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"Magnetic Properties of Condensed Matter Investigated by Neutron Scattering and Synchrotron Radiation Techniques"

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POLARIZED NEUTRON REFLECTOMETRY OF MAGNETIC THIN FILMS AND SURFACES

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These are preliminary lecture notes, intended only for distribution to participants.

Polarized Neutron Reflectometry of Magnetic Thin Films and Surfaces

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– Magnetometry of ultrathin films and PNR
– Neutron optical principles of PNR
– Polarised neutron techniques as a vectorial magnetisation technique
– Experimental methods and PNR studies of magnetic multilayers

References

- J Penfold and R K Thomas, J. Phys. CM 2, 1369 (1990)
- S J Blundell and J A C Bland, Phys. Rev. B46, 3391 (1992)
- G P Felcher,Physica B198 **150** (1994)
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Magnetometry of ultrathin films

- $M = \mu\rho$ emu/cm^3 where ρ is the # density
- MV measured
- $V = 2 \times 10^{-8}$ cm^3 e.g. for 1 ML sample
- $M(Fe) = 1.7 \times 10^3$ emu/cm^3

Magnetometry techniques/sensitivity emu/cm^3

- VSM 10^{-5}
- SQUID 5×10^{-7}
- AGFM 5×10^{-7}
- MOKE

Magnetic moment in solids

$$\mu = \mu_B \int (n^{\uparrow}(E) - n^{\downarrow}(E))dE$$

Bohr magneton $\mu_B = 0.93 \times 10^{-20}$ emu

$\mu = gS\mu_B$ neglecting orbital moment

$\mu = g(L,S)m_z\mu_B$ J = L + S

$-J \leq m_z \leq J$

Neutron optical principles

The neutron-solid interaction is defined by the coherent optical potential for medium i

$$V_i = \frac{h^2}{2\pi m_n}\rho_i b_i - \mu_n . B_i$$

m_n = neutron mass, ρ_i = atomic density, b_i = bound coherent neutron scattering length of the material; $\boldsymbol{\mu}_n$ = neutron magnetic moment, B_i is the magnetic induction

Neutron optical principles

The neutron magnetic moment is related to the Pauli spin operator via:

$$\mu_{\mathrm{n}} = \gamma \mu_{\mathrm{N}} \sigma_{\mathrm{n}}$$

$\gamma = -1.913$, μ_N is the nuclear magneton,
m_p is the proton mass and μ_B is the Bohr magneton.

Fermi potential and Zeeman interaction are comparable + weak: no multiple scattering, high magnetic contrast

Neutron optical principles

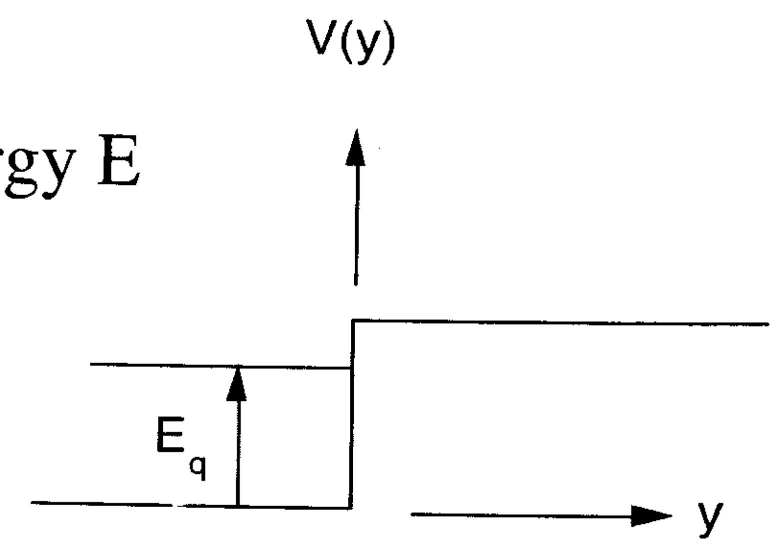
and the perpendicular wavevector in j is:

$$q_j = \sqrt{q_{i^2} + q_{ci^2} - q_{cj^2}}$$

from conservation of total energy E

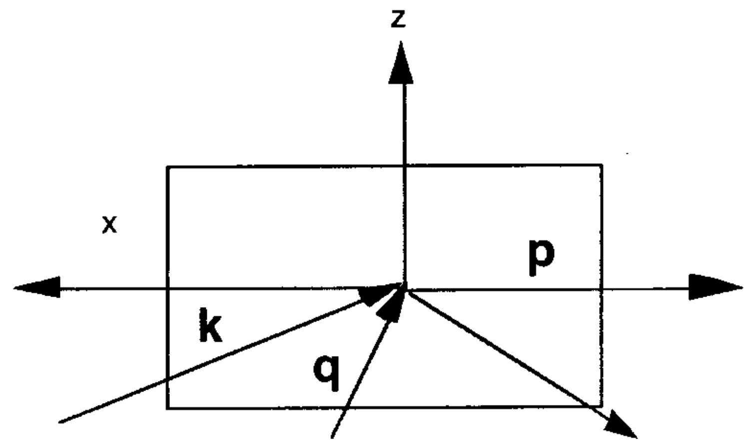
with a critical wavevector:

$$q_{ci^2} = \frac{8\pi^2 m_n}{h^2} V_i \, .$$



1D Schrodinger equation

$$[-\frac{h^2\nabla^2}{8\pi^2 m_n} + \mathrm{V_i}]\Psi(\mathrm{y}) = \mathrm{E}\Psi(\mathrm{y})$$



$$\Psi(\mathrm{y}) = \psi(\mathrm{y})\exp(\mathrm{ip}.\rho)$$

$$\psi_i(\mathrm{y}) = \mathrm{a_i}\exp(\mathrm{iq_i y}) + \mathrm{b_i}\exp(-\mathrm{iq_i y})$$

where a_i, b_i are spin dependent coefficients describing the wave in the medium i bounded at $y = 0$

