Experimental report

22/09/2023

Proposal: **5-42-571** **Council:** 10/2022

Title: The vortex lattice in 2H-NbS2 ¿ a potential FFLO candidate

Research area: Physics

This proposal is a continuation of 5-42-558

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Samples: NbS2

Instrument	Requested days	Allocated days	From	To
D33	6	5	07/04/2023	12/04/2023

Abstract:

2H-NbS2 has recently been proposed as a potential candidate material based on torque magnetometry, specific heat and thermal expansion measurements as a function of orientation in magnetic field. There is a strong anisotropy between the superconducting response in and out of the basal plane, indicating that when the field is in the basal plane, Pauli paramagnetic effects are important, with a
possible change seen in the superconducting state at 10 T. We propose to investigate this by studying the vortex lattice as a function of temperature.

Experimental Report
Instrument: D33
Experiment Number: 5-42-571

Title: Investigation of the vortex lattice in NbS_2 – a potential FFLO candidate.

Experiment Date: 07/04/2023 –12/04/2023

Experimental Team (on site): Ahmed Alshemi, Elizabeth Blackburn (Lund University), Ted Forgan (University of Birmingham)

Local Contact: Robert Cubitt

Introduction

Transition-metal dichalcogenides (TMDs) have sparked a lot of interest because they display different types of electronic order, including charge-density waves (CDWs), Mott insulating phases, and superconductivity [1], sometimes at the same time. Their crystal structure consists of hexagonal layers of transition metal interleaved by chalcogen layers, which couple through weak van der Waals forces, giving rise to strongly anisotropic properties [2]. We have used small angle neutron scattering (SANS) to study the vortex lattice (VL) in 2*H*-NbS_2 as a function of angle of the magnetic field with respect to the basal plane. We observed a strong intrinsic superconducting anisotropy between the **c** axis and the basal plane.

Sample Details

The sample consisted of thin platelets of high-quality single crystals of 2*H*-NbS_2 with optically flat surfaces on both sides, grown using the solvent evaporation technique. The samples were co-aligned on two aluminium plates (**Figure 1**) with the **c** axis perpendicular to the plates and mounted in the Birmingham (17 T) magnet. The total sample mass was 73.9 mg. These samples were grown by the group of Mahmoud Abdel-Hafiez (Uppsala University) using the same methods as in their work in Ref. [3]. The upper critical field H_{c2} goes between 1.8 and >15 T, depending on the sample orientation in the field, as shown in (**Figure 2**).

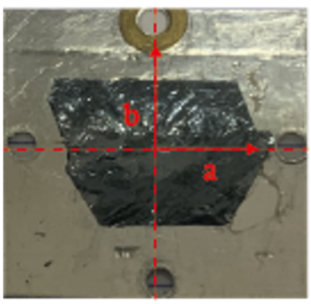

Figure (1): Image of the NbS_2 samples used in this experiment mounted on the aluminium plate. The red solid arrows indicates the **a**-**b** plane alignment of the crystals. The **c** axes point out of plane.

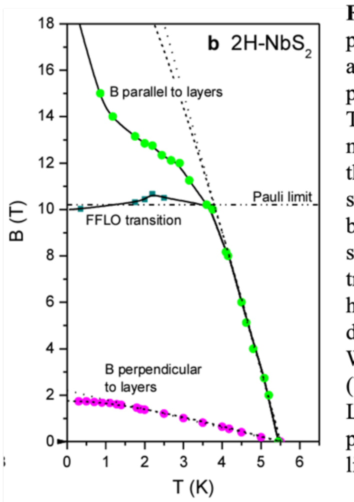

Figure (2): From Ref.[3] Magnetic phase diagram of 2H-NbS_2 in fields applied strictly parallel and perpendicular to the layer structure. The data were compiled from magnetic torque, specific heat and thermal expansion data. The olive squares mark a phase transition boundary within the superconducting state of NbS_2 attributed to the transition to an FFLO state in the high field region. The dashed and dotted lines are fits with the standard Werthamer–Helfand–Hohenberg (WHH) model and the Ginzburg-Landau (GL) model, respectively, providing estimates of the orbital limits for superconductivity.

