Magnetic Anisotropy studies in Ce/Fe and U/Fe multilayers

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Plan

Introduction

- multilayers
- magnetic anisotropy
- atomic properties

Ce/Fe multilayers

- characterization
- magnetic measurements

U/Fe multilayers

- early studies

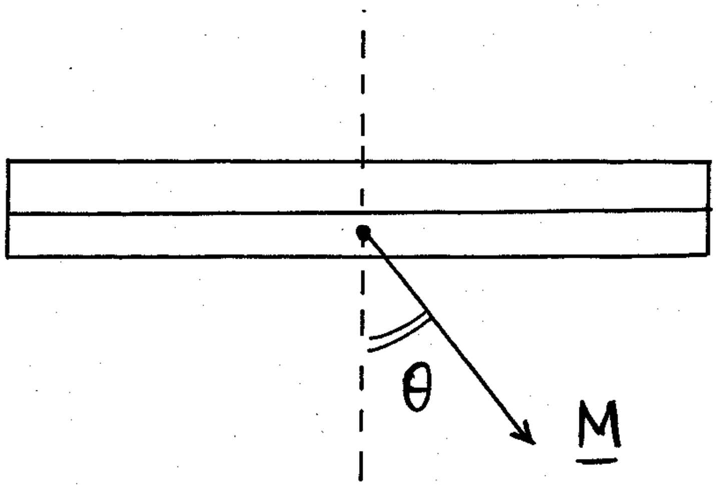
Summary

Magnetic Anisotropy

Dependence of magnetic energy E(θ) on angle θ between magnetization M and layer normal

Written as $E(\theta) = K\sin^2\theta$

K is anisotropy energy/unit volume



K +ve favours M out of plane

K –ve favours M in plane

Anisotropy terms

In a ferromagnetic layer, the sum of the dipolar interactions gives anisotropy energy / unit volume

$$E = -\tfrac{1}{2}\mu_0 M^2 \sin^2\theta$$

favours in plane M

For out of plane components of M – need compensating anisotropy terms.

Investigate interface anisotropy energy arising from Ce-Fe and U-Fe interactions

Anisotropy may arise from

1. Coupling of Fe to orbital moment of Ce or U

2 . Hybridising of Fe 3d electrons with outer electrons of Ce and U.

Atomic structure of Ce and U

Ce atom $[Xe][4f]^1[5d]^1[6s]^2$

U atom $[Rn][5f]^3[6d]^1[7s]^2$

Crystal structure (bulk)

α – Ce	**fcc a = 485 pm** **[4f][5d] largely itinerant** **no residual moment**
γ - Ce	**fcc a = 516 pm** **[4f][5d] – some localized moment**
α – U	**orthorhombic** **a = 285 pm** **b = 586 pm** **c = 495 pm** **no residual moment**
α – Fe	**bcc a = 287 pm**

Multilayer fabrication

Fabrication by DC magnetron sputtering

Ce/Fe

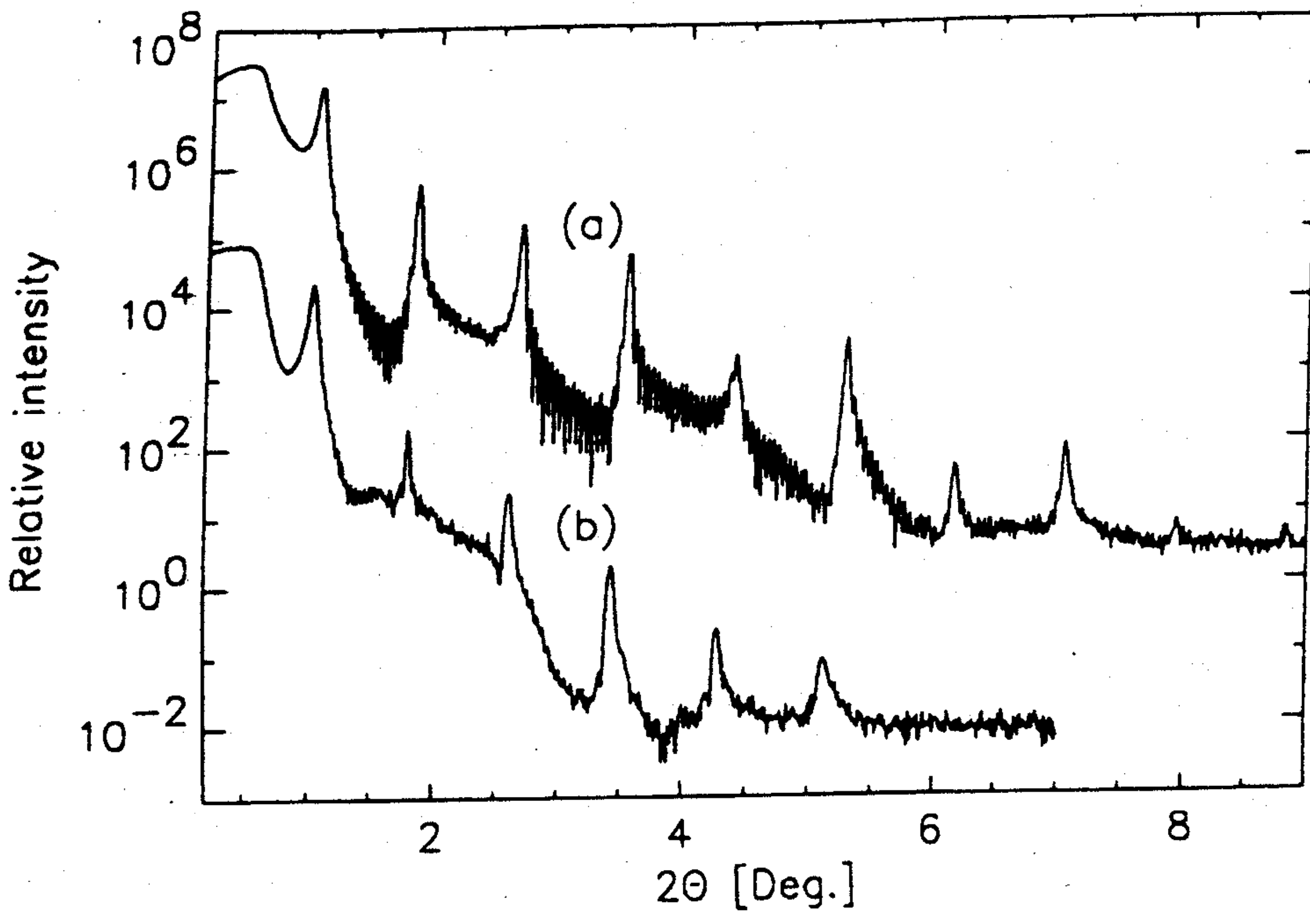
Base pressure	**10^{-7} mbar**
Substrates	**Si** **Kapton**
Substrate temperature	**330K**

U/Fe

Base pressure	**10^{-11} mbar**
Substrate	**Glass**
Substrate temperature	**330K**

