Magnetism in $M_{1/3}NbS_2$ (M = Fe, V): insight into intercalated transition-metal dichalcogenides using μSR

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μSR
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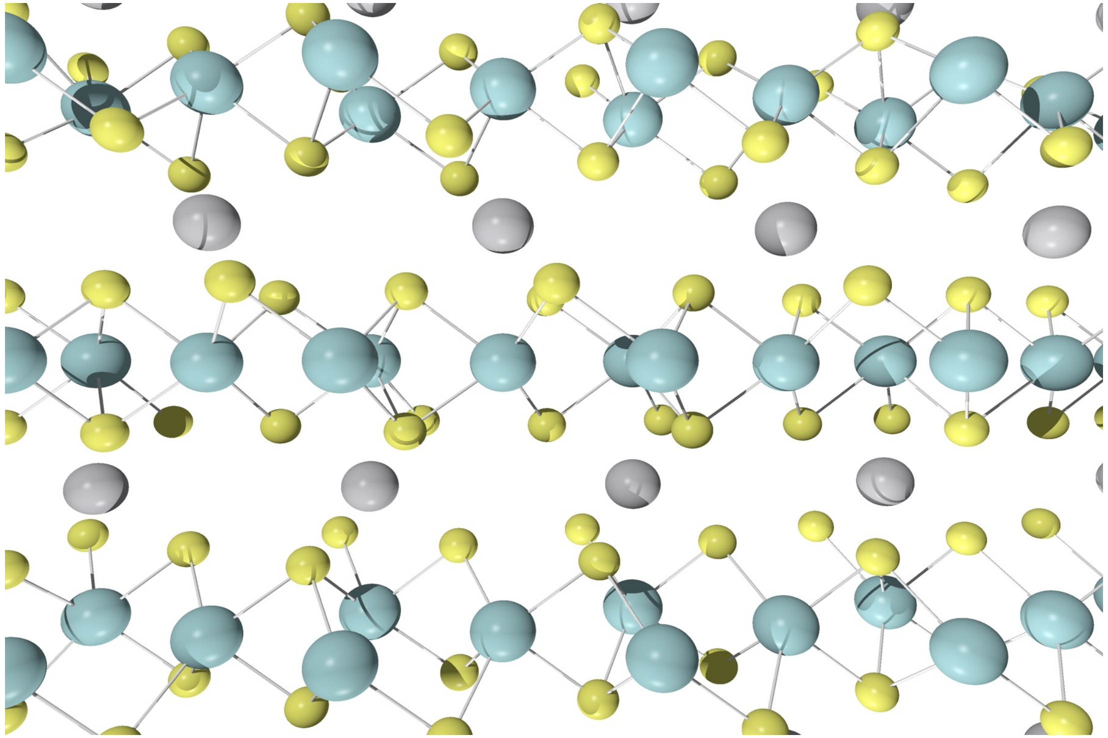
- Introduction to the intercalated transition-metal dichalcogenides
- $Fe_{1/3}NbS_2$ and magnetic phase separation
- $V_{1/3}NbS_2$ and topological excitations

$M_{1/3}NbS_2$

- Layered transition-metal dichalcogenide
- *M* ions are intercalated between layers
- Range of magnetic behaviours
- μSR and supporting computational techniques



$Fe_{1/3}NbS_2$

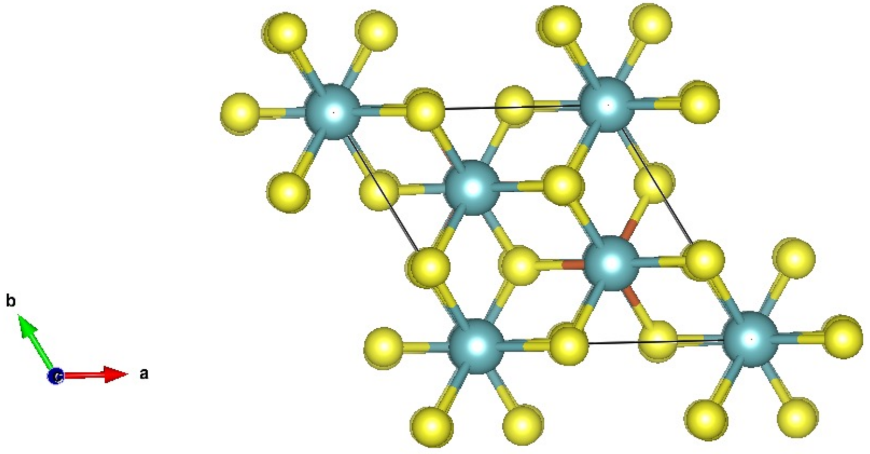
- Magnetic phase separation [1]

