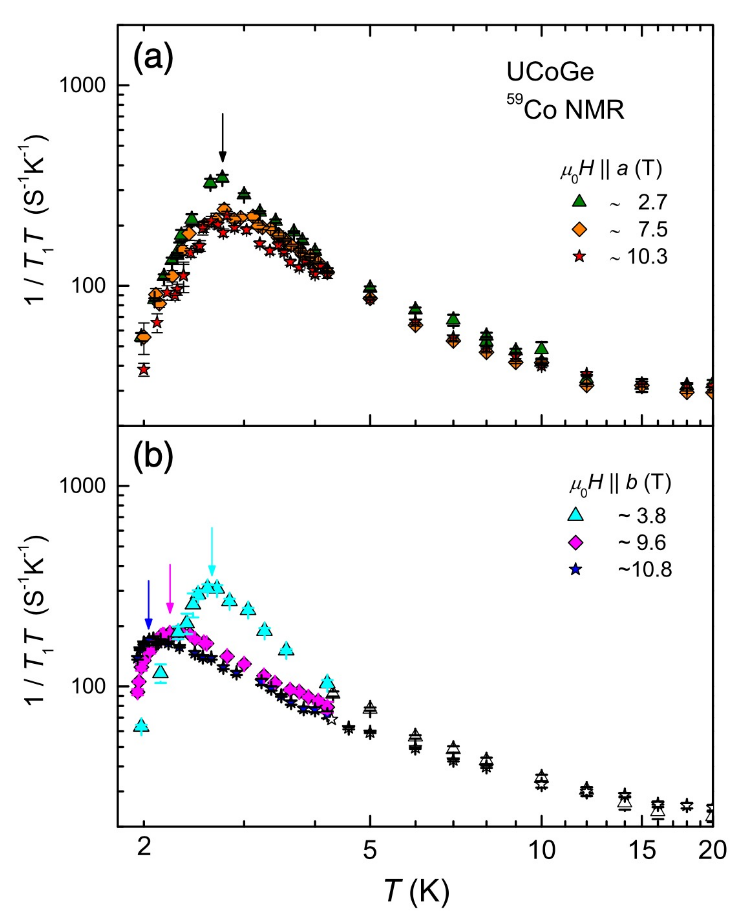
$$F = -\frac{H_b^2}{4\alpha_b} + \tilde{\alpha}_c M_c^2 + \tilde{\beta}_c M_c^4 + \ldots$$

T.Hattori et al, J.Phys.Soc.Jp. 2014

$$T_c(H_b) = T_{c0} - \frac{\beta_{bc} H_b^2}{4\alpha_b^2 \alpha_{c0}}$$

$$T_c(H_a) = T_{c0} - \frac{\beta_{ac} H_a^2}{4\alpha_a^2 \alpha_{c0}}$$

Longitudinal relaxation



T.Hattori et al, J.Phys.Soc.Jp. 2014

$$\chi_c(H_b) = \begin{cases} \dfrac{1}{4\alpha_{c0}\left(T_{c0} - \frac{\beta_{bc}H_b^2}{4\alpha_b^2\alpha_{c0}} - T\right)}, & T < T_c(H_b) \\ \dfrac{1}{2\alpha_{c0}\left(T - T_{c0} + \frac{\beta_{bc}H_b^2}{4\alpha_b^2\alpha_{c0}}\right)}, & T > T_c(H_b) \end{cases}$$

$$\chi_c(H_a) = \begin{cases} \dfrac{1}{4\alpha_{c0}(T_{c0} - T)}, & T < T_{c0} \\ \dfrac{1}{2\alpha_{c0}(T - T_{c0})}, & T > T_{co} \end{cases}$$

$$\left(\frac{1}{T_1 T}\right)_l \propto \int \frac{4\pi k^2 dk}{(2\pi)^3} \frac{A}{\omega^2 + A^2\left[(\chi_c(H_l))^{-1} + 2\gamma k^2\right]^2}$$
$$= \frac{\sqrt{2}}{32\pi A \gamma^{3/2}} \frac{\sqrt{\chi_c(H_l)}}{\left(1 + \frac{\omega^2 \chi_c^2(H_l)}{A^2}\right)^{1/4}} \frac{1}{\cos\left(\frac{1}{2}\arctan\frac{\omega\chi_c(H_l)}{A}\right)}$$

$l = a, b$

$$\frac{1}{T_1(H_b)T} \propto \begin{cases} \sqrt{\chi_c(H_b)}, & \chi_c(H_b) \ll \frac{A}{\omega} \\ \sqrt{\frac{A}{\omega}}, & \chi_c(H_b) \gg \frac{A}{\omega} \end{cases}$$

Conclusion

- In contrast with the isotropic weak ferromagnets the longitudinal spin-lattice relaxation rate in UCoGe is expressed through the static susceptibility in the perpendicular to magnetic field direction.
- The value of $(1/T_1T)$ in field perpendicular to spontaneous magnetisation has maximum in vicinity of the Curie temperature.
- It does not reveal similar behaviour in field parallel to spontaneous magnetisation.
- The longitudinal spin-lattice relaxation rate is strongly field dependent when the field is directed along b-crystallographic direction but field independent if magnetic field is oriented along a-axis.