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The Magnetic Behaviour of the Surface and Bulk Components of Tb(0001)Films

Orhan ZEYBEK
Department of Physics, Faculty of Arts and Science, Balıkesir University, Balıkesir, 10100, TURKEY

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Abstract

The use of circularly polarised light in photoemission from ferromagnetically ordered rare earth's (RE) shows large magnetic circular dichroism in angular dependence (MCDAD) effect. Therefore MCDAD in photoemission from RE's provides new perspectives for surface magnetism studies within the view of the recently postulated sum rules. This allows to probe magnitude and orientation of the sample magnetisation without time-consuming electron-spin analysis. The well-resolved multiplet structures have been obtained in 5p photoemission of Tb using circularly polarised light. This multiplet structure is caused by the interaction between the core level photohole and those partially filled subshell, i.e. as result of the unpaired 4f and 5p electrons. In 4f levels of Tb(0001) films, the well-resolved surface component of the Tb $^8S_{7/2}$ has been observed a separation of magnetic circular dichroism in the angular dependence effect for the surface layer and for the bulk.

Key Words: Magnetic Circular Dichroism in Angular Dependence, Magnetic Measurements, Terbium, Growth, Magnetic films, Tungsten

1. Introduction

An effect of the magnetic circular dichroism in angular dependence (MCDAD) on surface magnetism of the Tb(0001) films grown on W(110) will be analysed in this paper. Many of the rare earth (RE) metals possess exotic magnetic structures. In this investigation Tb was chosen for MCDAD experiment, because this metal possesses helical magnetic structure, where the magnetisation rotates from one crystal plane to next. The existence of this phase for Tb is 220 K $< T >$ 230K. Tb(0001) exhibits ferromagnetism at T_c = 220 K. The aims of this investigation are to carry out the first MCDAD experiment on beamline 4.1 at Daresbury Synchrotron Radiation Source (SRS), UK. and to perform the temperature dependence of surface and bulk magnetic behaviour of Tb(0001) films on W(110) respectively.

2. Experimental Method

The photoemission experiments were carried out with circularly polarised light from beamline 4.1 at the Daresbury SRS. This beamline has three flexible flux ranges, which provides polarised light at different photon energies for MCDAD experiments. The data from this beamline were collected using Scienta 200 analyser. W(110) substrate was cleaned with oxygen roasting and then followed by flashing over 2300 K. The base pressure in the experimental chamber was typically $\cong$1x10^{-10} mbar, raising to 3x10^{-10} mbar during Tb evaporation. The clean and well-ordered Tb films was obtained at room temperature and confirmed by Low Energy Electron Diffrection (LEED). Tb films showed only a diffuse LEED pattern, which indicates a

rough surface sample. It was followed by annealing of the film for 5 min at 500-700 K depending on the thickness of the film [1]. After annealing, sharp LEED spots were obtained [2]. The film thickness was monitored taking 4f photoemission spectra of W(110) sample. The contaminations of the growth Tb films were checked by monitoring 1s photoemission intensities of O and C as well as by the O - 2p photoemission spectra and valence band, because oxygen 2p level can exist at a binding energy of 5 - 6 eV. The Tb films were magnetised using home-made search coils which were close to the sample. Due to the relatively large coercivity fields in Tb metal, the remanent magnetisation was achieved by pulsing high current (200 A) under the 1 kV in short time. The shape of the MCDAD for Tb(0001) films is determined by the relative angles between the magnetisation direction, the photoemission direction and the helicity vector of the photons as shown in Figure 1.

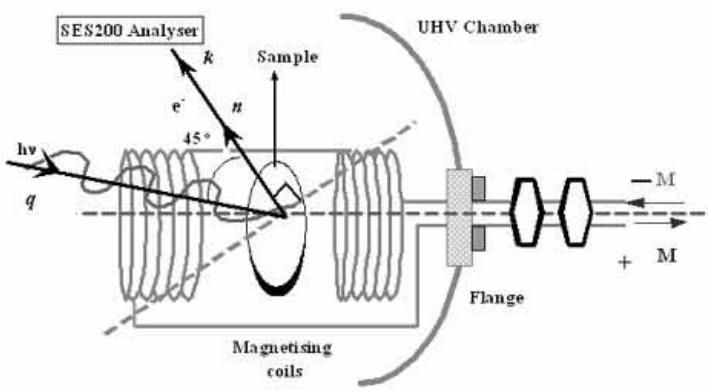

Figure 1. Experimental setup for MCDAD spectrum for Tb(0001) (schematic only).