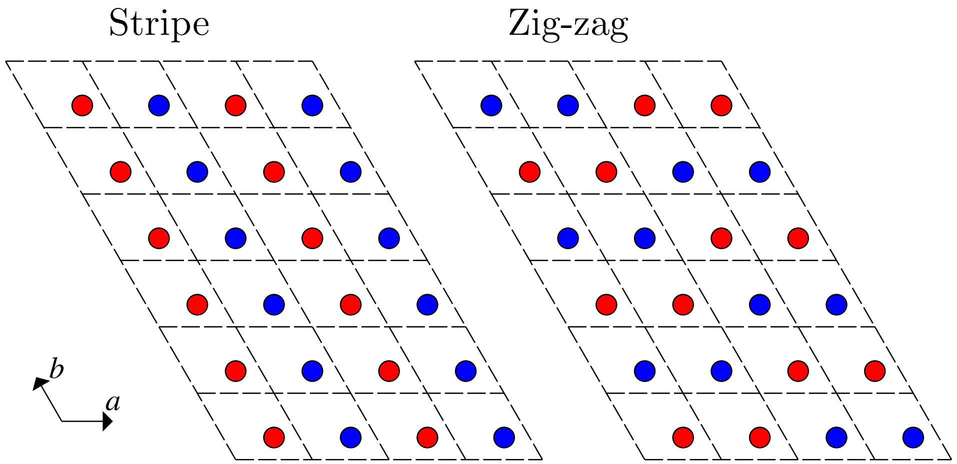
- Presence of two AFM orderings:

  Stripe : $k_1 = (0.5, 0, 0)$

  Zig-zag : $k_2 = (0.25, 0.5, 0)$

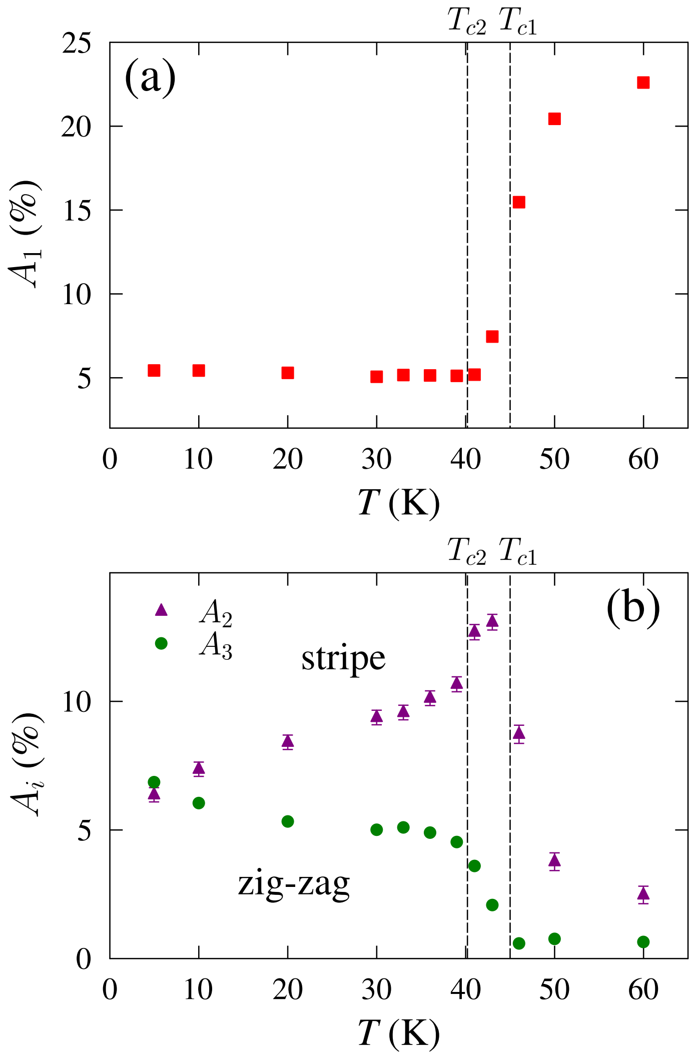
- Evolve independently with temperature – see with muons