Ce/Fe multilayer characterization

x-ray reflectivity

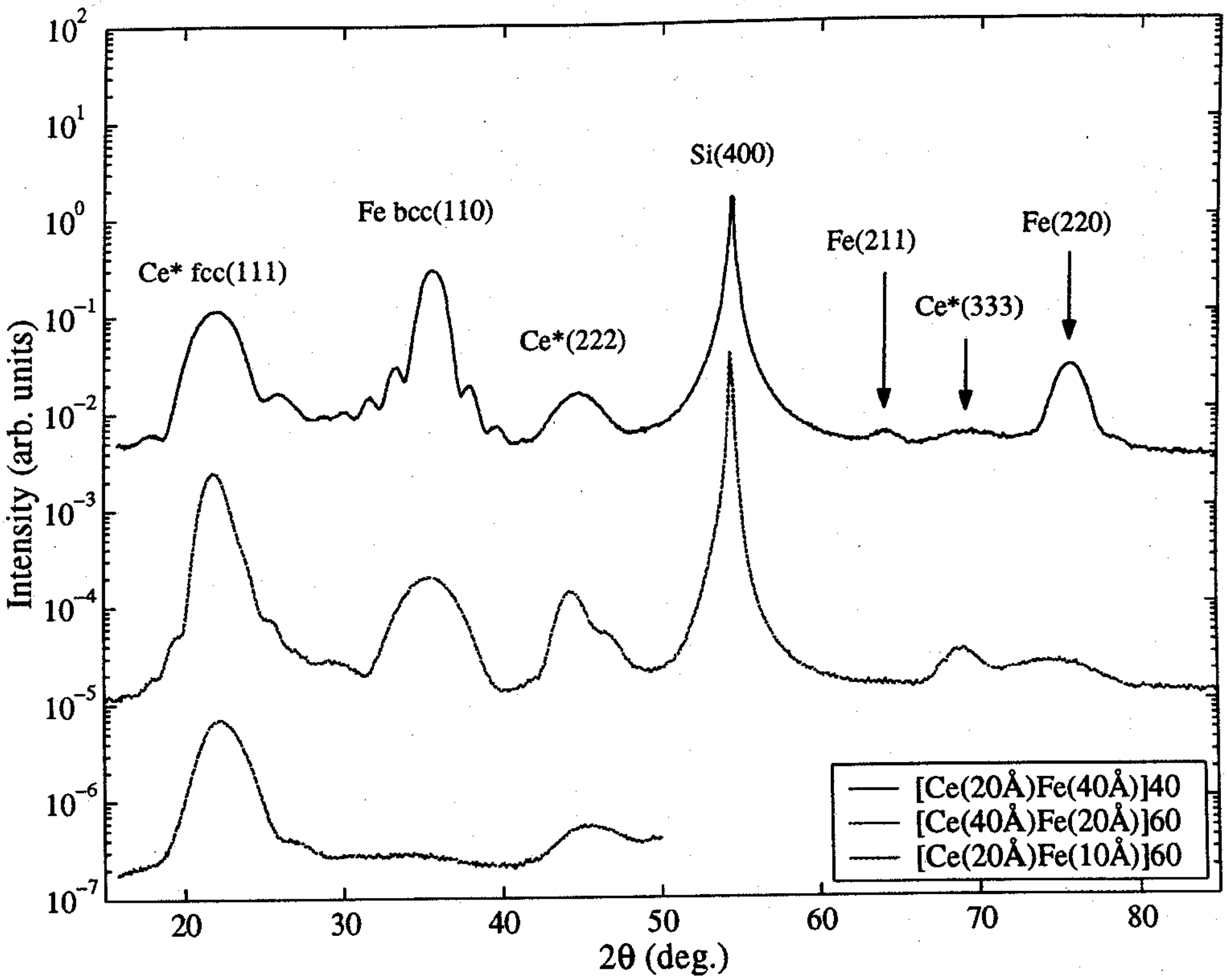


(a) $[Ce(40Å)/FeCoV(40Å)]_{20}$

(b) $[Ce(40Å)/Fe(40Å)]_{20}$

Ce/Fe multilayer characterization

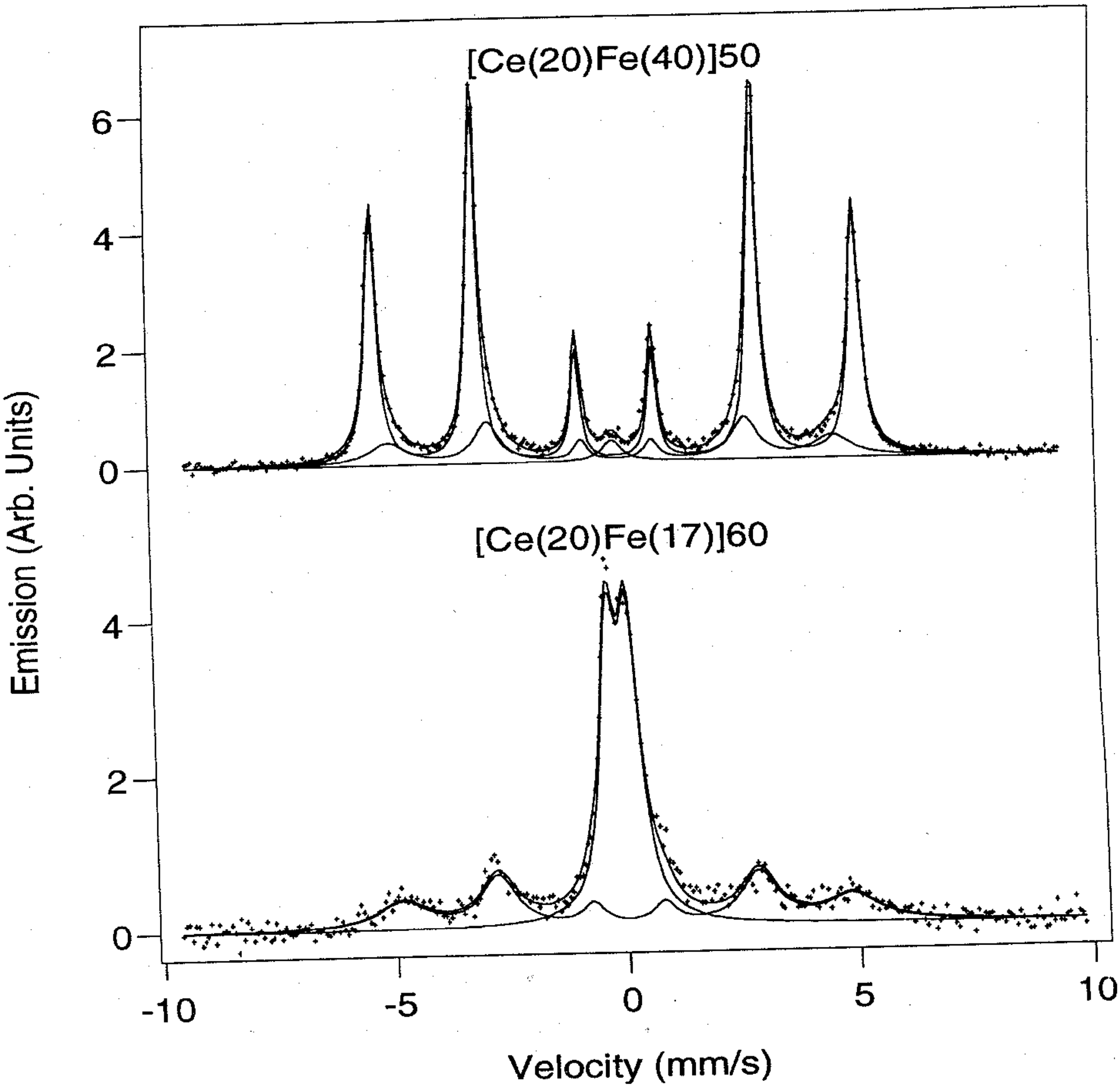
x-ray diffraction



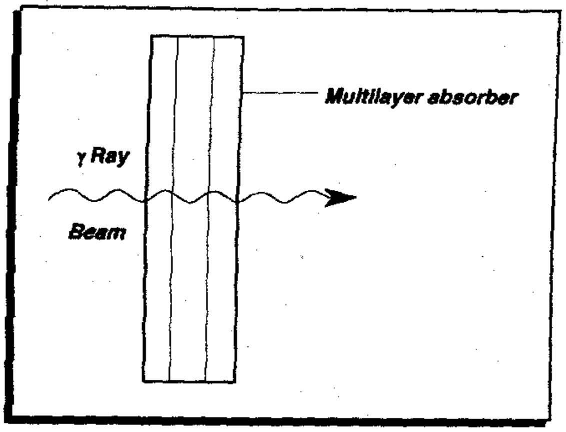
Ce* Thickness (Å)	Fe Thickness (Å)	Ce* Average Lattice Spacing (Å)	Fe Average Lattice Spacing (Å)	Crystallite Size (Å)	
20	10	5.56 ±0.01	2.97 ±0.03	23±3	15±4
20	20	5.63 ±0.01	2.88 ±0.01	23±3	18±3
40	40	5.68 ±0.01	2.87 ±0.01	39±3	43±3
Bulk fcc γ-Ce	Bulk bcc α-Fe	5.16	2.87	-	-