Neutron optical principles

For total reflection in terms of refractive index n:

$$q_i^2 < q_{cj}^2 - q_{ci}^2 = k^2 \sin^2\theta_{cij}$$

$$n_{ij} = k_i / k_j = n_i / n_j$$

$$\sin^2\theta_{cij} = 1 - n_{ij}^2$$

For neutrons the vacuum is denser than the solid and so total reflection occurs in the vacuum

1D Schrodinger equation

By matching the wavefunction and its derivative With respect to y can obtain a,b coefficients. For a simple interface bounding i,j at y_0 we obtain:

$$\psi_i(y - y_o) = a_i \exp(iq_i(y - y_o)) + b_i \exp(-iq_i(y - y_0))$$

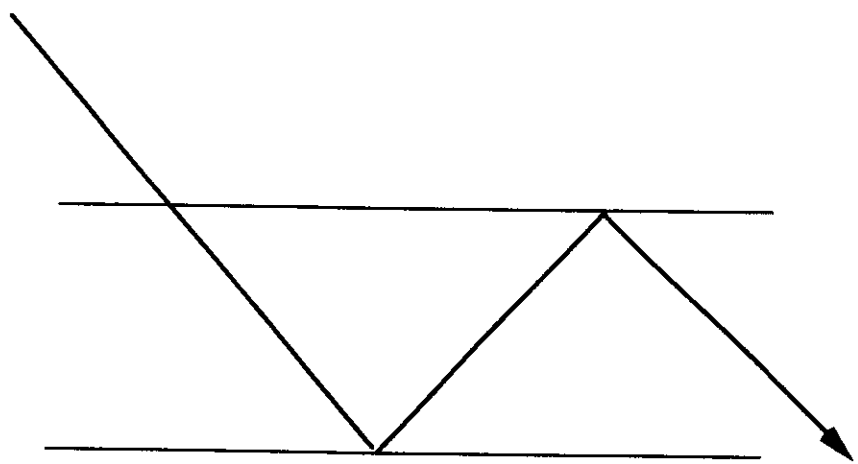
$$r_{ij} = \frac{q_i - q_j}{q_i + q_j}$$

$$t_{ij} = \frac{2q_i}{q_i + q_j},$$

$$\boxed{\begin{array}{l} a_i = 1, \;\; b_i = r_{ij} \\ a_j = 0, \;\; b_j = t_{ij} \end{array}}$$

Reflection from a 3 layer system

$$r_{123} = r_{12} + t_{12}\, r_{23}\, t_{21}\, \phi_2 \left(1 + (r_{21}\, r_{23}\, \phi_2) + (r_{21}\, r_{23}\, \phi_2)^2 + \ldots\right)$$



$$r_{123} = \frac{r_{12} + r_{23}\, \phi_2}{1 + r_{12}\, r_{23}\phi_2}$$

Magnetic interfaces

$$\boldsymbol{B}_i = \mu_o (\boldsymbol{H} + \boldsymbol{M}_i)$$

components of $\boldsymbol{H}$ parallel to the (x,y) plane and the normal component of $\boldsymbol{B}$ are continuous across interface.

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$$\xi_{ij} = \frac{1}{\mathrm{E}} (V_{jn} - V_{in} - \mu_o \boldsymbol{\mu_n}.(\boldsymbol{M}_{j//} - \boldsymbol{M}_{i//}))$$

$$\sin^2\theta_{\mathrm{cij}} = \zeta_{\mathrm{ij}}. \qquad \xi^{\pm\mathrm{ij}} = \frac{4\pi}{K^2}(\rho_j b^{\pm_j} - \rho_i b^{\pm_i})$$

$b^{\pm}{}_i = b_i \pm 2cs_i c = \mu_B \mu_n = 0.2695 \times 10^{-15}$m

s_i = moment per atom in Bohr magnetons

Overlayer enhancement

$$F = \frac{R^{+}}{R^{-}} \qquad S = \frac{R^{+} - R^{-}}{R^{+} + R^{-}}$$

$$F = 1 + \frac{4(cs_3\rho_3)t_3q_1}{b_2\rho_2}\sin(2q_2t_2) \text{ for } q_3t_3 \ll 1$$

for covered magnetic layer

$$S = f(q)\rho_2 s_2 t_2^{\,2} \quad \text{for overlayer only}$$

Transfer matrix approach

The total wave function is a spinor with each component having forward and backwards waves

$$\Psi_{\mathrm{i}} = \begin{pmatrix} \psi_{i^+} \\ \psi_{i^-} \end{pmatrix}$$

with each each spin state of the form

$$\begin{pmatrix} a^{\pm_i} \\ b^{\pm_i} \end{pmatrix}$$

Vector magnetisation

Assume the direction of the quantisation axis changes in the plane of the film by an angle Φ_{ij} between media i and j

Need the transformation of the vector $\boldsymbol{\Psi}_i$ to $\boldsymbol{\Psi}_j$

$$\mathbf{D}_i \boldsymbol{\Psi}_i = \mathbf{R}_{ij} \mathbf{D}_j \boldsymbol{\Psi}_j:$$

where the matrix $\mathbf{D}_i$ is a 4 x 4 'refraction' matrix and where the spin rotation matrix $\mathbf{R}_{ij}$ satisfies the 4π spinor symmetry and is a function of Φ_{ij} only