[1] S. Wu *et al.,* Phys. Rev. X **12**, 021003 (2022)

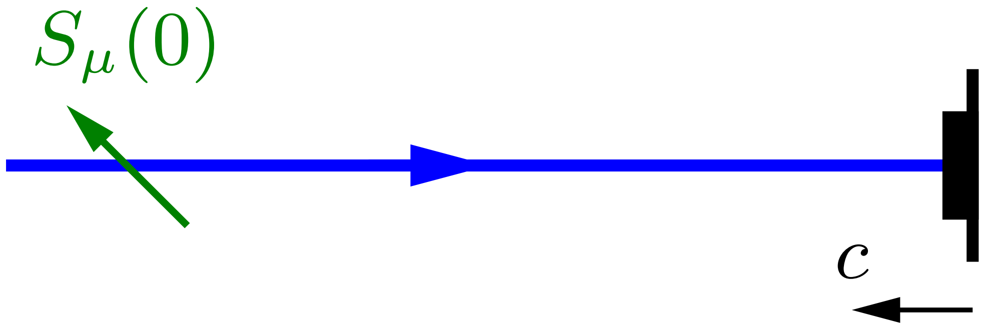
wTF measurements on $Fe_{1/3}NbS_2$



- $A(t) = A_1 \cos(\gamma_\mu B_{wTF} t) e^{-\lambda_1 t} + A_2 e^{-\lambda_2 t} + A_3$
- Low temperatures ($T < T_{c2}$) correspond to a mixed region
- Intermediate temperatures ($T_{c2} < T < T_{c1}$) is a region of stripe-dominated magnetism
- Assigned via neutron and magnetometry results [1]

[1] S. Wu *et al.*, Phys. Rev. X **12**, 021003 (2022)

