Experimental report

07/09/2022

Proposal: **5-42-558**

Council: 4/2021

Title: Investigation of the vortex lattice in NbS2 - a potential FFLO candidate

Research area: Physics

This proposal is a new proposal

Main proposer: **Ahmed ALSHEMI**

Experimental team:
Annika STELLHORN
Lingjia SHEN
Ahmed ALSHEMI
Elizabeth BLACKBURN

Local contacts: Robert CUBITT

Samples: NbS2

Instrument	Requested days	Allocated days	From	To
D33	6	4	27/09/2021	01/10/2021

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: 5-42-558

Title: Investigation of the vortex lattice in NbS$_2$ – a potential FFLO candidate.

Experiment Date: 27/09/2021 – 01/10/2022

Experimental Team: Ahmed Alshemi, Emma Campillo, Lingjia Shen, Annika Stellhorn, Ted Forgan, Elizabeth Blackburn (Lund University)

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 Blue Charlie (9T) magnet. The total sample mass was 42.28 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**.

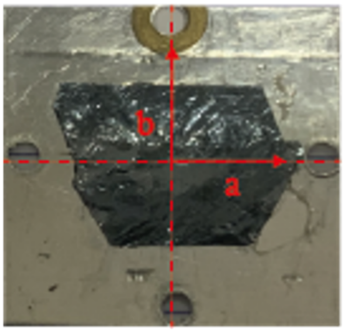

Figure (1): Image of the NbS$_2$ samples used in this experiment mounted on the aluminium plate. The red solid arrows indicates the **a**-**b** plane alignment of the crystals. The **c** axis point out of plane.

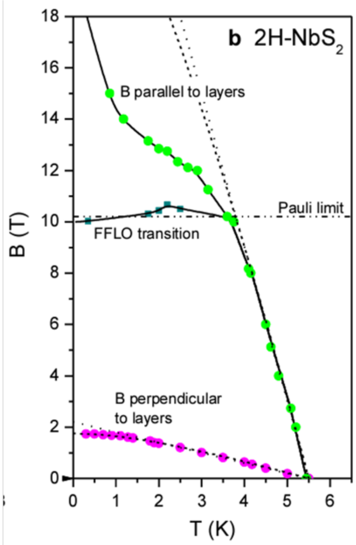

Figure (2): From Ref. [3] Magnetic phase diagram of 2H-NbS$_2$ in fields applied strictly parallel and perpendicular to the layer structure. The data were compiled from magnetic torque, specific heat and thermal expansion data. The olive squares mark a phase transition boundary within the superconducting 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 SANS-D33 instrument, with neutron wavelength λ_n=10 Å, collimation of 10.3 m, detector distance 10 m and a wavelength spread $\Delta\lambda_n / \lambda_n$ = 10%. Then we cooled down to 1.5 K in a field from above T_c. Our intention was to use the Birmingham 17 T magnet, but due to a vacuum leak (now fixed) we were not able to use it for the experiment. Instead, we used the blue Charlie cryostat and concentrated on the parts of the phase diagram accessible here ($T > 1.5$ K and lower magnetic fields). To bring the vortex lattice into the Bragg diffraction condition, the sample and the magnetic field were rotated together through small angles about two axes perpendicular to the incident neutron beam. The angle between the magnetic field and the c-axis is denoted by Ω.

Results

We observed diffraction from the vortex lattice in 2H-NbS$_2$. Oscillation field cooling 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 but on rotating the field towards the basal plane, a strong anisotropy is seen (**Figure 3**). Given the phase diagram in **Figure 2**, this is to be expected, and bears a strong resemblance to the behaviour observed in KFe$_2$As$_2$ [4] and Sr$_2$RuO$_4$ [5].