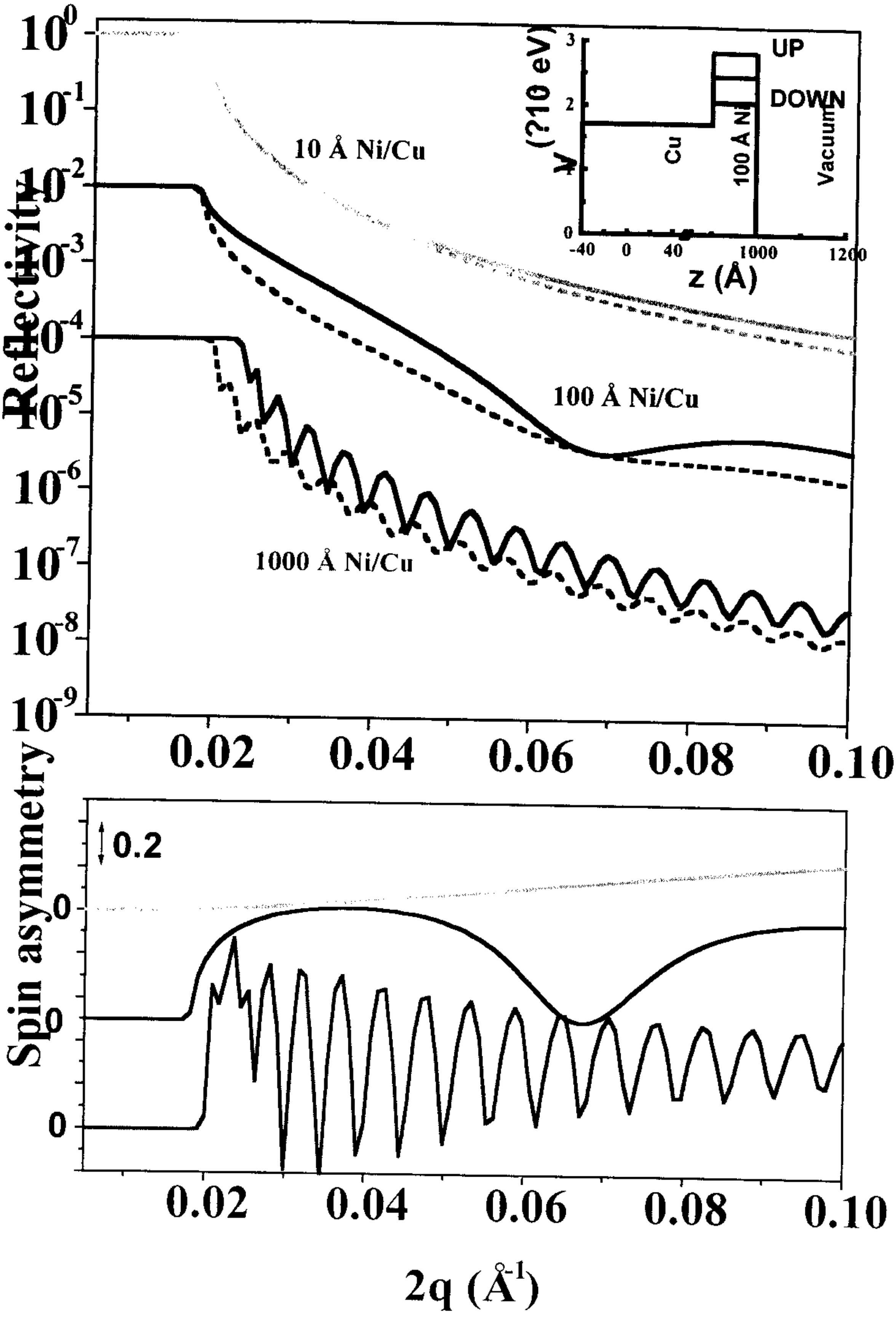
Spin reflectivity from multilayers

$$\Psi_1 = \mathrm{M}_{1\ldots\mathrm{N}}\Psi_\mathrm{N}$$

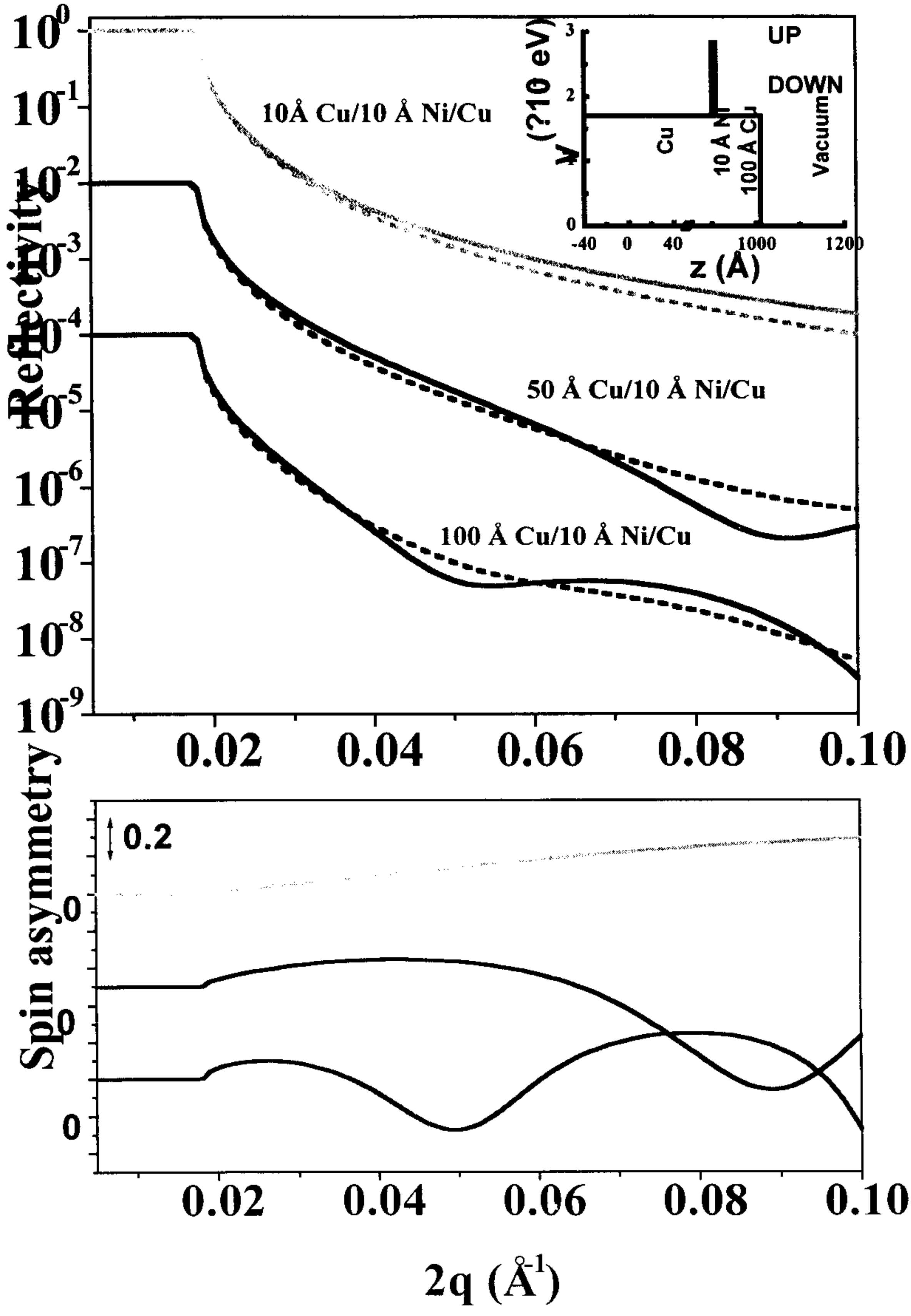
$$\Psi_1 = \begin{pmatrix} 1 \\ r^{++} \\ 0 \\ r^{+-} \end{pmatrix} \text{ and } \Psi_\mathrm{N} = \begin{pmatrix} t^{++} \\ 0 \\ t^{+-} \\ 0 \end{pmatrix}$$