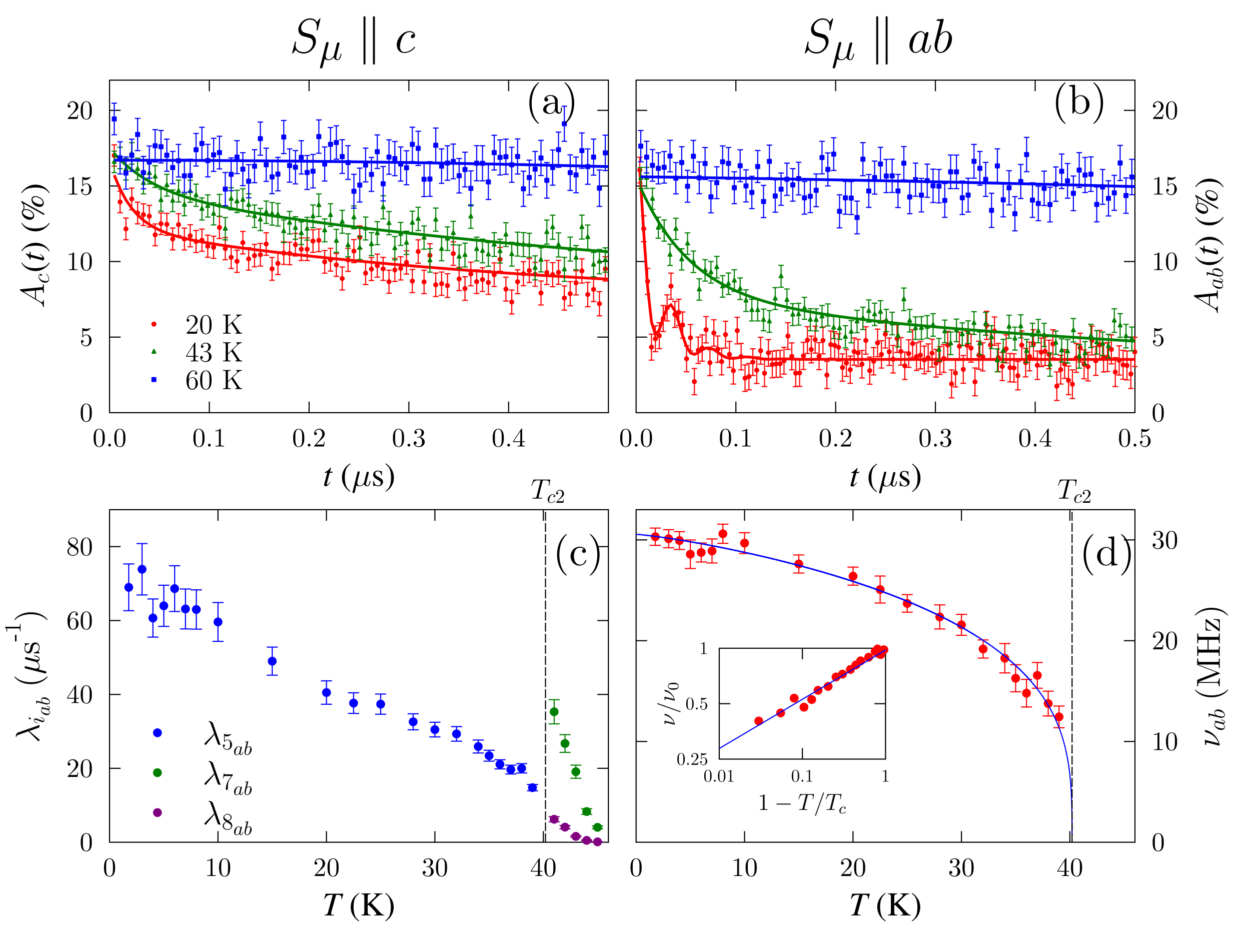
Sample Orientation in ZF measurements



- Partially orientated mosaic of single crystals, with *c*-axis parallel to muon beam direction

- Initial muon spin direction rotated $45°$, components in both the *c* and the *ab* directions

ZF measurements on $Fe_{1/3}NbS_2$



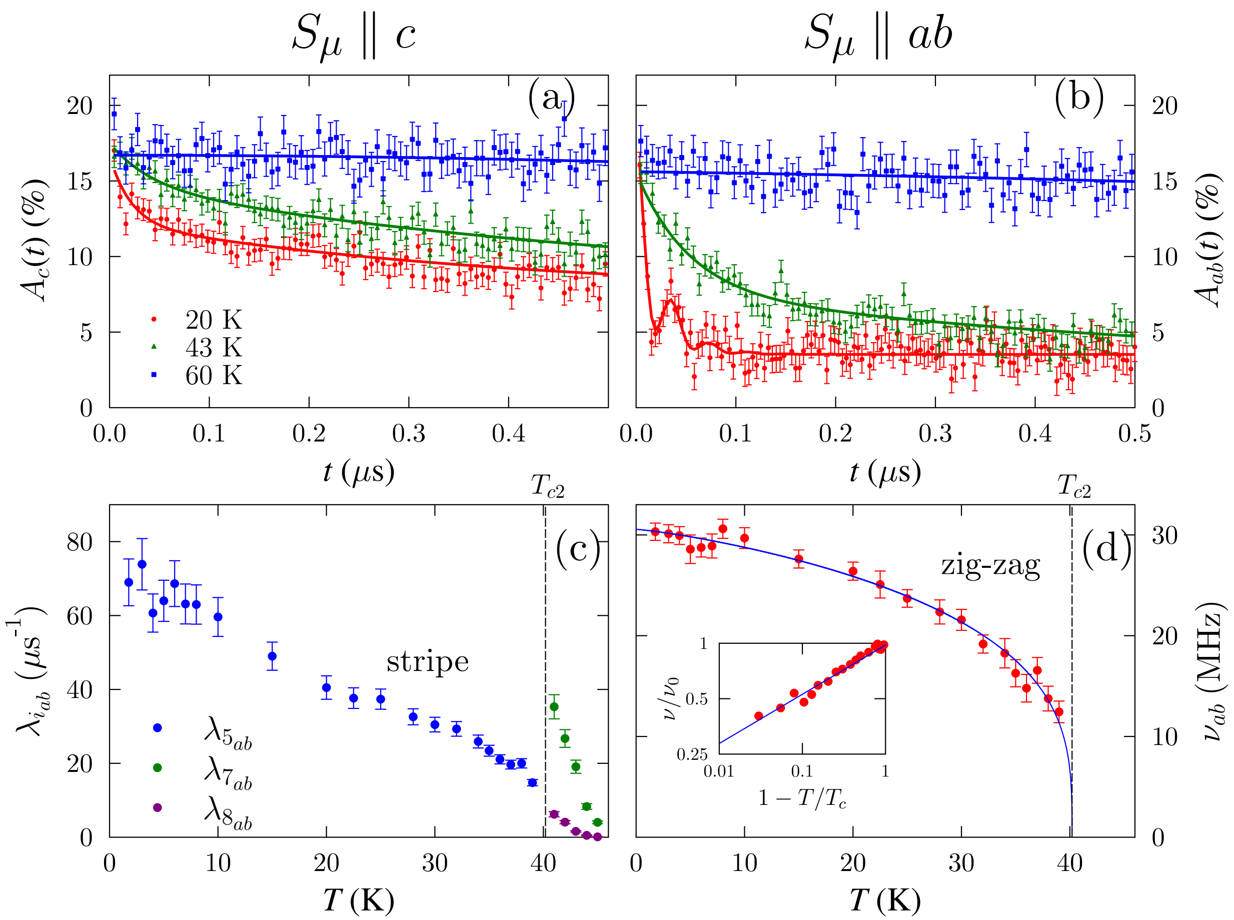
- Behaviour of $A(t)$ varies with direction below T_{c2}