Ce/Fe multilayer characterization

Mossbauer spectroscopy



Measurement of Fe moment orientation from Mössbauer spectra

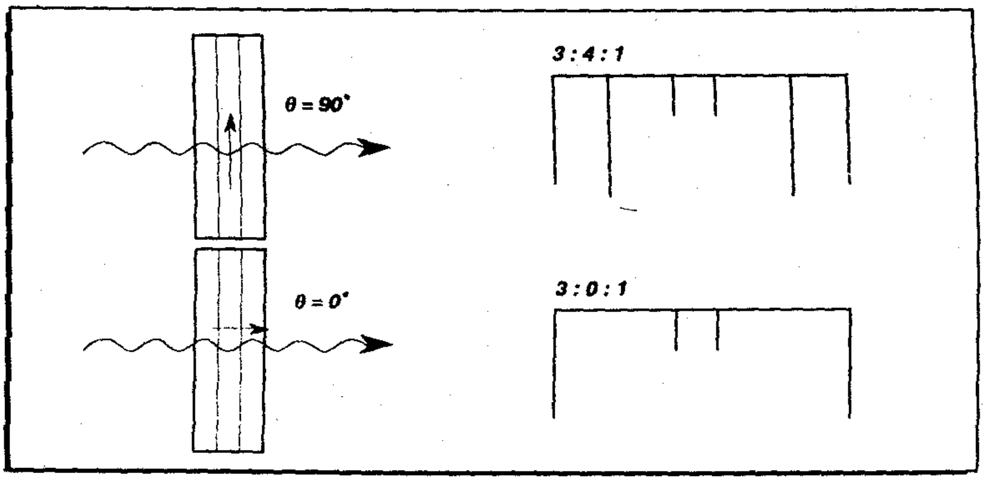


Generates 6 line absorption spectrum where line intensities are

$$3 : \frac{4\sin^2\theta}{1+\cos^2\theta} : 1 : 1 : \frac{4\sin^2\theta}{1+\cos^2\theta} : 3$$

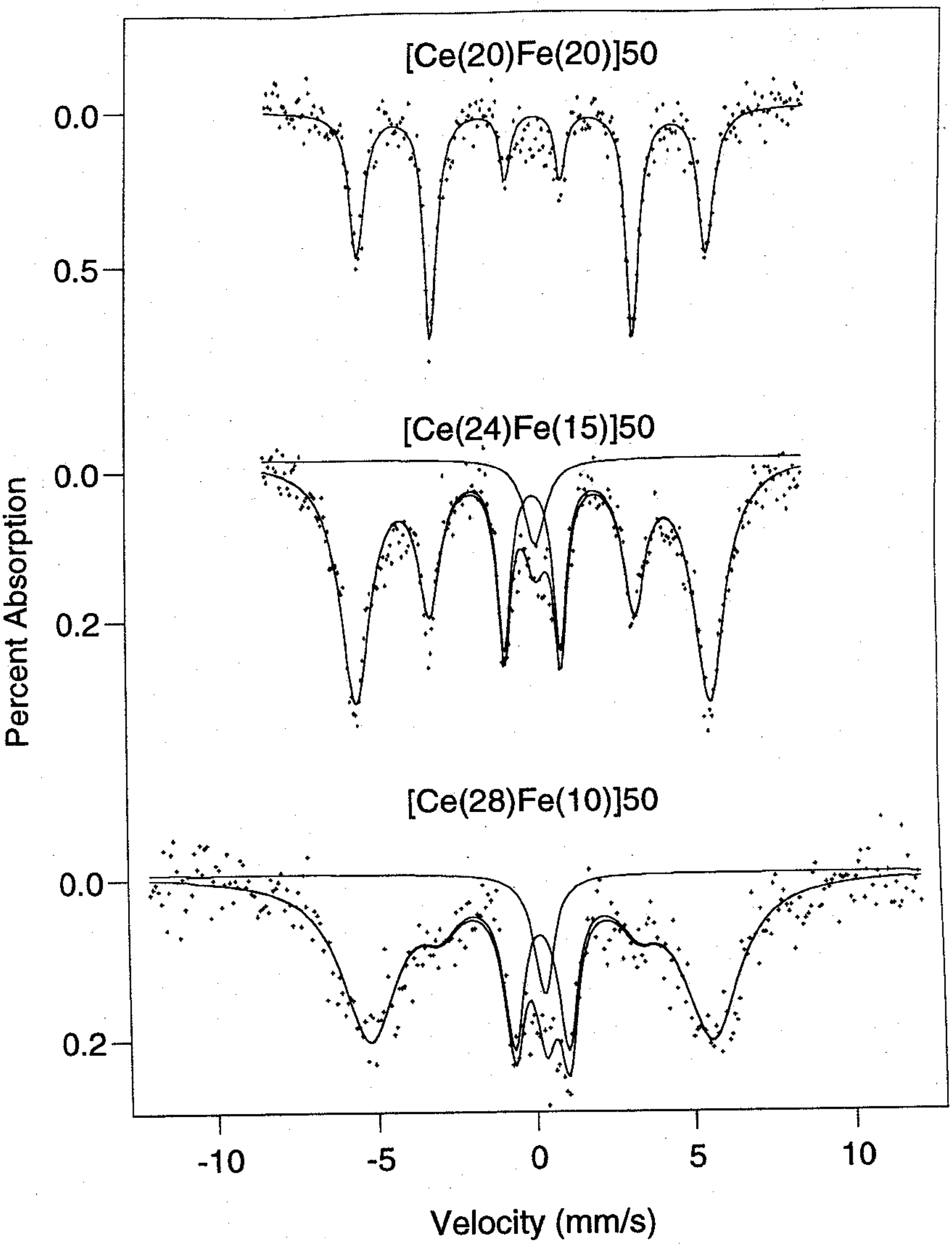
Where θ is angle between Fe spin and γ ray

