ESRF	**Experiment title:** Proximity Coupling at Rare-Earth Doped Dy:Bi2Te3 Topological Insulator Interfaces	**Experiment number**: HC-3325
Beamline:	**Date of experiment**: from: 5 February 2018 to: 12 Feburay 2018	**Date of report**:
Shifts:	**Local contact(s)**: Flora YAKHOU	*Received at ESRF:*

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Report:

Introduction:

The samples investigated during the experiment at ID32 were thin-film heterostructures consisting of the magnetically doped topological insulators (TIs) Cr:Sb_2Te_3 and Dy:Bi_2Te_3, grown by molecular beam epitaxy (MBE). Previously, we have demonstrated that by engineering magnetically doped Cr:Sb_2Te_3/Dy:Bi_2Te_3 TI heterostructures, we can induce long range ferromagnetic order in the Dy:Bi_2Te_3 layers, despite single layer Dy:Bi_2Te_3 being paramagnetic, through proximity coupling [1]. Long range ferromagnetic order in a TI breaks time-reversal symmetry, opening a band gap and leading to exotic quantum effects such as the quantum anomalous Hall effect.

In order to understand the mechanism behind this induced long range ferromagnetic order within the heterostructure, an investigation of how it is affected by various properties of the heterostructure, such as the number of bilayers, must be conducted. During our investigation at ID32, the bilayer thicknesses of each of the heterostructure samples was kept constant (8 nm bilayer thicknesses with equal parts Cr:Sb_2Te_3 and Dy:Bi_2Te_3) while the number of bilayers was varied. Samples investigated during the beamtime consisted of 2, 4, 6, and 8 bilayers. The samples were characterised structurally using x-ray reflectometry and x-ray diffraction prior to the beamtime, and were found to have a consistent structure with previously grown samples. By using x-ray magnetic circular dichroism (XMCD) to investigate the magnetic properties of each of the elements within the heterostructure we hoped to observe how the number of bilayers affected the magnetic properties of the samples.

Experimental details:
The remanent magnetization of Cr and Sb, at zero applied magnetic field, was measured using x-ray absorption spectroscopy (XAS) and XMCD at the Cr $L_{2,3}$ edges (565-595 eV) and Sb $M_{4,5}$ edges (520-560 eV). The remanent magnetization was measured at increasing temperatures until the XMCD was observed to disappear in order to find the ferromagnetic transition temperature (T_C) of the Cr-doped layers, as well as Sb.

The T_C of Dy was expected to be in the range of the base temperature of the cryostat, about 5 K, as concluded from magnetisation versus temperature measurements done in a SQUID magnetometer. Therefore, Arrott plots were used to find the Dy T_C [2]. At temperatures between 5 and 40 K, the saturation magnetisation was measured at the Dy $M_{4,5}$ edges (1270-1350 eV) for applied fields between 0.5 and 9 T. All measurements were performed with the x-rays incident on the samples at the magic angle (~55º) to obtain maximum signal from both the Cr, which is expected to be magnetised out-of-plane, and Dy, which is expected to be in-plane. The XAS was recorded in total-electron yield (TEY) mode by measuring the drain current from the samples, and also in fluorescence-yield (FY) mode by using a photodiode.

Results:
All samples had a 5-nm-thick Bi capping layer. However, since there was an indication of an oxide contribution in the TEY of the Cr XAS (see Fig. 1), it can be concluded that the cap is not effective in protecting the top layers from oxidation. Nevertheless, the oxidation does not appear to affect the magnetic signal.

Further, Sb showed a magnetic moment even at remanence (see Fig. 1), where in single films of Cr:Sb_2Te_3, a field of 8 T has been required to observe an XMCD signal [3]. It was hard to observe if the T_C of Cr and Sb was the same as the XMCD signal from Sb was obscured by the noise level at higher temperatures (see Fig. 1). Unfortunately, no correlation between T_C and the number of layers could be found. For Dy, a negative T_C was observed for all samples (see Fig. 2). Recent neutron reflectometry measurements have demonstrated that the interfaces of the samples used for this experiment were inconsistent across the series, however, that for optimized surface roughness a Dy T_C of 17 K can be reached [3]. It is not too surprising that the interface quality can have a larger influence on the magnetic properties of the heterostructures than the number of repeats.