$$A(t) = A_{4_c} e^{-\lambda_{4_c} t} + A_{5_c} e^{-\lambda_{5_c} t} + A_{6_c}$$

$$A(t) = A_{4_{ab}} \cos(2\pi\nu_{ab} t) e^{-\lambda_{4_{ab}} t} + A_{5_{ab}} e^{-\lambda_{5_{ab}} t} + A_{6_{ab}}$$

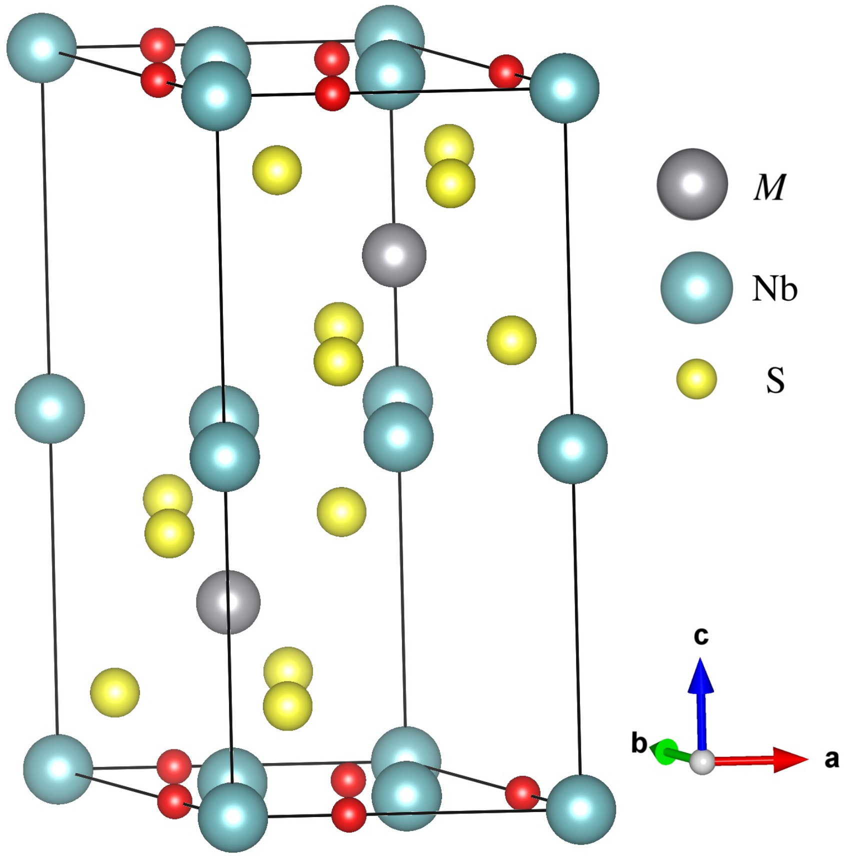
- Oscillations follow order parameter-like behaviour with $T_{c2} = 40.2(4)$ K