Limiting Cases

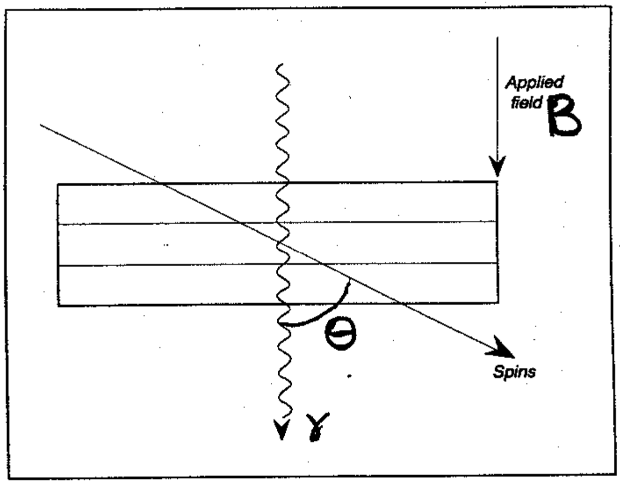


Ce/Fe multilayers

Change of Fe moment orientation θ with Fe layer thickness at 4.2K



Applied field geometry



Anisotropy energy E given by

$$E = K\sin^2\theta - \tfrac{1}{2}\mu_0 M^2 \sin^2\theta - \mu_0 M$$

↓ intrinsic anisotropy energy

↓ shape anisotropy energy

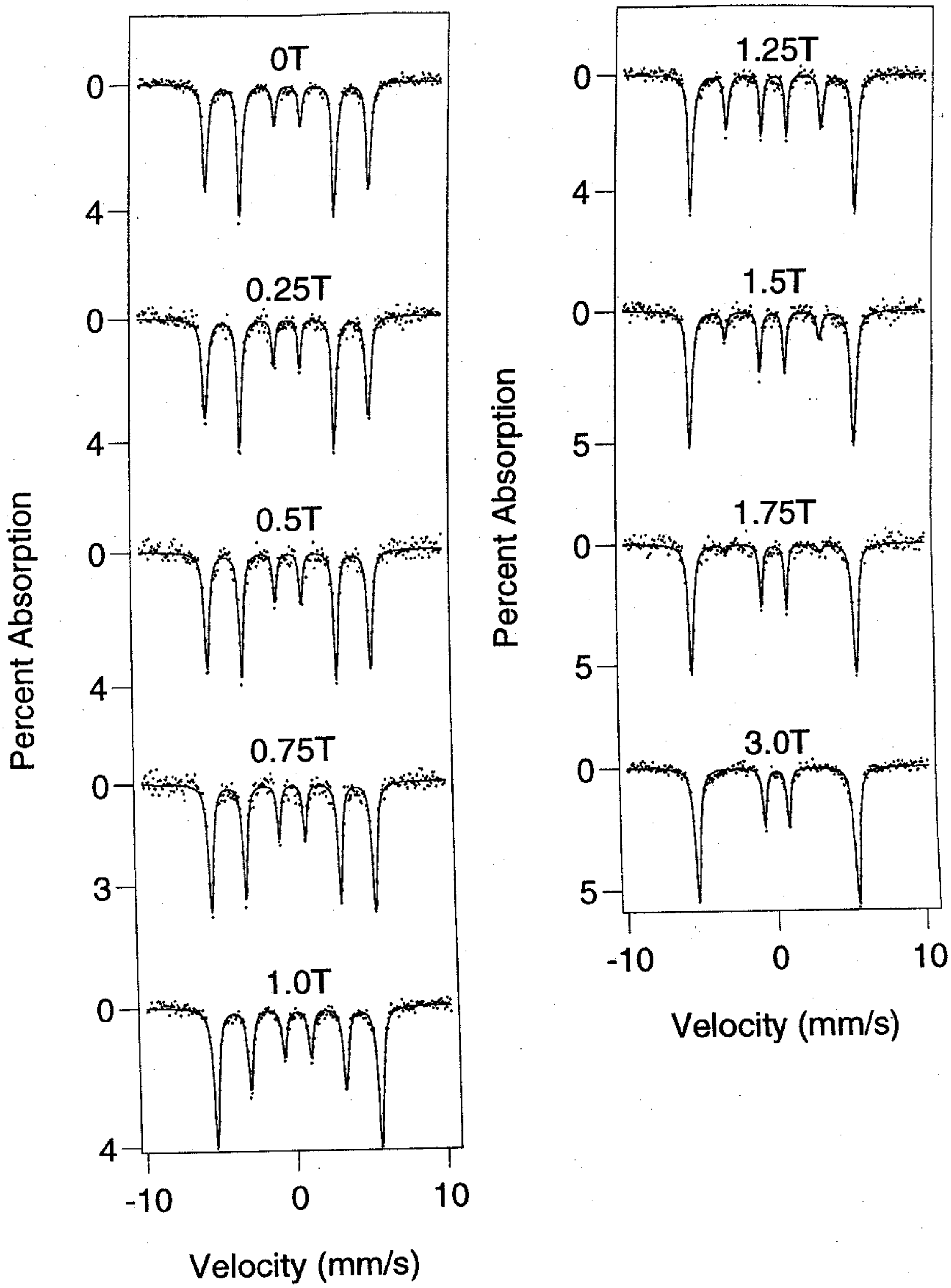
↓ applied field energy

gives equilibrium angle θ from

$$\cos\theta = \frac{MB}{\mu_0 M^2 - 2K}$$

$[Ce(20Å)/Fe(40Å)]_{50}$ multilayer

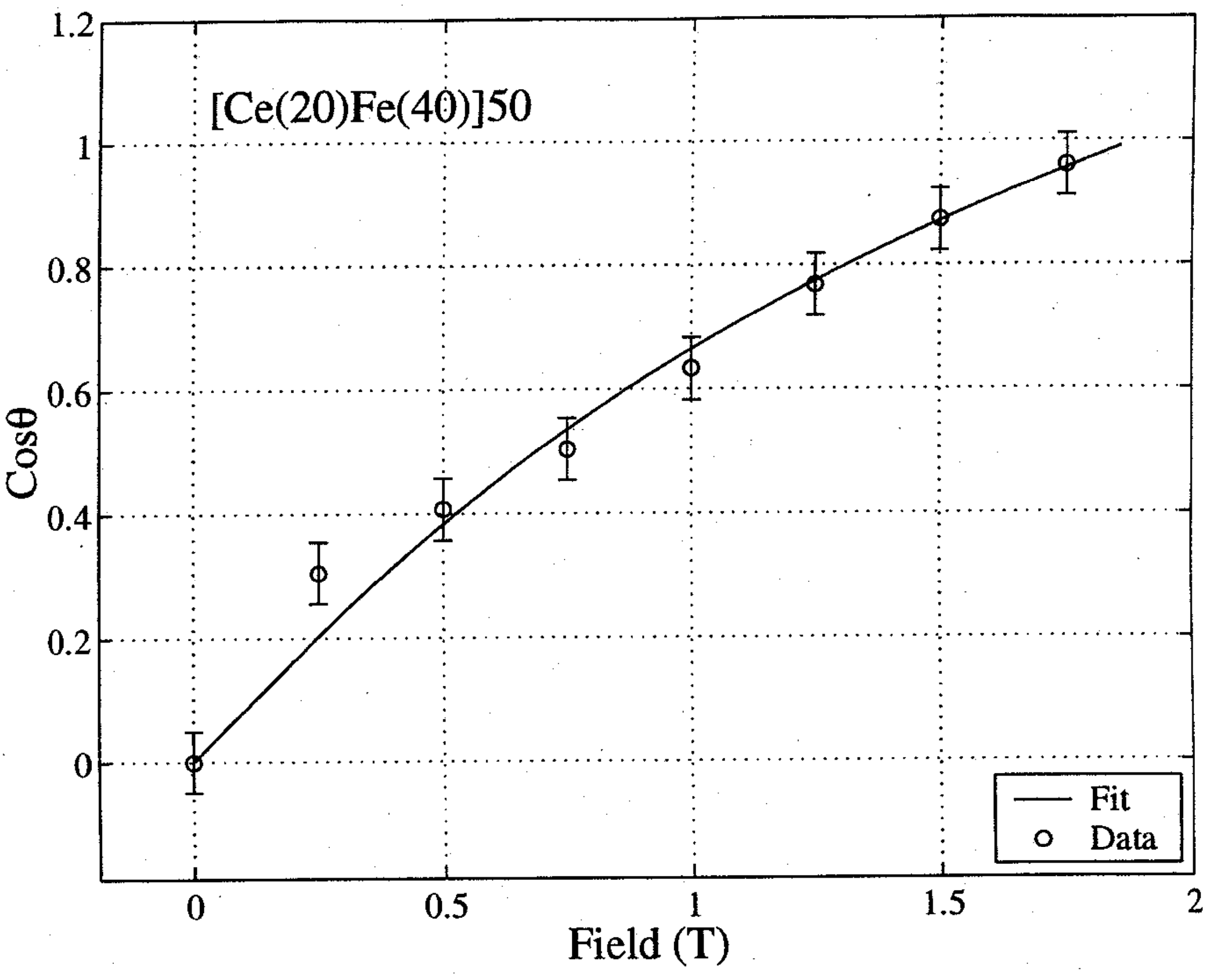
Change of Fe moment orientation with applied field at 4.2K



