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Uranium-Iron multilayers: investigations by XMCD</td><td>Experiment number:
HE-1465</td></tr>
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<tr><td>Shifts:
18</td><td>Local contact(s):
Wilhelm Fabrice
Jaouen Nicolas
Rogalev Andrei</td></tr>
<tr><td colspan="3">Names and affiliations of applicants (* indicates experimentalists):
STIRLING William G.*, E.S.R.F. Grenoble, France
ROWN Simon *, E.S.R.F. Grenoble, France
LANDER Gerry, ITU Karlsruhe, Germany
LANGRIDGE Sean, I.S.I.S. Didcot, United Kingdom
THOMAS M.F., Liverpool University, United Kingdom
ZOCHOWSKI Stan, University College London, United Kingdom
WARD Roger, Oxford University, United Kingdom
BOUCHENOIRE Laurence *, E.S.R.F. Grenoble, France
BEESLEY Angela *, Liverpool University, United Kingdom</td></tr>
</table>

Report:

We report here on X-ray magnetic circular dichroism (XMCD) studies at the U $M_{4,5}$-edges and Fe-K-edge in a series of U/Fe multilayers with different thicknesses ($[U_{26}/Fe_{29}]_{30}$, $[U_{19}/Fe_{33}]_{100}$ and $[U_{41}/Fe_{6}]_{100}$; the subscripts denotes the layer thickness in Å). The XMCD spectra were measured at 5K and 300K under applied magnetic fields of 0.5 Tesla. The second harmonic of the EMPHU undulator spectrum has been used to record XMCD spectra at the U $M_{4,5}$-edges by flipping the helicity of X-rays at each energy point of the scan. The Uranium $M_{4,5}$ spectra were measured using the total fluorescence detection mode. At those edges, self-absorption effects are known to be extremely important and, therefore, one has to correct the spectra. We have extended the procedure for these corrections to take into account the real structure of the multilayer (respective thicknesses in a multilayer and a buffer) and the complete geometry of the experiment (incident angle of X-rays, active area of detector and its position with respect to the sample surface). The validity of this new procedure has been checked by comparing the spectra measured at various angles of incidence. For the experiments at the Fe K-edge, we used the first harmonic of the helical undulator (HU-38) and the XMCD was obtained as the direct difference between XANES spectra recorded with opposite helicities of the X-rays. In both cases (U $M_{4,5}$-edges and Fe K-edge), to ensure that the XMCD spectra are free from any small artificial signals, experiments were performed with two directions of the applied magnetic field (parallel and antiparallel).

In Fig. 1 we have reproduced the U $M_{4,5}$ XMCD spectra recorded at 5K and under 0.5 Tesla field for three multilayers. One can see that there is a strong dependence of the XMCD signals on both U and Fe thicknesses. As the thickness of U layer increases from 19Å to 26Å with the thickness of Fe layer kept approximately constant we observe that the amplitude of the U XMCD signal decreases while its spectral shape does not change. This observation indicates, as expected, that the U 5*f* induced magnetic moment is not constant across the layer and that the U atoms located at the interfaces carry a larger magnetic moment. For a much thinner Fe layer (~ 6Å), we observe that the XMCD signal from the 41Å thick U layers is reduced by only 15% confirming the previous observation if one assumes that the Fe moment is the same in all three samples. We would like to underline that the XMCD signal at the U M-edges was also observed at 300K in all multilayers studied. However, the amplitude of the XMCD signals was reduced following the reduction of the Fe magnetization due to the proximity of the respective Curie temperatures T_C. The reduction of the U XMCD signal is larger for $[U_{41}/Fe_6]_{100}$ multilayer (~57%) compared to the $[U_{19}/Fe_{33}]_{100}$ multilayer (~13%) because the Curie temperature of a 6Å thick Fe layer (T_C~400K) is much lower than the one for the 33Å thick layer (nearly the bulk value of Fe T_C ~1050K).