ZF measurements on $Fe_{1/3}NbS_2$



- Oscillations correspond to regions of zig-zag magnetic order (A_4)
- Terms with temperature dependent λ correspond to stripe magnetic order (A_5)
- No oscillations in regions of stripe dominated order

Muon Site in $Fe_{1/3}NbS_2$ (and $V_{1/3}NbS_2$)



- Identify single muon site:

$$\frac{1}{3}, 0, 0$$

(and crystallographic equivalent positions)

- In agreement with a previously report muon site in $Cr_{1/3}NbS_2$ [1]

[1] T. J. Hicken *et al.,* Phys. Rev. B. **105**, L060407 (2022).

Dipole field calculations in $Fe_{1/3}NbS_2$

$$\mathbf{B}_{\mathrm{dip}}(\mathbf{r}_i) = \frac{\mu_0}{4\pi}\sum_i \left[\frac{(\boldsymbol{m}_i \cdot \boldsymbol{r}_i) r_i}{r_i^5} - \frac{\boldsymbol{m}_i}{r_i^3}\right]$$

$$\mathbf{B} = \mathbf{B}_{\mathrm{dip}} + \mathbf{B}_L + \mathbf{B}_{\mathrm{dem}}$$

Zig-zag

- Field direction:

$$\sim[0, 0, 1]$$

- Agrees with observation of oscillations in only the *ab* plane

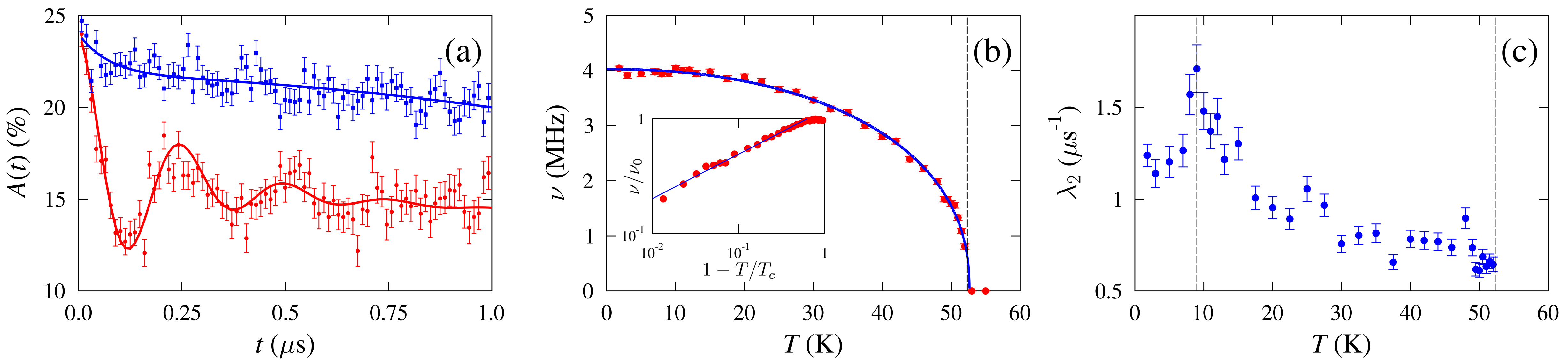
Stripe

- Field direction:

$$\sim[0.7, 0.4, 0.55]$$

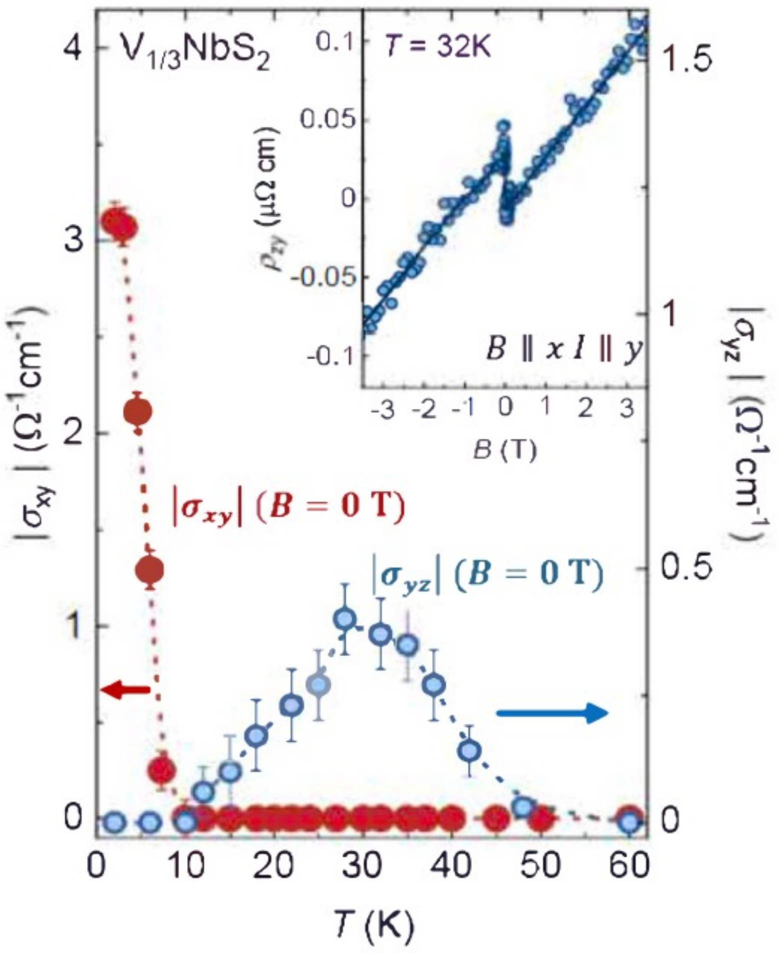
- Agrees with similar muon response seen in *ab* and along *c* for muons in stripe magnetism

$V_{1/3}NbS_2$ – muon results



- Single observed precession frequency with $T_c = 52.7(2)$ K
- Temperature dependence in dynamical frequency term

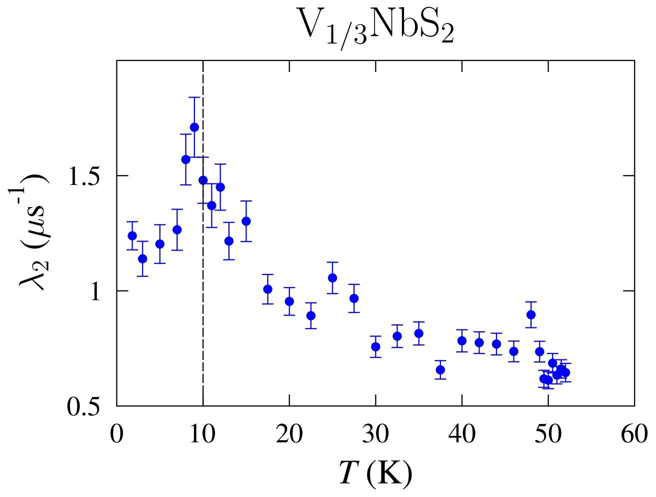
Low-temperature phase in $V_{1/3}NbS_2$



- Low-temperature transition seen with several techniques [1]
- Large spontaneous anomalous Hall effect (AHE)
- Non-Fermi liquid behaviour in $\rho(t)$

[1] M. K. Ray *et al.,* Nature Communications **16**, 3532 (2025).