$$\mathrm{M}_{1\ldots\mathrm{N}} = \mathrm{D}_1^{-1}\mathrm{R}_{1,2}\ldots\ldots\mathrm{D}_{\mathrm{N}-1}\,\mathrm{P}_{\mathrm{N}-1}\,\mathrm{D}^{-1}{}_{\mathrm{N}-1}\,\mathrm{R}_{\mathrm{N}-1,\mathrm{N}}\,\mathrm{D}_\mathrm{N}$$

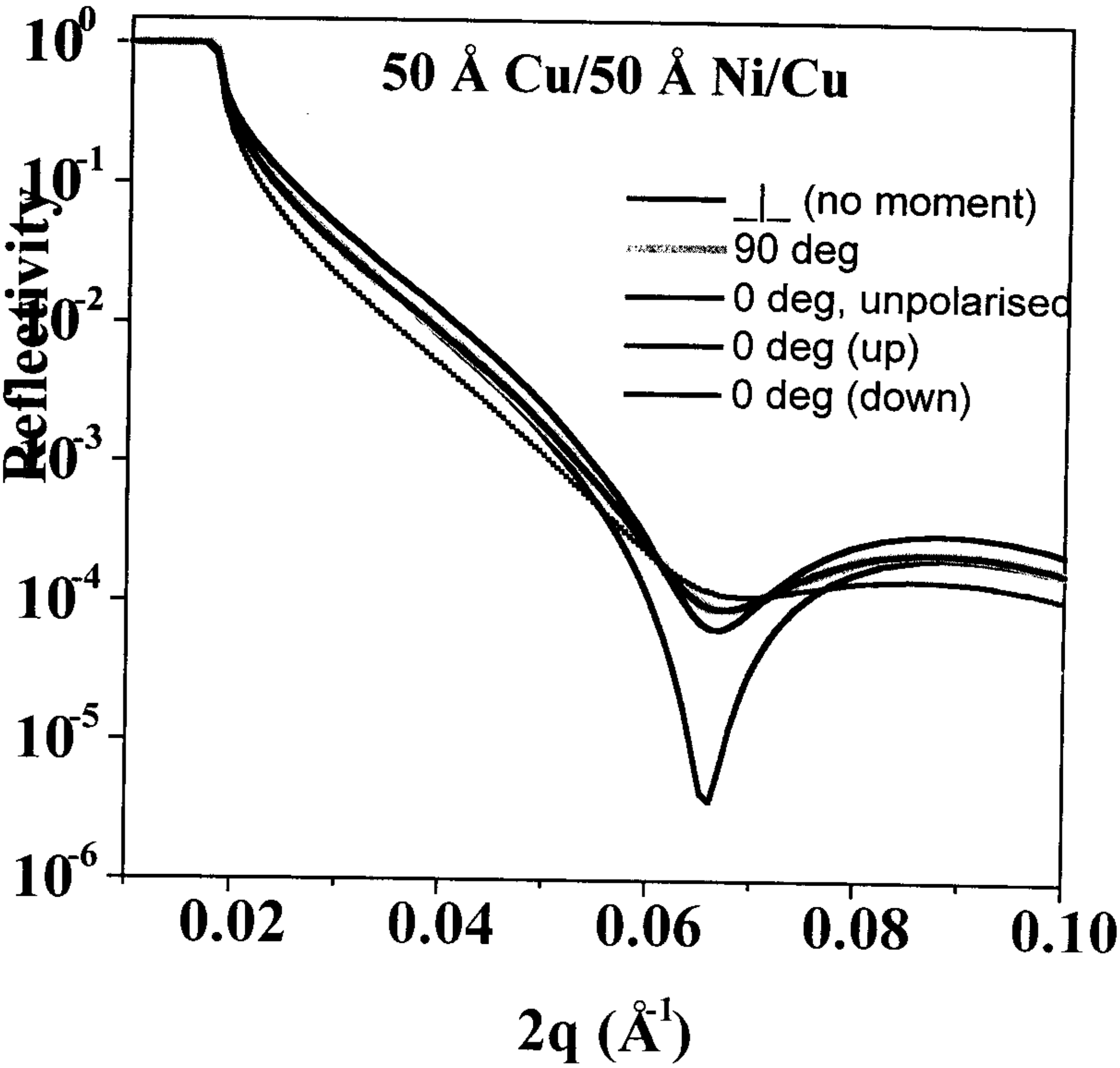
PNR spectra for different Ni thickness



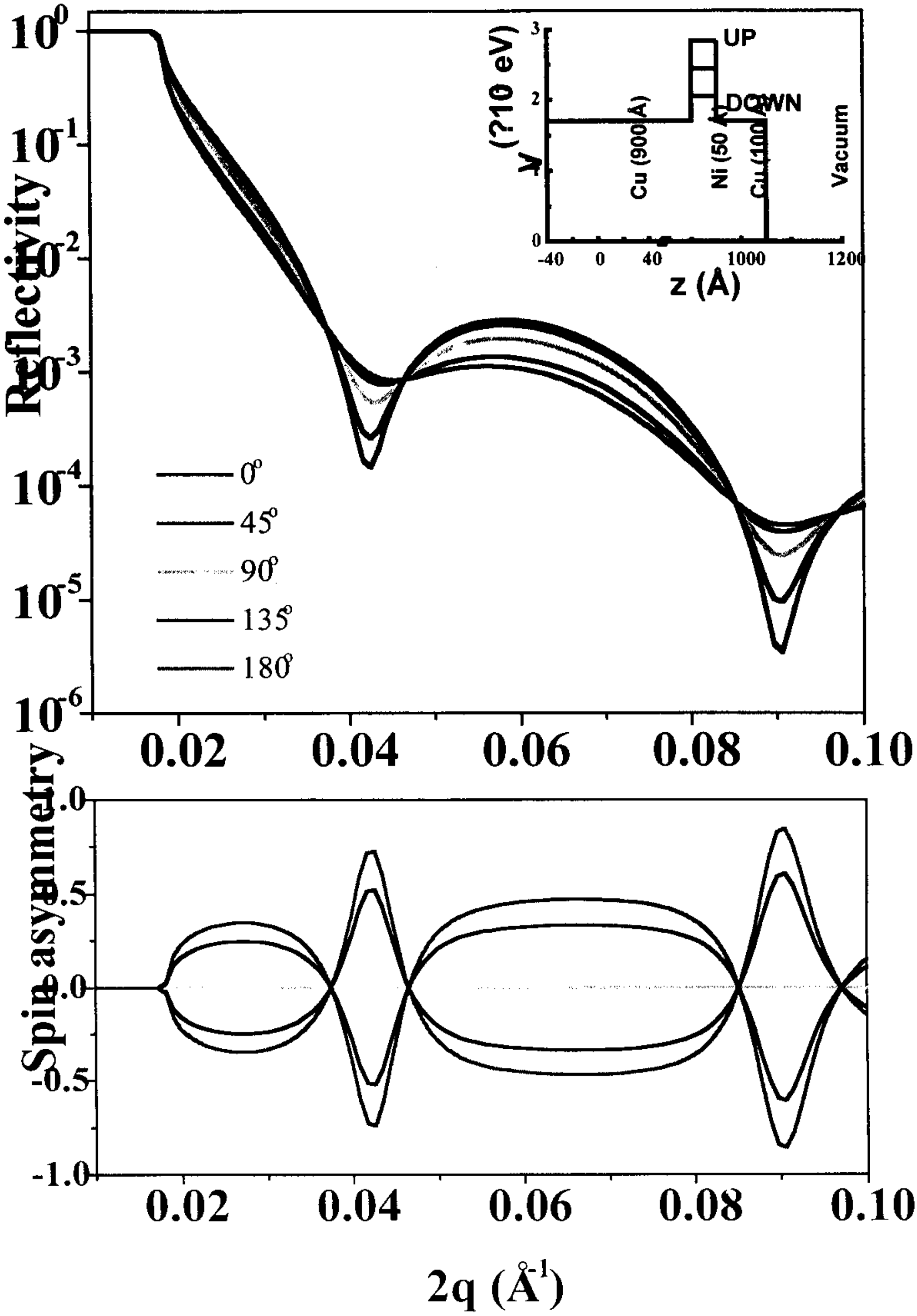
PNR spectra for different capping laye



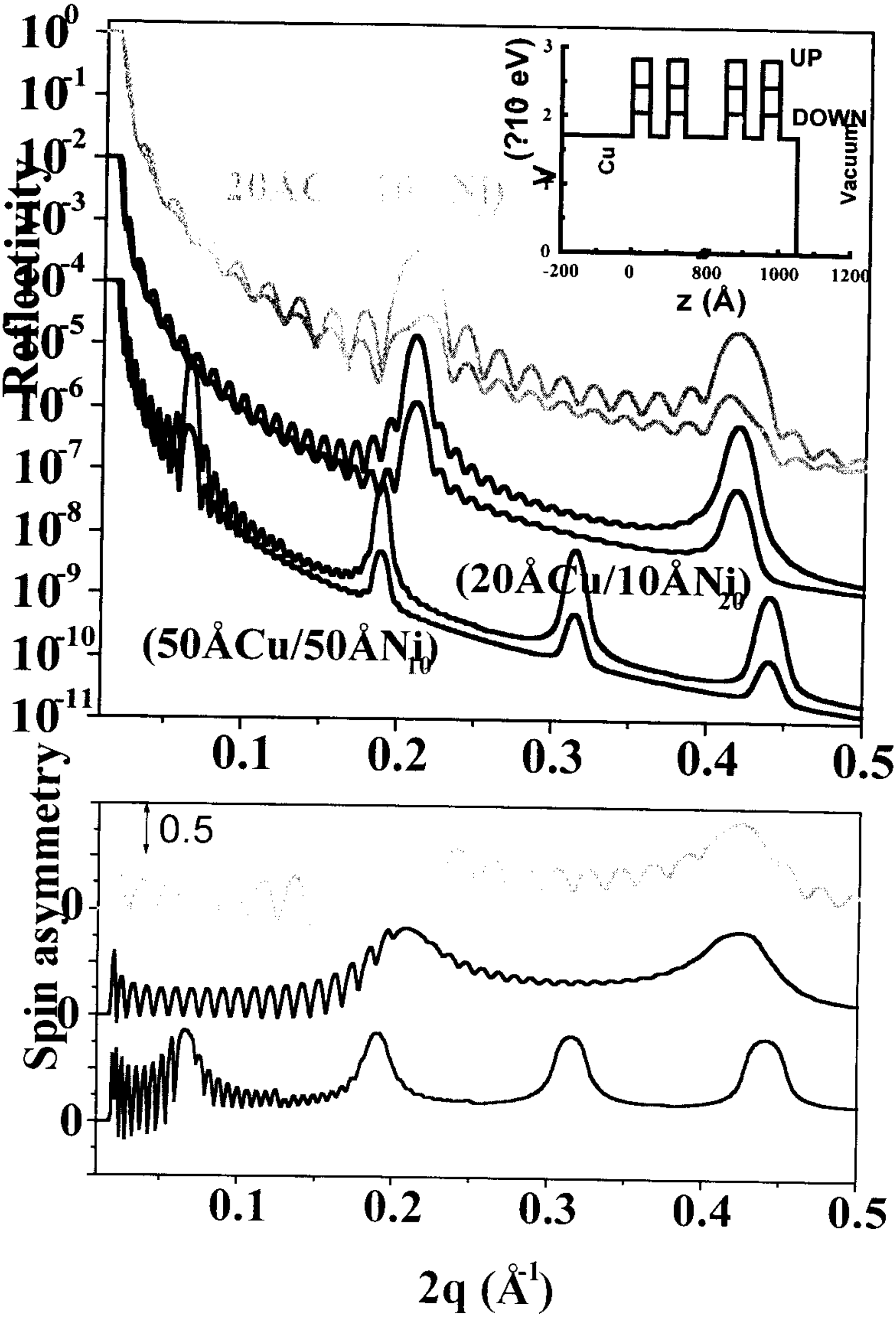
Polarised *vs* Unpolarised Neutron Reflectio