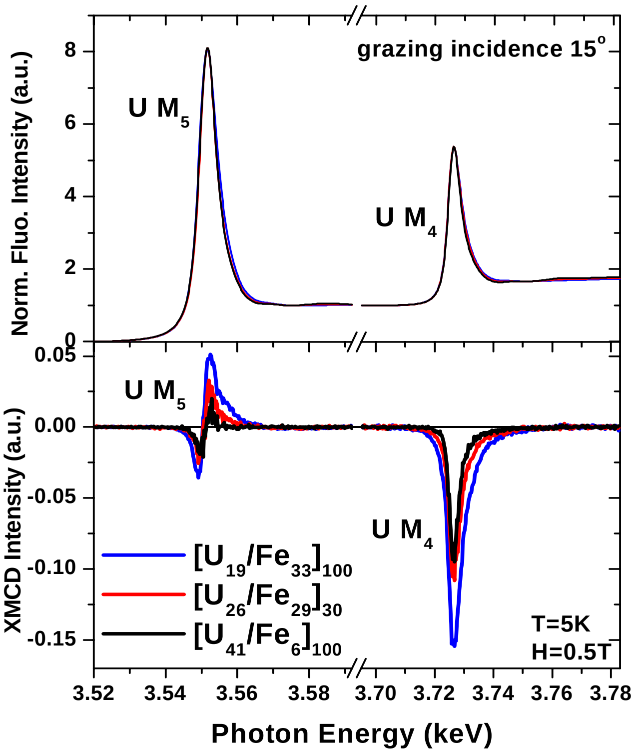

Fig. 1: U $M_{4,5}$-edge XAS and XMCD spectra recorded at 5K and under 0.5Tesla at grazing incidence (15°) for U/Fe multilayers with different composition. All spectra have been corrected for self-absorption effects.

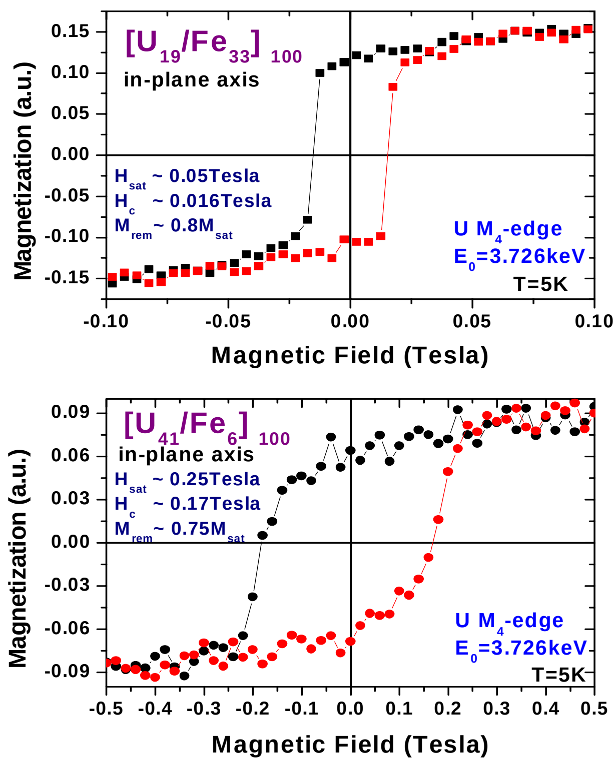

Fig. 2: Element specific hysteresis loops recorded at the maximum XMCD signal at the U M_4-edge (E=3.726keV) at 5K and at grazing incidence (15°).

To make sure that the experiments were performed under complete magnetic saturation of the samples, element specific magnetization curves were recorded at the maximum of XMCD spectrum at the U M_4-edge at 5K for the$[U_{19}/Fe_{33}]_{100}$ and $[U_{41}/Fe_6]_{100}$ multilayers (see Fig. 2) and at 300K for the $[U_{26}/Fe_{29}]_{30}$ multilayer. In both cases, a nearly square hysteresis loops was observed with a coercive field of 0.016Tesla for thick Fe layers (33Å) and of 0.17 Tesla for thin Fe layers (6Å); this is in a good agreement with what one would expect for thin ferromagnetic films. In fact, the coercive field is inversely proportional to the thickness of the ferromagnetic Fe layers and the U 5f induced moment, to a first approximation, reflects this behaviour.