Topological magnetism in $V_{1/3}NbS_2$



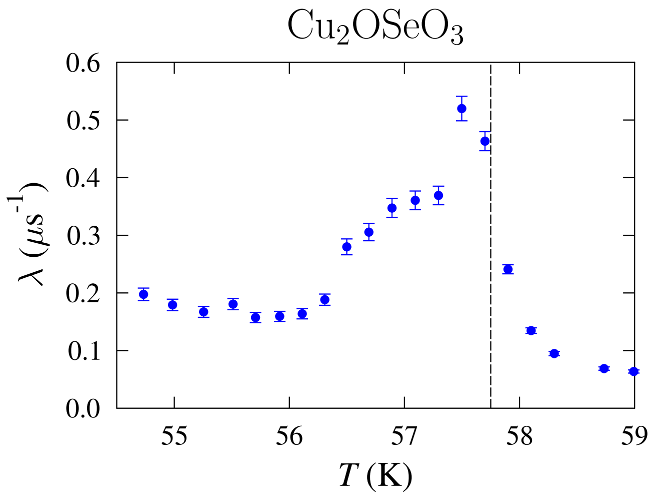


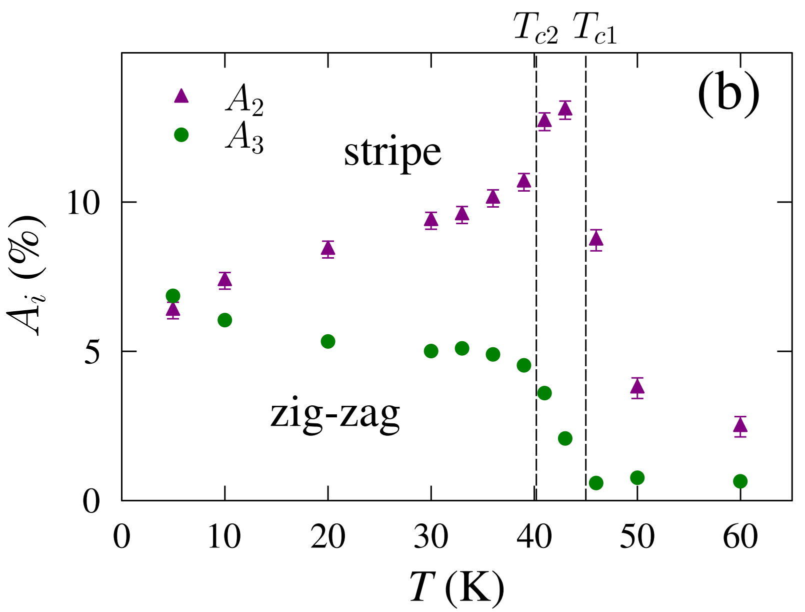
Figure adapted from ref [2]

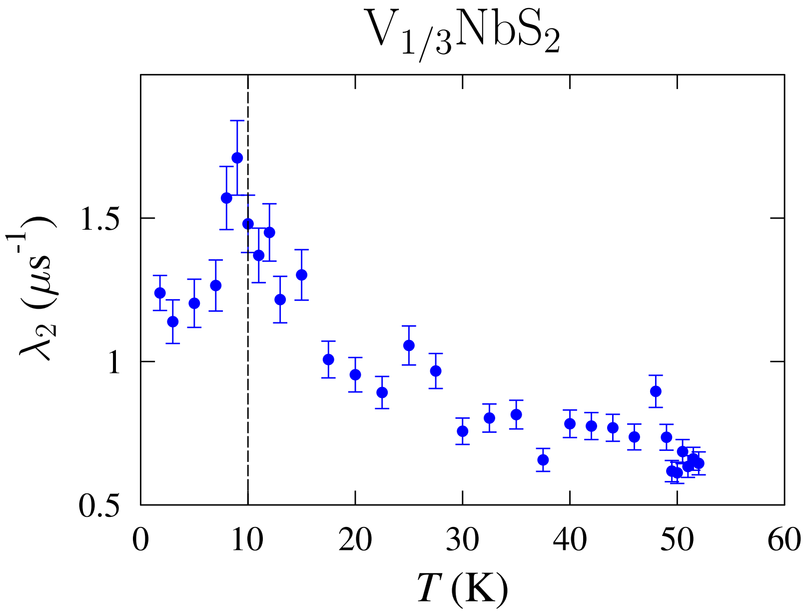
- Topological magnetic excitations [1]
- Corresponds to a peak in the dynamical relaxation rate on the muon timescale
- Similar to behaviour in skyrmion lattice hosting Cu_2OSeO_3 [2]

[1] M. K. Ray *et al.*, Nature Communications **16**, 3532 (2025).
[2] T. J. Hicken *et al.*, Phys. Rev. B **103**, 024428 (2021).

Conclusion

- Large differences in magnetism driven by intercalate species, *M*
- Magnetic phase separation, demonstrating independent temperature evolution of phases
- Low temperature transition corresponds to peak in dynamic response, associated with suggested formation of topological excitations





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Read the preprint at:

arXiv:2506.06111 [cond-mat.str-el]