Fe moment orientation, θ, related to magnetization, M, applied field, B and anisotropy energy K as:

$$\text{Cos}\theta = \frac{MB}{(\mu_0 M^2 - 2K)}$$

Evaluate K for multilayer

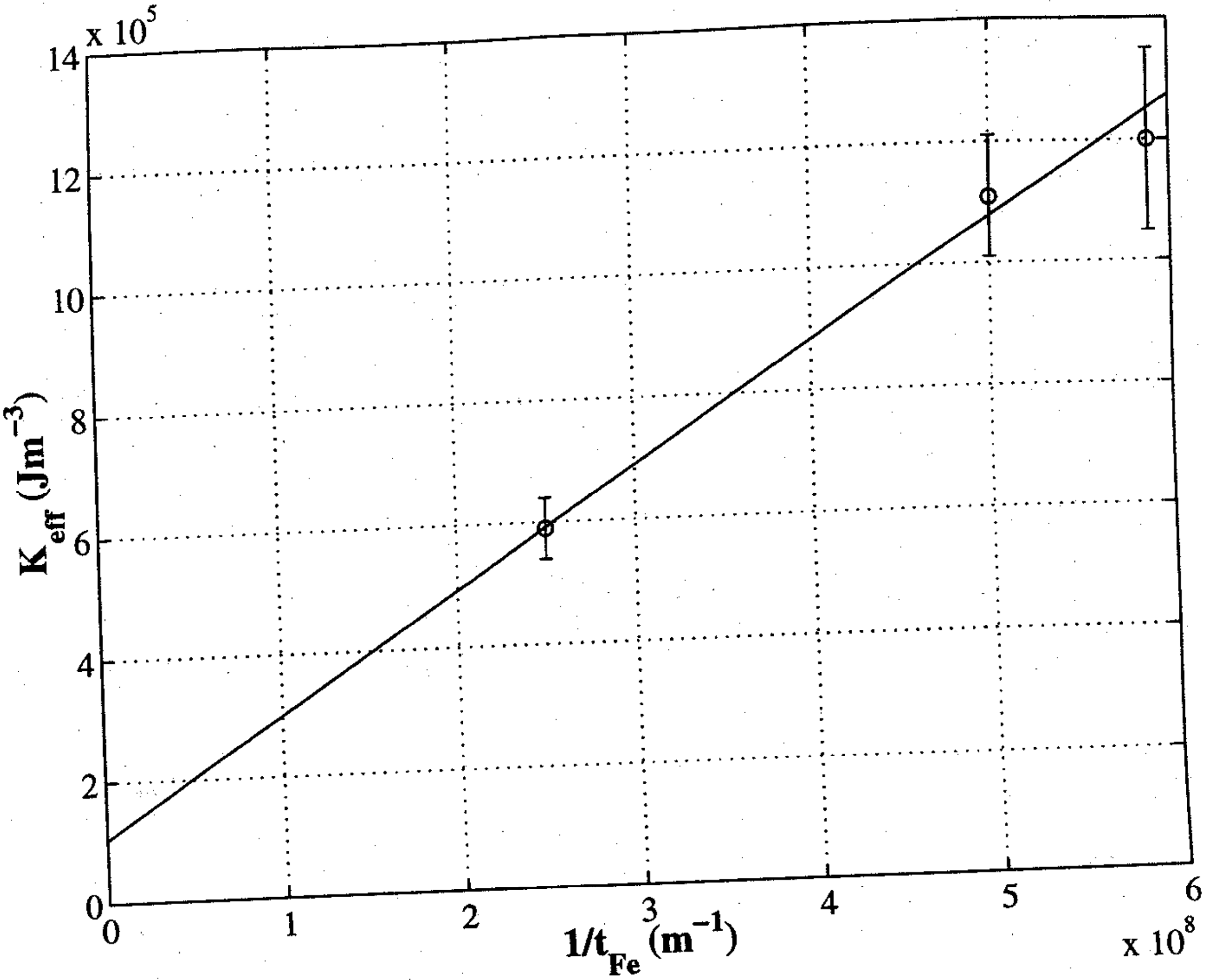


K split into K^{Xtal} (vol) and K_S(interface)

$$K = K^{Xtal} + 2K_S/t$$

Where t is the magnetic layer thickness

Plot of K versus 1/t gives K^{Xtal} and K_S



K_S values for Ce/Fe (and Ce/FeCoV)

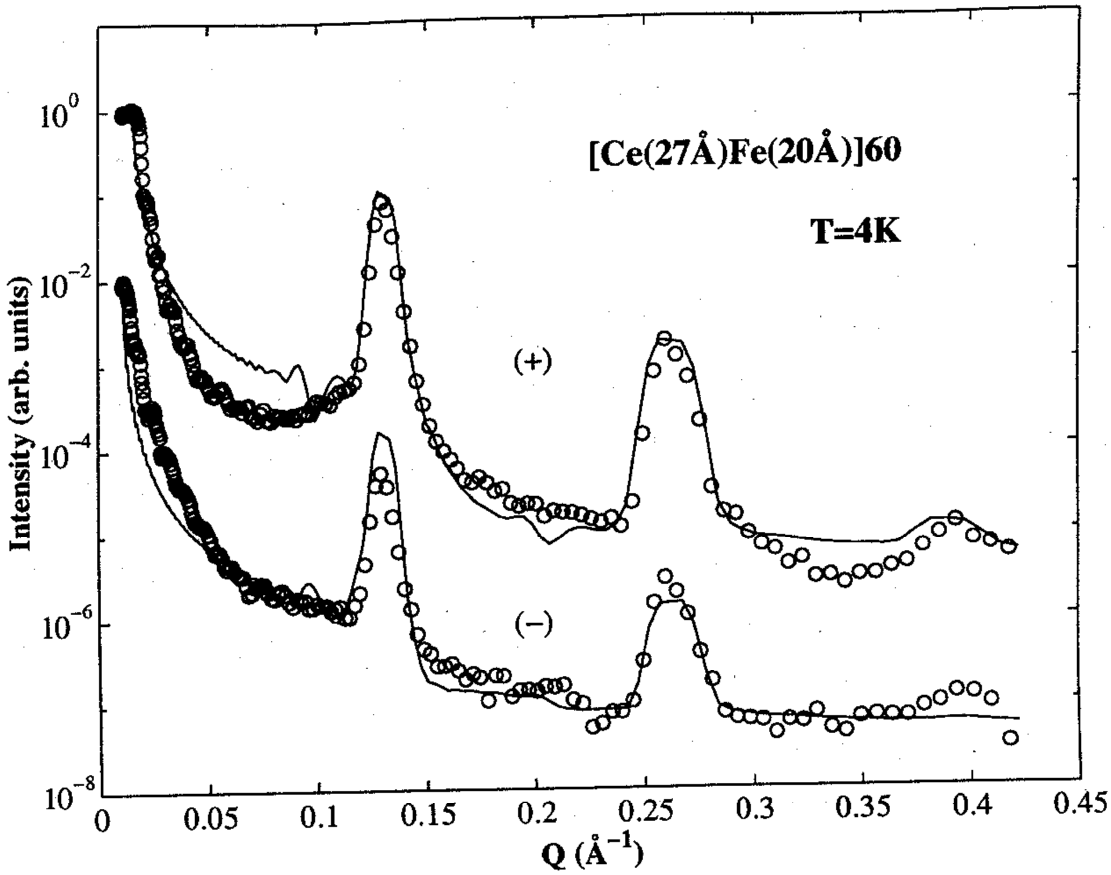
	$K_S(mJm^{-2})$
Ce/Fe	0.98 ±0.15
Ce/FeCoV	1.40±0.10

These are among largest (+ve) K_S values for any interface

$$K^{Xtal}(vol) = 1.1 \pm 1.2 \times 10^5\ Jm^{-3}$$

Magnetic moment on Ce layers?