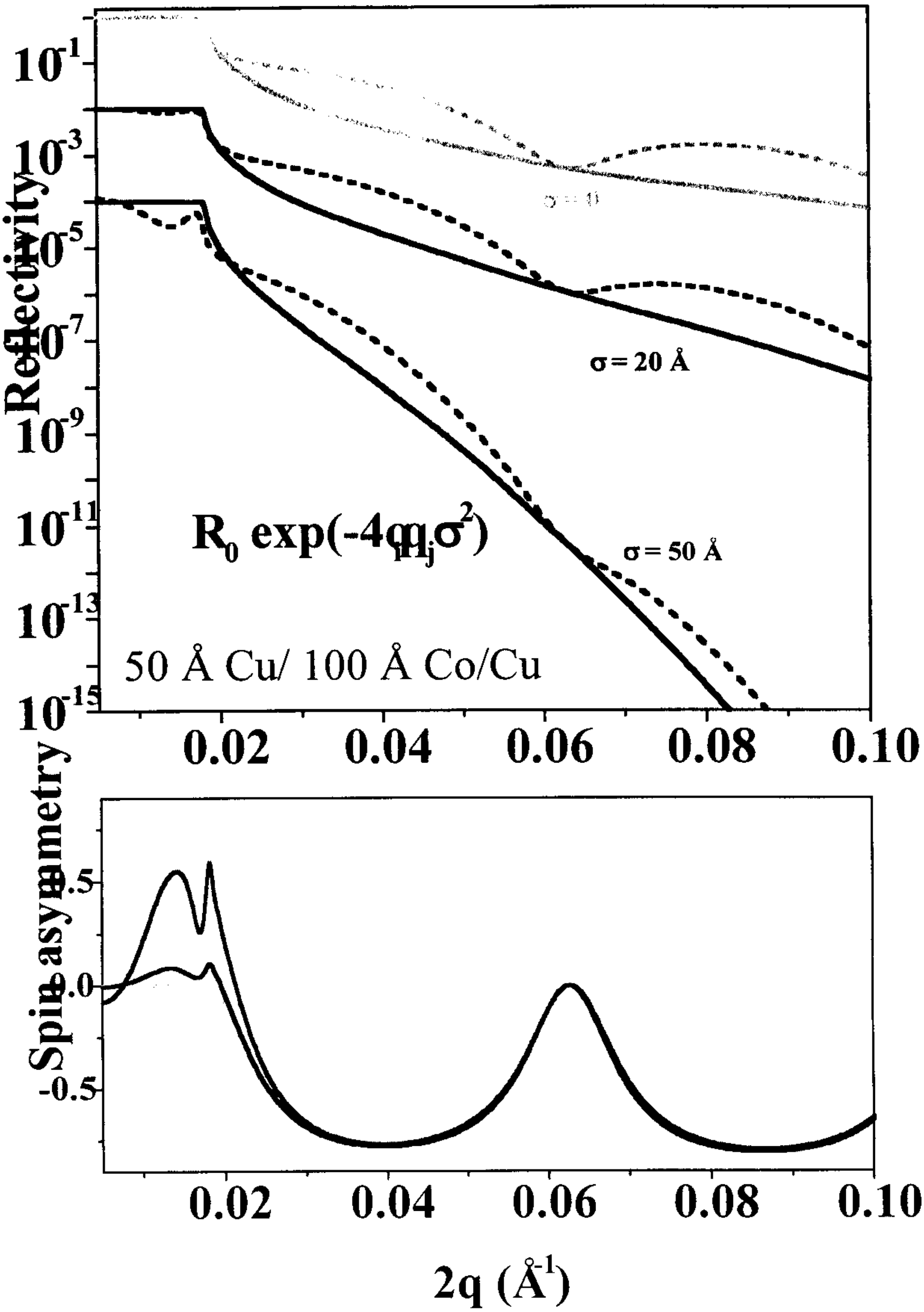
PNR spectra for various moment directio



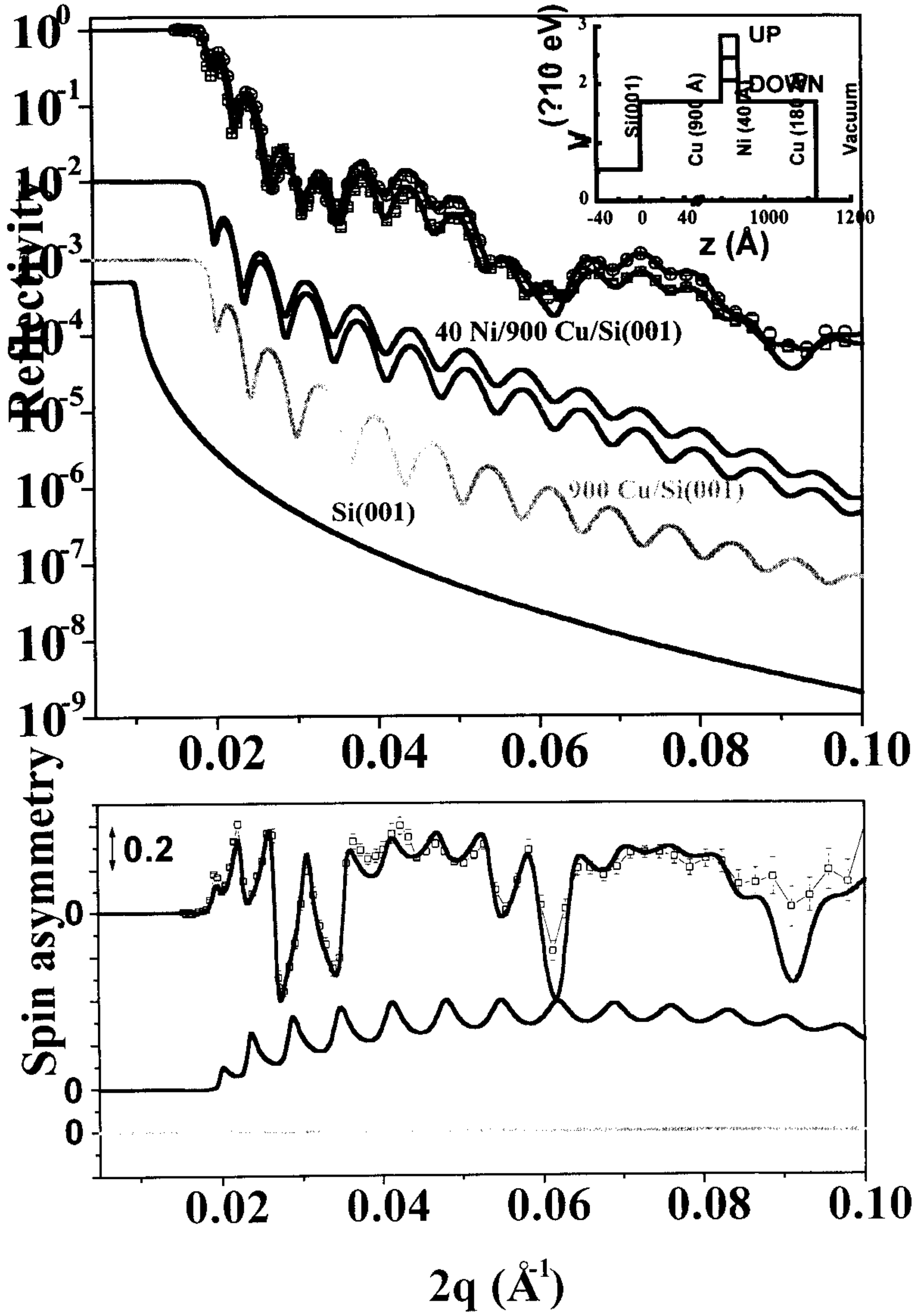
Onset of Bragg diffraction for Ni/Cu multilaye