Experimental details

The experiment was carried out at the D33 instrument, with neutron wavelength λ_n=10Å, collimation 10.3 m, detector distance 10 m and a wavelength spread $\Delta\lambda_n / \lambda_n$ = 10%. We cooled the sample to 500 mK in a field from above T_c, using the Birmingham 17 T cryomagnet with dilution insert. To cause the VL planes to pass through the Bragg diffraction condition, the sample and the magnet (field direction) were rotated (or tilted) together through small angles with respect to the incident neutron beam. the angle between the magnetic field and the c-axis is denoted by Ω.

We had a number of technical issues that led to the loss of time during the experiment. There were problems with the interface between Nomad and the cryomagnet control computer that led to about 8 hours of lost time. The problem arose because during the long shutdown, some aspects of the Nomad files for the 17 T cryomagnet had been replaced assuming that the current through the coils was being controlled directly, rather than this being done by the 17 T control computer. The following day, we were not able to observe any signal; this was because the motor offsets for the san and phi motors had been overwritten at some point during the reloading and restarting of Nomad, so that we were measuring in the wrong place. Diagnosing this unexpected change (normally the motor offsets are not changed when restarting Nomad or after it crashes) took us most of the following day due to the long counting times to first realise and then check the absence of signal.

Results

We observed diffraction from the vortex lattice in 2*H*-NbS_2. Oscillation field cooling (1% of target field) was required to form a well-structured vortex crystal. With the field applied parallel to the **c** axis, the VL is very close to hexagonal. We studied the field dependence at this condition (**Figure 3**), and observed a change in orientation of the vortex lattice as the field is increased.

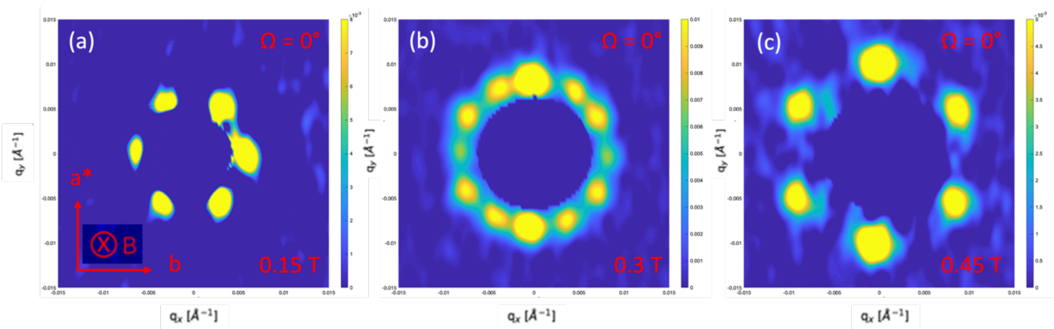

Figure 3: SANS diffraction patterns from the VL in 2*H*-NbS_2 for with the field parallel to the **c** axis, Ω = 0°, recorded at 0.15 T, 0.3 T and 0.45 T and at 500 mK. The images are sums over rocking scans about the horizontal axis perpendicular to the beam. The direct beam has been masked off. At B = 0.3 T, two VL domains can be seen, indicating a first order transition as the field is increased.

We then rotated the field towards the basal plane, and observed a strong anisotropy, as during our previous experiment [4]. Given the phase diagram in **Figure 2**, this is to be expected, and bears a strong resemblance to the behaviour observed in KFe_2As_2 [5] and Sr_2RuO_4 [6]. We wanted to concentrate on the behaviour very close to Ω = 90°, but ran out of time to complete this section of the experiment.

Conclusions

We have observed the VL in NbS_2, and we are able to assess the penetration depth and coherence length at certain conditions at $\Omega = 0°$. The sample shows strong intrinsic superconducting anisotropy between the **c** axis and the basal plane.

References:

[1] M. Leroux et al., Physica B : Condensed Matter 407, 1813 (2012).
[2] V.G. Tissen et al., Phys. Rev. B 87, 134502 (2013).
[3] C.-W. Cho et al., Nature Comm. 12, 3676 (2021).
[4] A. Alshemi et al., ILL Experiment Report 5-42-558 (2022).
[5] S. J. Kuhn et al., Phys. Rev. B 93, 104527 (2016).
[6] C. Rastovski et al., PRL 111, 087003 (2013).