Polarised Neutron Reflectivity – magnetic profile normal to layers



Layer	Thickness (Å)	Roughness (Å)	Number Density (m^{-3}) x10^{28}	Nuclear Scattering Length (Å) x10^{-5}	Magnetic moment (μ_B)
Ce	29 ±3	4 ±1	2.44	4.84	0 ±0.3
Fe	20 ±3	4 ±1	8.5	9.45	1.6 ±0.2
Sub (Si)	-	2 ±1	5.0	4.15	0 ±0.3

Fabrication.

- UHV ~$1*10^{-11}$ mbar.
- 2 guns, sputtering ~$1*10^{-2}$ mbar Ar.
- Limited control of sputtering rate.
- ~48hrs to produce 2 samples.
- Usual to have 3 guns.
- Four different types of multilayer have been produced, Ce/Nb, Gd/Fe, U/Nb and U/Fe.
- All U/Fe samples sputtered on glass substrates with Fe top layers to stop U oxidisation.

Samples Made.

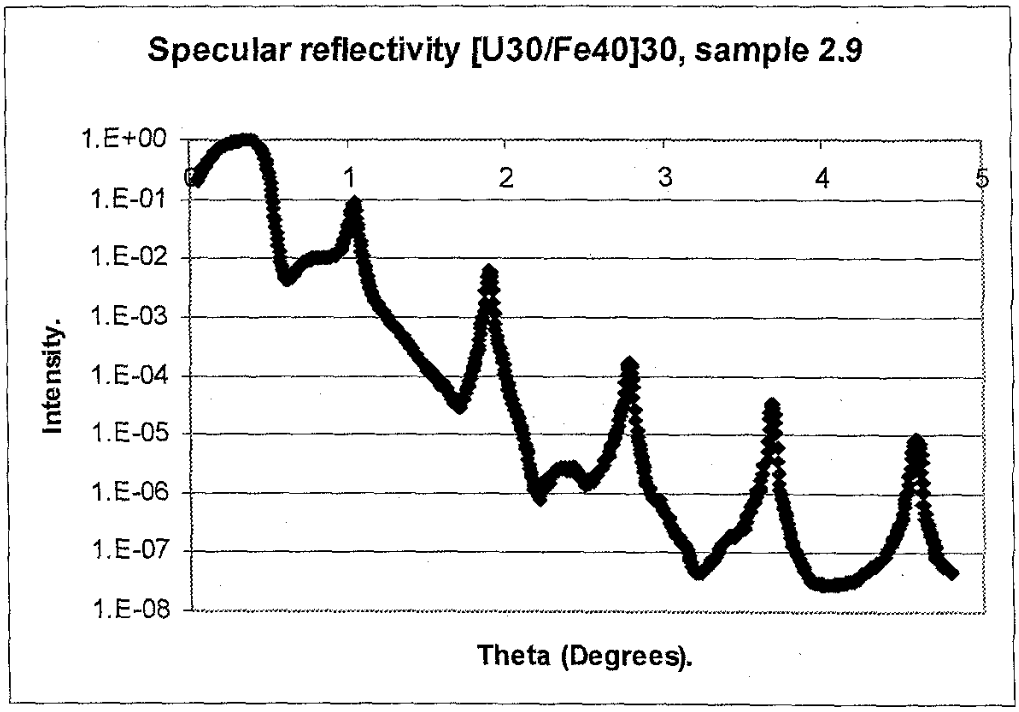
U thickness' 21-101Å

Fe thickness' 30-143Å

Bilayers 10-31

Nominal Thickness.	Sample No.	Room Temp.	Low Temp (5-7K)
$[U_{40}/Fe_{60}]_{10}$	2.1	Yes.	
$[U_{42}/Fe_{56}]_{11}$	2.2		
$[U_{101}/Fe_{100}]_{20}$	2.3		
$[U_{70}/Fe_{143}]_{21}$	2.4		
$[U_{101}/Fe_{60}]_{20}$	2.5	Yes.	Yes.
$[U_{40}/Fe_{143}]_{21}$	2.6		Yes.
$[U_{80}/Fe_{60}]_{20}$	2.7	Yes.	
$[U_{42}/Fe_{113}]_{21}$	2.8	Yes.	Yes.
$[U_{30}/Fe_{40}]_{30}$	2.9		Yes.
$[U_{28}/Fe_{43}]_{31}$	2.10		
$[U_{21}/Fe_{40}]_{30}$	2.11		Yes.
$[U_{28}/Fe_{30}]_{31}$	2.12		

X-ray Reflectivity.



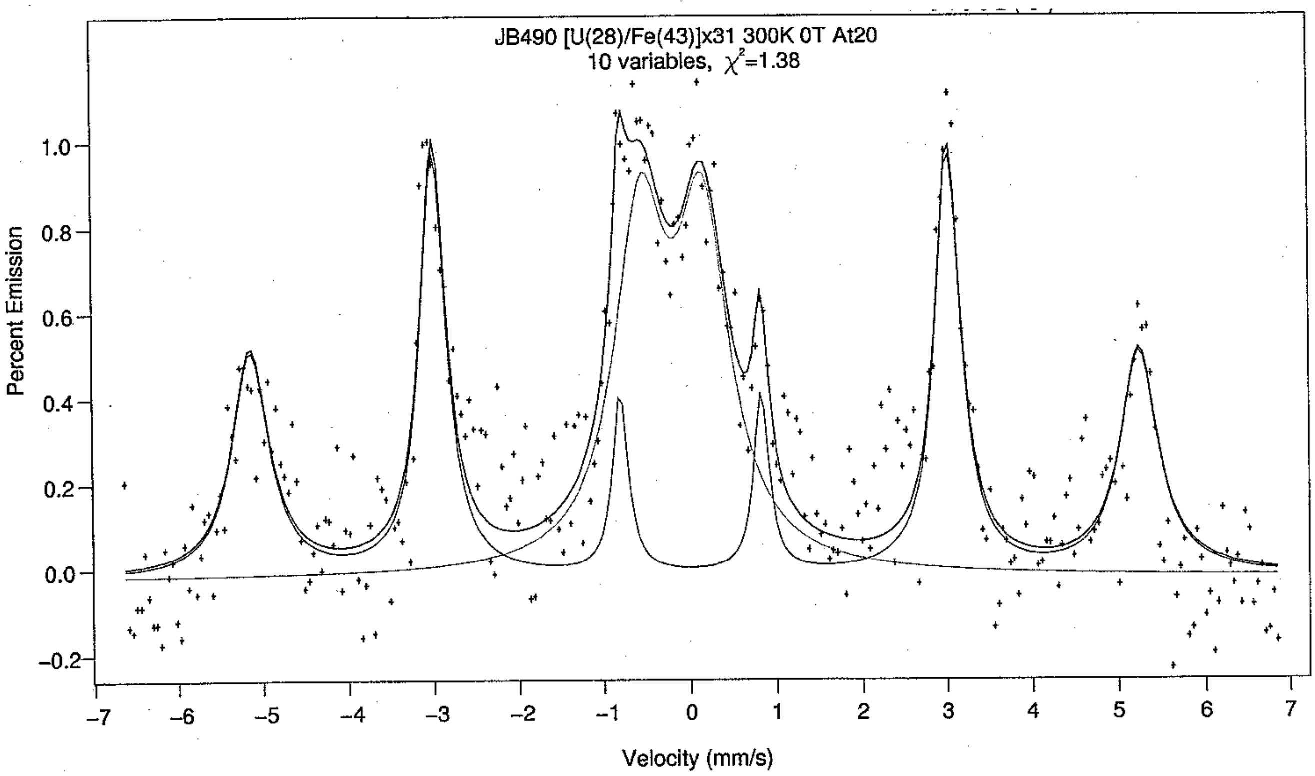
Spectra was taken using 7keV x-rays at XMaS beamline by Dr Simon Brown.