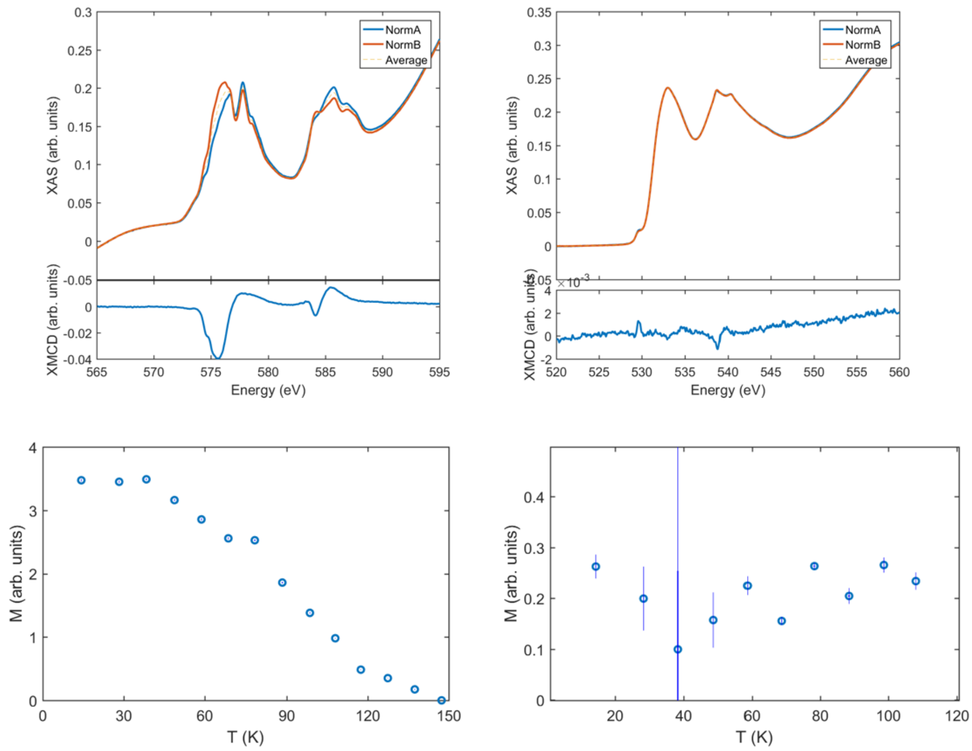

Fig. 1. *XAS and XMCD from TEY at zero applied field at 15 K for the sample with 6 bilayers. Top left: Cr $L_{2,3}$ spectra. The extra peaks in XAS at 578 eV indicate that there is Cr oxide present at the surface. Top right: Sb $M_{4,5}$ spectra. XAS also demonstrates an oxygen presence at 533 eV. The M_4 and M_5 XMCD peaks of Sb are clearly visible, and the negative L_2 peak of Cr and a positive M_4 peak of Sb indicate that the moments are aligned parallel. Bottom left: Remanent magnetisation of Cr in the 6 bilayer sample for different temperatures. T_C is about 120 K, which is expected for this doping concentration of Cr:Sb_2Te_3. Bottom right: Remanent magnetisation of Sb in the 6 bilayer sample for different temperatures. In this case, T_C is difficult to determine since the Sb XMCD is obscured by noise at higher temperatures.*

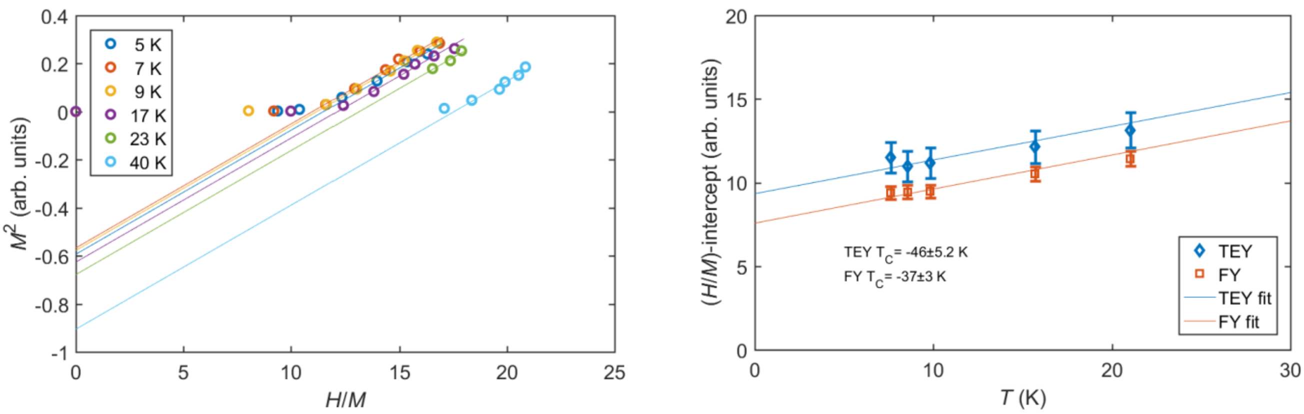

Fig. 2. *Left: Arrott plot from the TEY signal of Dy in the 6 bilayer sample. Right: Corresponding intercept plot. The intercept of the fitted lines gives the T_C of the Dy within the heterostructure. The plot shows that the T_C for the Dy within the sample is negative in both FY and TEY, demonstrating there is a negative ferromagnetic transition temperature. This was the case for all samples.*

References:

[1] Duffy, L. B., *et al.* "Microscopic effects of Dy doping in the topological insulator Bi_2Te_3", *Phys. Rev.B* **97**, 174427 (2018). [2] Arrott, A. and Noakes, J. E. "Approximate equation of state for nickel near its critical temperature", *Phys. Rev. Lett.* **19**, 785 (1967). [3] Duffy, L. B., *et al.* "Magnetic proximity coupling to Cr-doped Sb_2Te_3 thin films", *Phys. Rev. B* **95**, 224422 (2017).