3. Results and Discussions

As shown in Figure 2, three different peak groups can be resolved from Tb(0001) photoelectron spectrum:
(i) 5s photoemission structure is around 50 - 45 eV binding energies.
(ii) 5p photoemission structure is around 30 - 20 eV binding energies.
(iii) Tb(0001) 4f's with valence band emission lines are between 12 eV and 0 eV binding energies. The detailed of the MCDAD results are given in the following sections.

3.0.1. Tb(0001) 5p's

In Figure 3, the 5p photoemission peaks of Tb show fine structures because of the multiplet splitting, which is caused by the unfilled 4f levels. Multiplet structures can be understood as a final state effect in photoemission. These structures have been reported by Li and Dowben [3]. When one 5p electron excites, the hole will be created behind this electron. Thus the hole will have direct (Coulomb) and indirect (exchange) electrostatic interaction with the electron in unfilled subshells to form different final states. This effect has been studied on filled s and p core levels of RE's and transition metals [4 - 6]. These studies were concentrated on the exchange interaction between the unpaired spins. This interaction forms in two features characterised by spin parallel or antiparallel to that of the unpaired electrons. For s levels, they have no orbital momentum, so there is no spin-orbit interaction. For p levels, spin-orbit interaction can be ignored if exchange interaction between the hole and other electrons is stronger than spin-orbit interaction.

Figure 3 provides a comparison between the experimental and theoretical calculation from van der Laan [7] and the experimental data presented here. The peaks (A), (B) and (C) indicate that a reasonably good agreements is obtained. The line shapes from both experiments follow the shape of the calculation spectra. The calculated intensities show similar results with experiments. However some discrepancy is obtained for peak (B). The Tb $5p_{1/2}$ and $5p_{3/2}$ levels can bee seen through the multiplet splitting at binding energies of

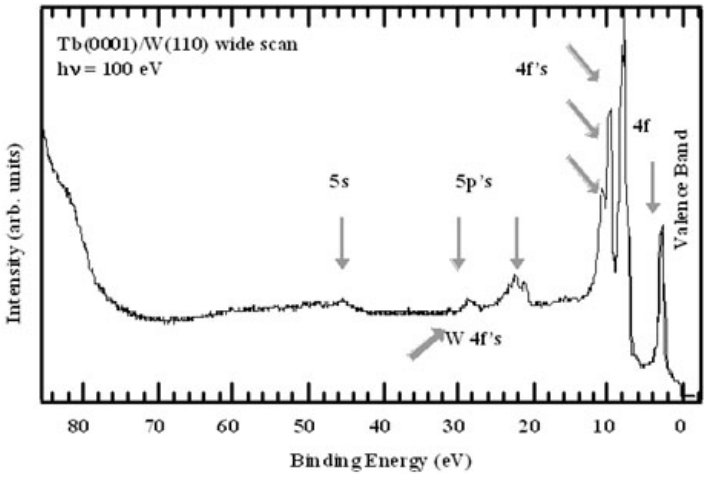

Figure 2. Tb(0001) wide MCDAD spectra taken from a 19 ML film at 300 K, normal emission, hν = 100 eV.

28.4 and 22.2 eV respectively. Because of coupling of the 5p with the 5d state in the final state, the outgoing electron can be d-character [8, 9]. This coupling can happen more strongly with $5p_{3/2}$ level than $5p_{1/2}$ due to spin ordering of the occupied 5d state near the Fermi energy [8].

3.0.2. Tb(0001) 4f's

The 4f photoemission structure is split over a wide energy range and can be divided into two main areas:

(i) The structure at around 2 eV binding energy corresponding to the case when the remaining seven electrons in the 4f subshell have parallel spins ($^8S_{7/2}$ final state, see following section),

(ii) The structure between 4 eV and 12 eV binding energies corresponding to the case when one of the remaining electrons have an opposite spin (mainly ^{6}P, ^{6}I, ^{6}D, ^{6}G and ^{6}H final states) as shown in Figure 4.These various multiplets were reported using X-ray Photoelectron Spectroscopy and bremsstrahlung isochromat spectroscopy by Lang *et al.* [10]. In comparison with results from Lang *et al.* [10], the corresponding binding energies are changed in this study as a result of the changing oscillator strengths of the different 4f levels.