Actual composition is [U22/Fe34]30. Roughness of 3Å U and 5Å Fe.

U/Fe multilayers characterization

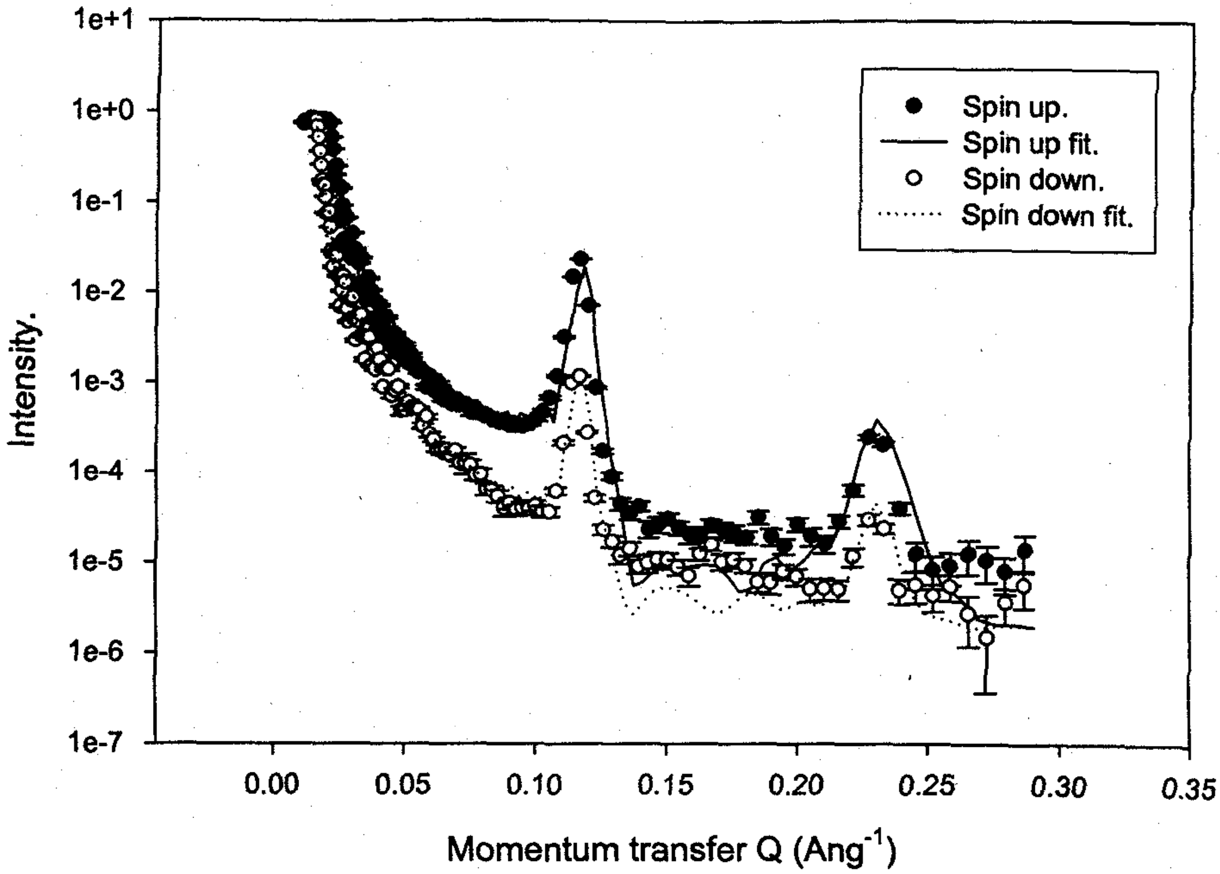
Mossbauer Spectroscopy

[U(28Å)/Fe(43Å)]$_{31}$



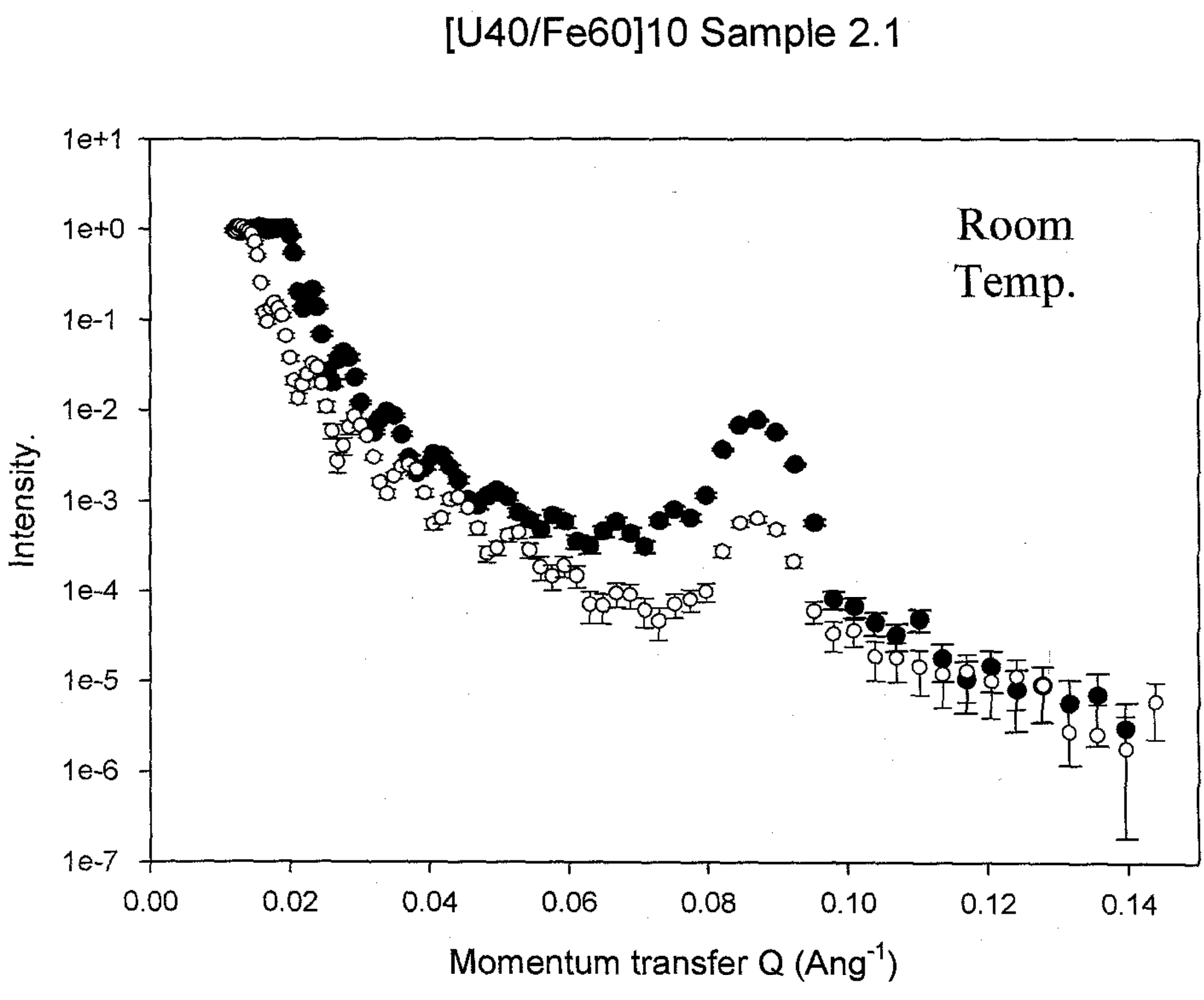
Magnetic moment on U layers?