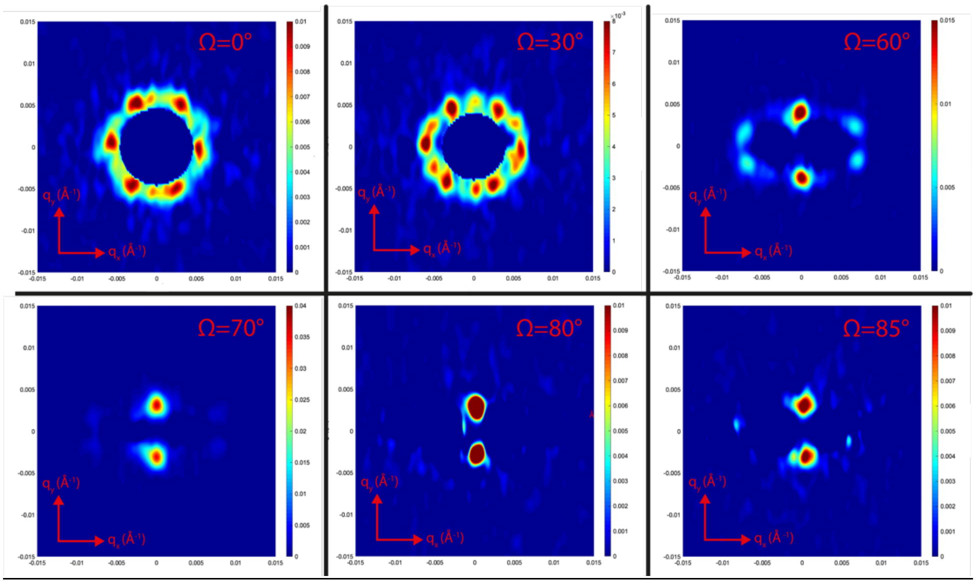

Figure 3: SANS diffraction patterns from the VL in 2H-NbS$_2$ for six different angles of the field to the **c** axis, Ω, recorded at 0.15 T and 1.5 K. The images are sums over rocking scans about the horizontal axis perpendicular to the beam. The direct beam has been masked off. At Ω = 30°, two VL domains can be seen. At higher field angles, the lattice becomes so anisotropic that only the top and bottom spots can be seen.

When the field was applied at an angle Ω = 85° we see that when rocking about the horizontal axis perpendicular to the incident neutron beam (φ) two peaks are observed for a given position on the detector (**Figure 4**). This has previously been observed in anisotropic VLs, and is due to the energy difference brought about by the neutrons being spin flipped by local transverse field components [5].

In addition to the angular dependence, the VL was studied as a function of magnetic field at some of the field angles. This was done by extracting the form factor from the integrated intensities associated with given Bragg reflections [6]. The field dependence at certain angles is shown in **Figure 5**. Qualitatively, the form factor decreases with applied magnetic field, as expected when using a London model for the field variation in the sample, modified by a correction for finite core size as described by Brandt [7]. This model works well for Ω = 30°, 80° and 85°. At Ω = 87.5°, the correspondence is not so clear, and so this may be an indication of the increasing importance of Pauli paramagnetic effects as the field moves towards the basal plane [3,8].

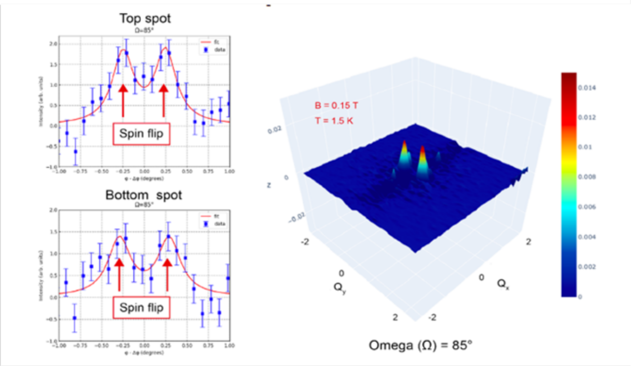

Figure (4): Diffraction pattern at Ω = 85° showing spin flip scattering from the VL due to the transverse field modulation which leads to a Zeeman splitting of the VL rocking curves

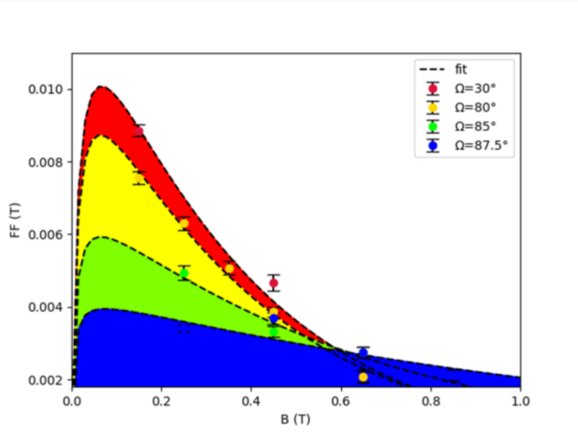

Figure (5): Magnetic field dependence of the form factor estimated from the SANS neutron intensities at T = 1.5 K. The dashed line shows the fit to the London model modified by a core correction.

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 Ω = 30°, the estimated values of the penetration depth and coherent length were 87.8 and 14.3 nm, respectively. These values are consistent with that estimated from M. Leroux [1]. The sample also showed 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 Communications **12**, 3676 (2021).
[4] S. J. Kuhn *et al.*, Phys. Rev. B **93**, 104527 (2016).
[5] C. Rastovski *et al.,* Phys. Rev. Lett. **111**, 087003 (2013).
[6] D. K. Christen *et al.*, Phys. Rev. B, **15**, 4506 (1977).
[7] E. H. Brandt, Phys. Stat. Sol. (b), **51**, 345 (1972).
[8] E. Campillo *et al.,* Phys. Rev. B **104**, 184508 (2021).