Figure 5 shows MCDAD in 4f photoemission spectra from 8 ML Tb(0001) films on W(110) substrate at 210 K. This figure is also an evidence that how the temperature is an important factor to magnetise Tb films below the Curie temperature.

3.0.3. Tb(0001) Surface Magnetism

In Figure 6, the isolated $^8S_{7/2}$ 4f photoemission component shows a clear spectroscopic separation of bulk layer from surface at 2.3 eV binding energy. This separation indicates the bulk component higher than surface component at 300 K. This is also observed by Navas *et al.* [11]. In their study, the spectrum of the well-annealed Tb(0001) film described by only a single surface component in addition to the bulk component.

The ^{8}S component is separated from other multiplet lines as shown in Figure 4. The surface component of the Tb(0001) film is well-resolved in Figure 6. It therefore allows to study surface magnetism. When photon energy increases, the surface (higher binding energy side) component decreases relative to the bulk component (lower binding energy side) due to the rising photoelectron mean free path's. The difference in magnetic behaviour of the surface and bulk can be seen in Figure 7. The results show that the MCD effect is significantly larger for the topmost surface layer than for the bulk. Therefore Figure 7 displays a more clear MCD effect for $^8S_{7/2}$ component. Figure 7 shows that the strong MCDAD in $^8S_{7/2}$ photoemission from Tb strongly depends on the temperature, circularly polarised light upon transmission into the bulk and a changing photoelectron-angular distribution upon reversal of light helicity and experimental magnetisation geometry.

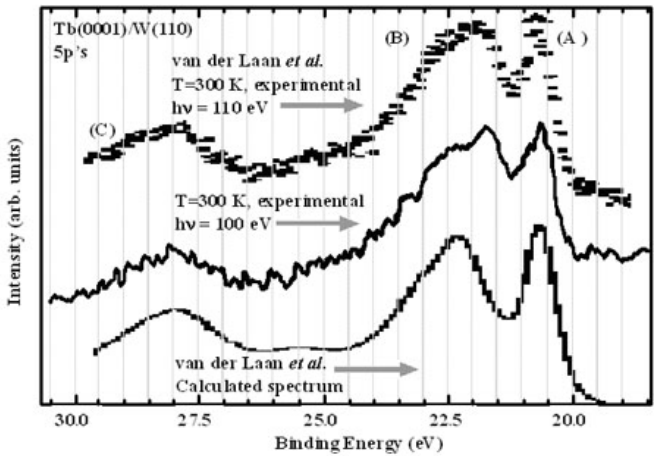

Figure 3. Top spectrum: 5p's of Tb(0001) on W(110) taken from 40 ML films, at hν = 110 eV, 300 K with linearly polarised light. Lower panel: the calculated 5p's [7]. In the middle: it is taken from 19 ML film at hν = 100 eV, 300 K.

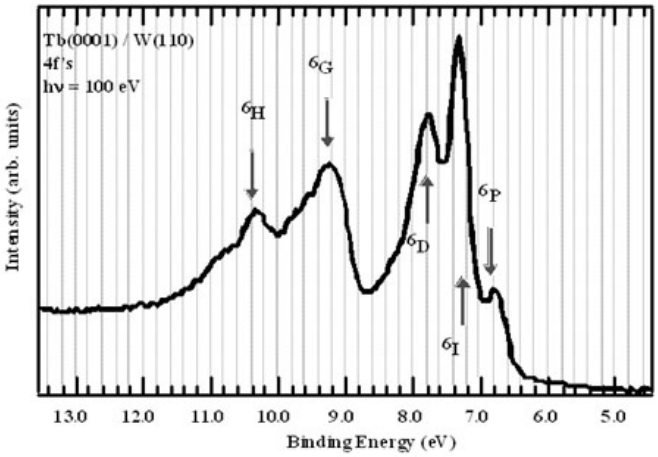

Figure 4. The Tb(0001) films growth on W(110) 4f's of photoemission spectra from a 19 ML film at 300 K, normal emission, hν = 100 eV.