Polarised Neutron Reflectivity
[U(30Å)/Fe(40Å)]$_{30}$



Layer	Thickness (Å)	Roughness (Å)	Moment (μ_B)
Fe	33.9	7.2	1.07
U	20.5	2.2	0
Cap (FeO)	30	4.3	2.0

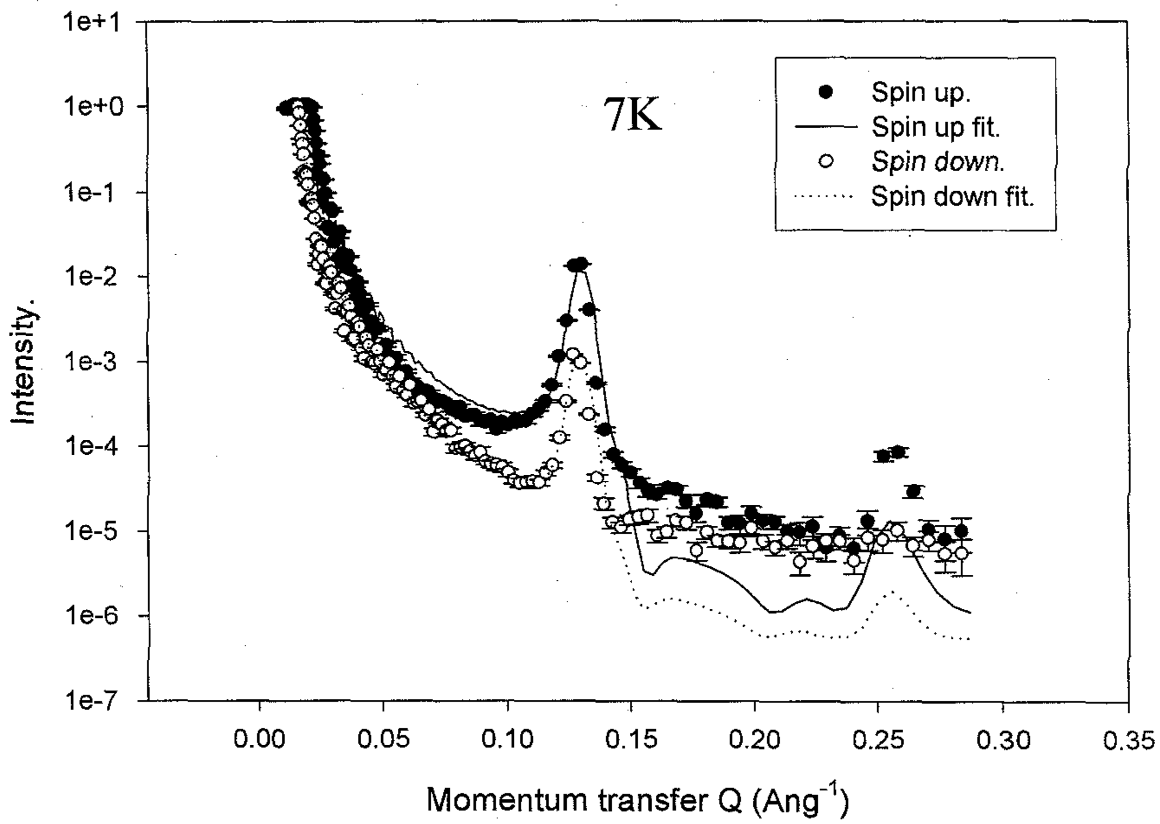
Results.



Clear Kiessig fringes due to thin multilayer, 1000Å.

Results.

[U21/Fe40]30 Sample 2.11

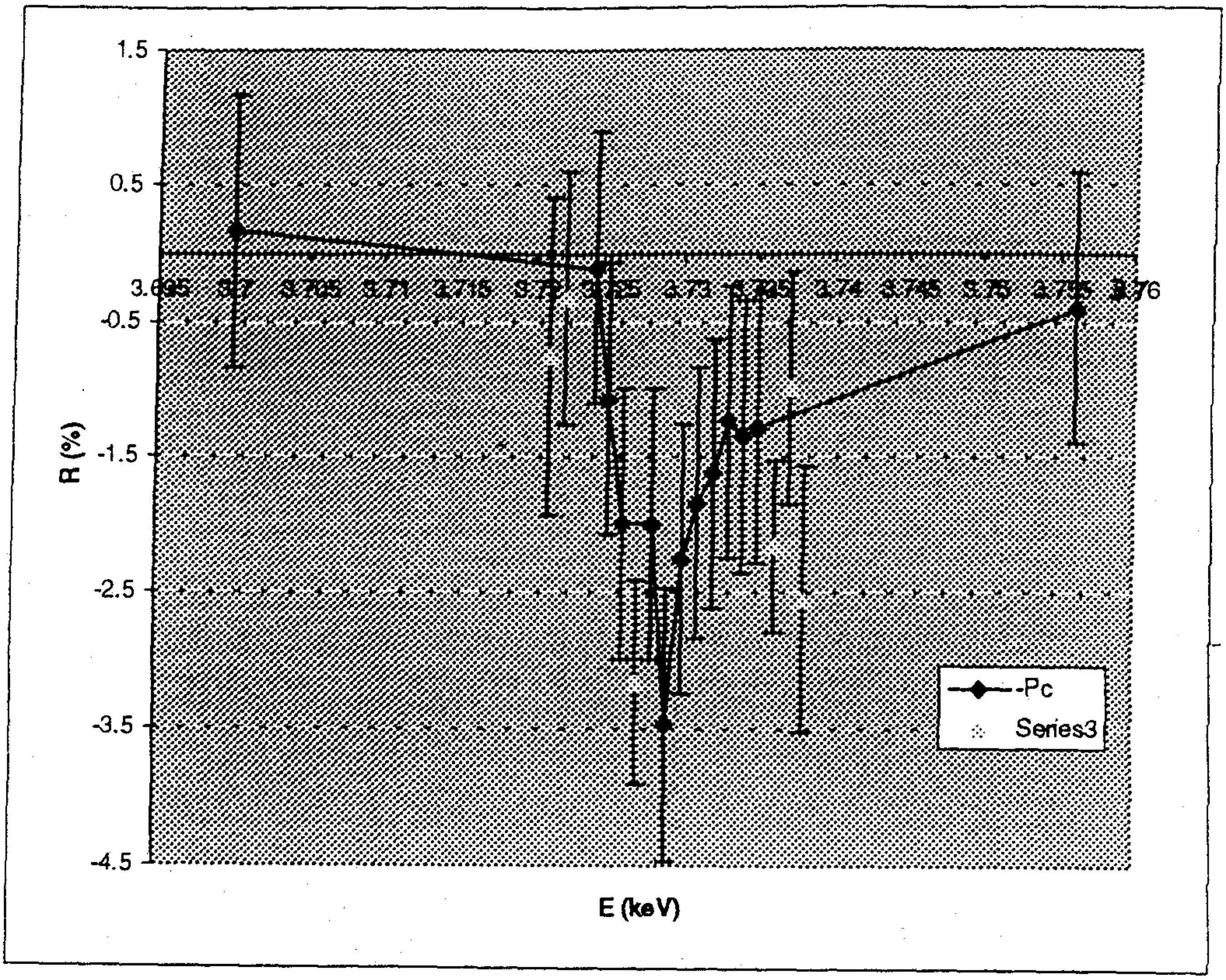


Actual composition is [U18/Fe31]30. Roughness of 7Å U and 7Å Fe.

Moment of ~1±0.2μ_B on the Fe and 0±0.3μ_B on the U.

Magnetic moment on U layers?

XMCD at M_5 edge of U



Indication of moment on U layers

Summary

1. **Large (+ve) interface anisotropy energy found in Ce/Fe favouring perpendicular moment orientation.**

2. **Linked to measurements which indicate no large moment on Ce layers.**

3. **Do U layers carry sizeable moments?**

4. **Will U/Fe multilayers show more extreme anisotropy?**