U (5*f*)	μ_L (μ_B/atom)		$<L_Z>/2<S_Z^{eff}>$	μ_S (μ_B/atom)		μ_L / μ_S		μ_{tot} (μ_B/atom)	
T=5K	$5f^2$	$5f^3$		$5f^2$	$5f^3$	$5f^2$	$5f^3$	$5f^2$	$5f^3$
$[U_{19}/Fe_{33}]_{100}$	0.147	0.135	-0.54	-0.061	-0.088	-2.41	-1.53	0.086	0.047
$[U_{26}/Fe_{29}]_{30}$	0.097	0.089	-0.59	-0.036	-0.052	-2.69	-1.71	0.061	0.037
$[U_{41}/Fe_{6}]_{100}$	0.077	0.071	-0.73	-0.024	-0.034	-3.21	-2.09	0.053	0.037

Table 1: Uranium 5*f* magnetic moments of U/Fe multilayers deduced from XMCD spectra using the theoretical values of the $<T_z>/<S_z>$ ratio for two possible configurations $5f^2$ (U^{4+}) and $5f^3$ (U^{3+}).

The use of the sum-rules allows one to extract the ground state orbital $<L_z>$ and spin $<S_z>$ magnetic moments of the U 5*f* states from the integrated U 4,5 XMCD signals. The spin magnetic moment is, in the case of 5*f* electrons, is given by $<S_z> = <S_z^{eff}> - 3<T_z>$, where $<T_z>$ is the expectation value of the magnetic dipole operator and $<S_z^{eff}>$ the value determined from the sum rules. In the case of actinides, the $<T_z>$ term is not negligible: in the intermediate coupling scheme, the ratio of $<T_z>$ to $<S_z>$ is 1.16 and 0.62 for $5f^2$ and $5f^3$ ground-state configurations, respectively. Moreover, both $<L_z>$ and $<S_z>$ are dependent on the number of holes in the 5*f* band, which is, however, unknown due to the strong hybridization of the 5*f* states. Within these limitationsthe spin and orbital magnetic moment of the U 5*f* states were evaluated for two possible configurations $5f^2$ (U^{4+}) and $5f^3$ (U^{3+}). The results are summarized in Table 1.

Fig. 3 presents the Fe K-edge XMCD spectra recorded under the same experimental conditions as U $M_{4,5}$-spectra. In the multilayers with thick Fe layers, we have observed an unexpectedly strong and sharp Fe K-edge XMCD signal. For thin Fe layers (6Å), the Fe K-edge XMCD signal is strongly reduced, by nearly a factor of 10. We think that this sharp XMCD signal is due to quadrupolar 1s-3d transitions and its reduction may be explained by the admixture of the U 5*f*-states with the Fe 3*d*-band states.
Further work is planned on a new set of U/Fe multilayers.

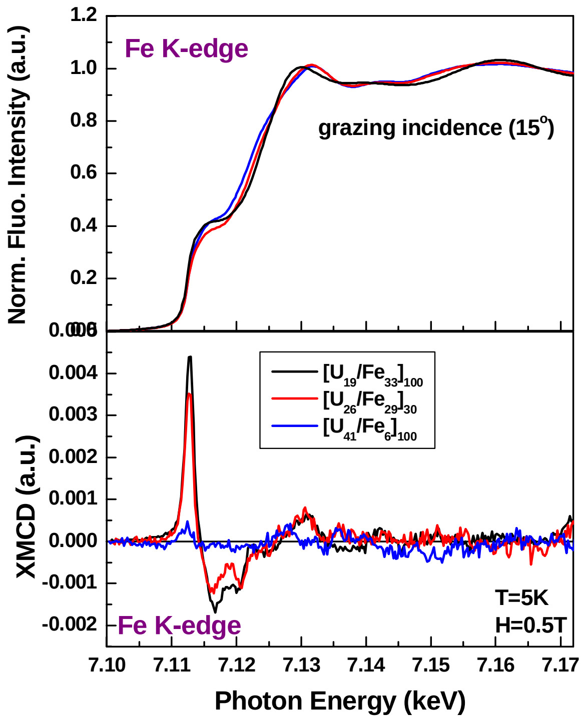

Fig. 3: Fe K-edge XAS and XMCD spectra recorded at 5K and under 0.5Tesla at grzing incidence (15°) for U/Fe multilayers with different composition.