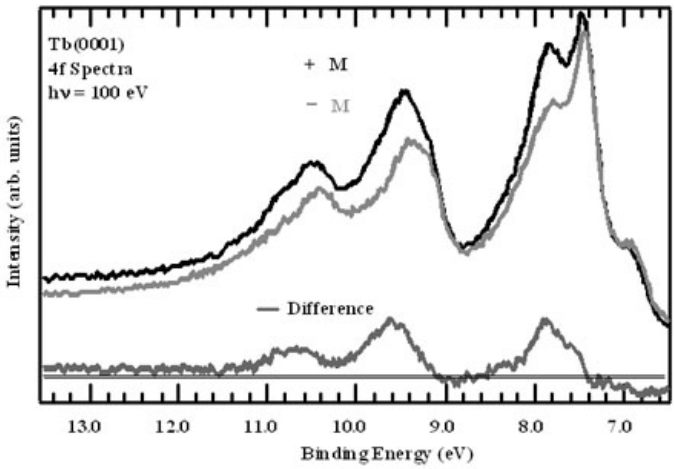

Figure 5. Tb(0001) $4f_{5/2}$ of MCDAD spectra taken from a 8 ML film at 210 K, normal emission, hν = 100 eV.

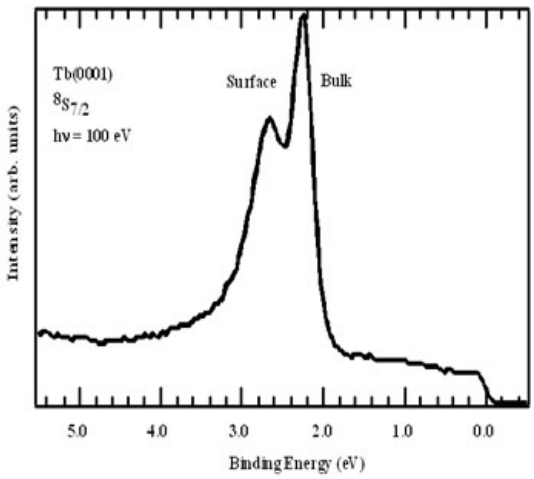

Figure 6. Tb(0001) $4f_{7/2}$ in photoemission spectra of the surface/bulk split $^8S_{7/2}$ component taken from a 19 ML film at 300 K, normal emission, hν = 100 eV.

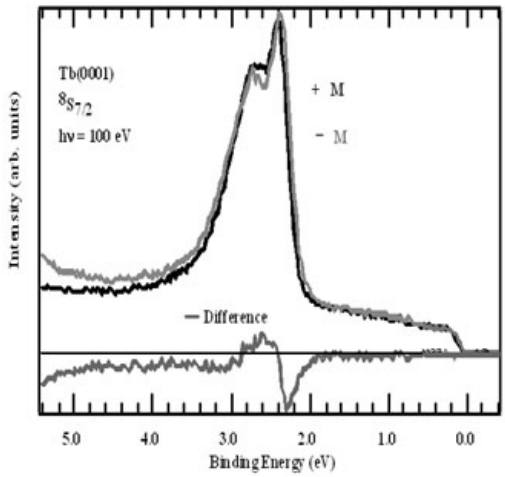

Figure 6. Tb(0001) MCDAD spectra on $^8S_{7/2}$ component taken from a 8 ML film at 175 K, normal emission, hν = 100 eV.

4. Results and Conclusions

For a more quantitative understanding of the MCDAD effect in photoemission from RE's, thin films of Tb(0001) have been studied in this paper. The first MCDAD experiment on beamline 4.1at Daresbury SRS has been carried out successfully. The data presented in this paper are an evidence the existence of strong circularly polarised light on this beamline. The well-resolved multiplet structures have been performed in 5p photoemission of Tb. This is caused by the interaction between the core level photohole and those partially filled subshell, i.e. as result of the unpaired 4f and 5p electrons. Since MCDAD is expected to vanish above Tc and to reach a maximum at saturation magnetisation, the sample temperature has to be significantly smaller than 220 K to probe large MCDAD effects. For the ferromagnetic ground state (t = $T/T_c = 0$), only the lowest-lying magnetic m level would be occupied, i.e. $< m >$ = -J. Higher m levels also become populated at high temperatures, which reduce the MCDAD effect. For $< m> \longrightarrow 0$, i.e., for equal population of all m levels, the MCDAD effect is expected to disappear. The magnetisation of RE metal surfaces has been received considerable attention since knowing the surface-enhanced magnetic order. In this study, the magnetic behaviour of the surface and the bulk components of Tb(0001) films show differences

with changing temperature. The well-resolved surface component of the Tb $^8S_{7/2}$ provides a separation observation of MCDAD effect for the surface layer and for the bulk.

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