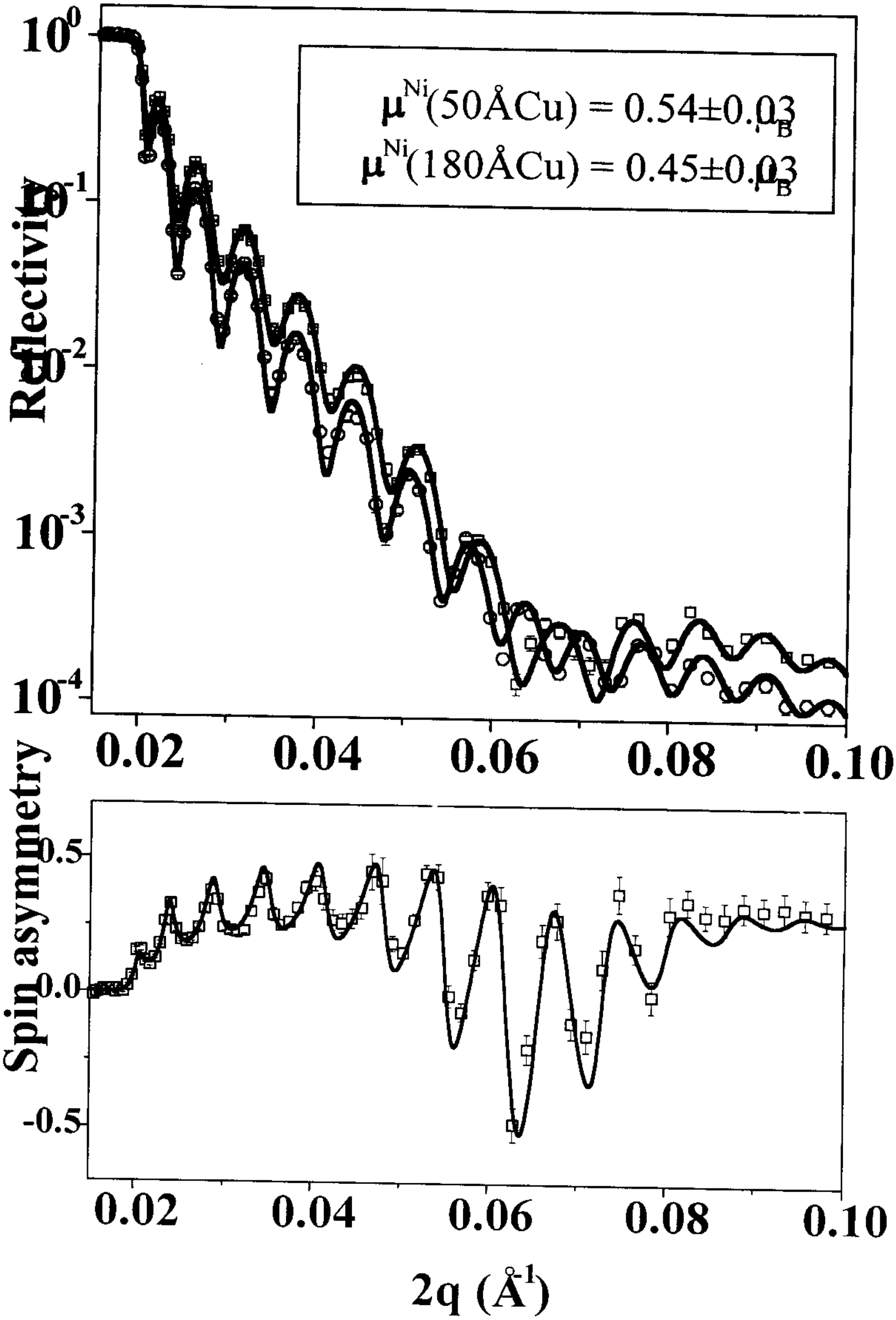
Effect of roughness on the PNR spectr



PNR for sample 180Cu/40Ni/900Cu/Si(0(



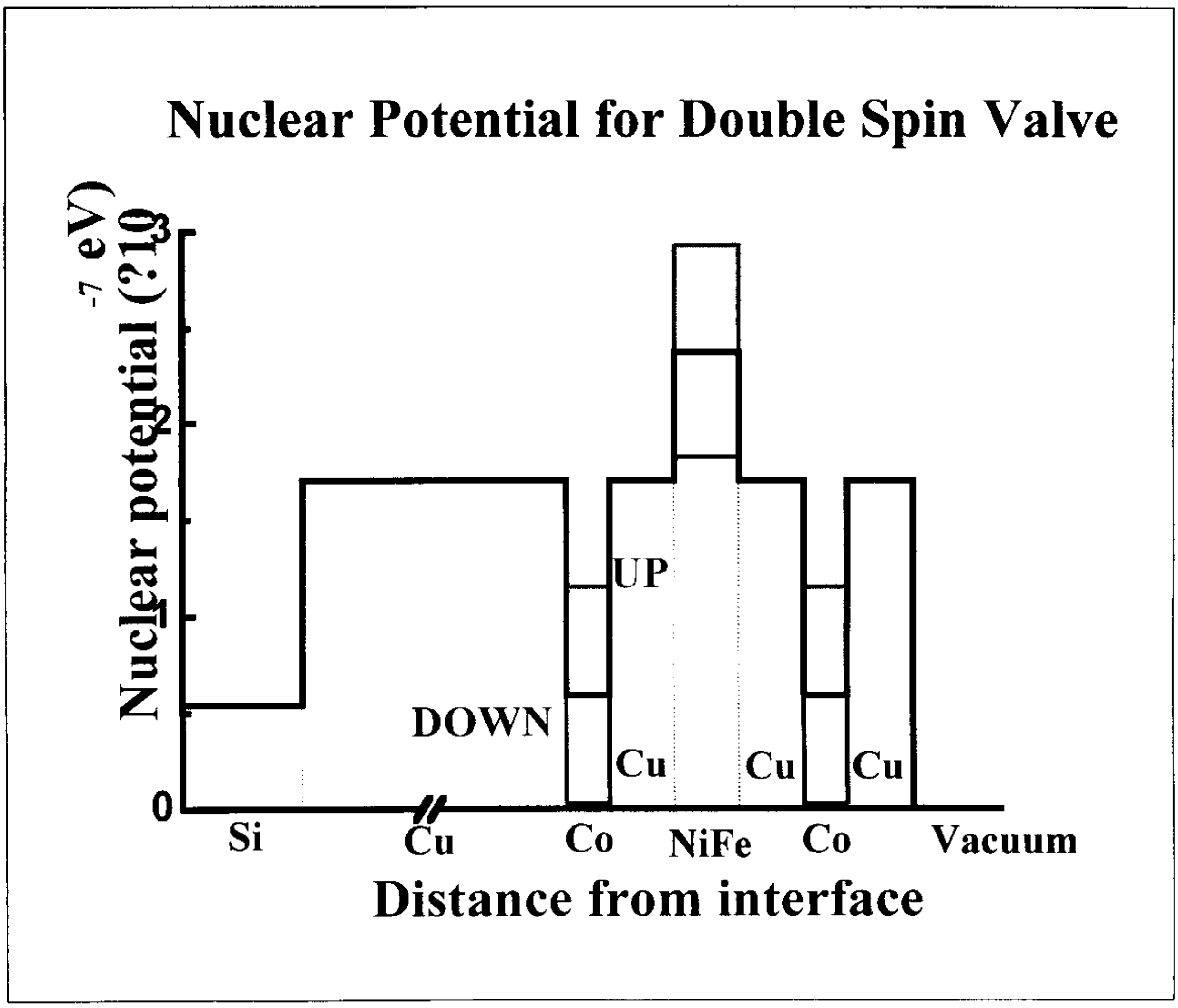
PNR for sample 50Cu/40Ni/900Cu/Si(00

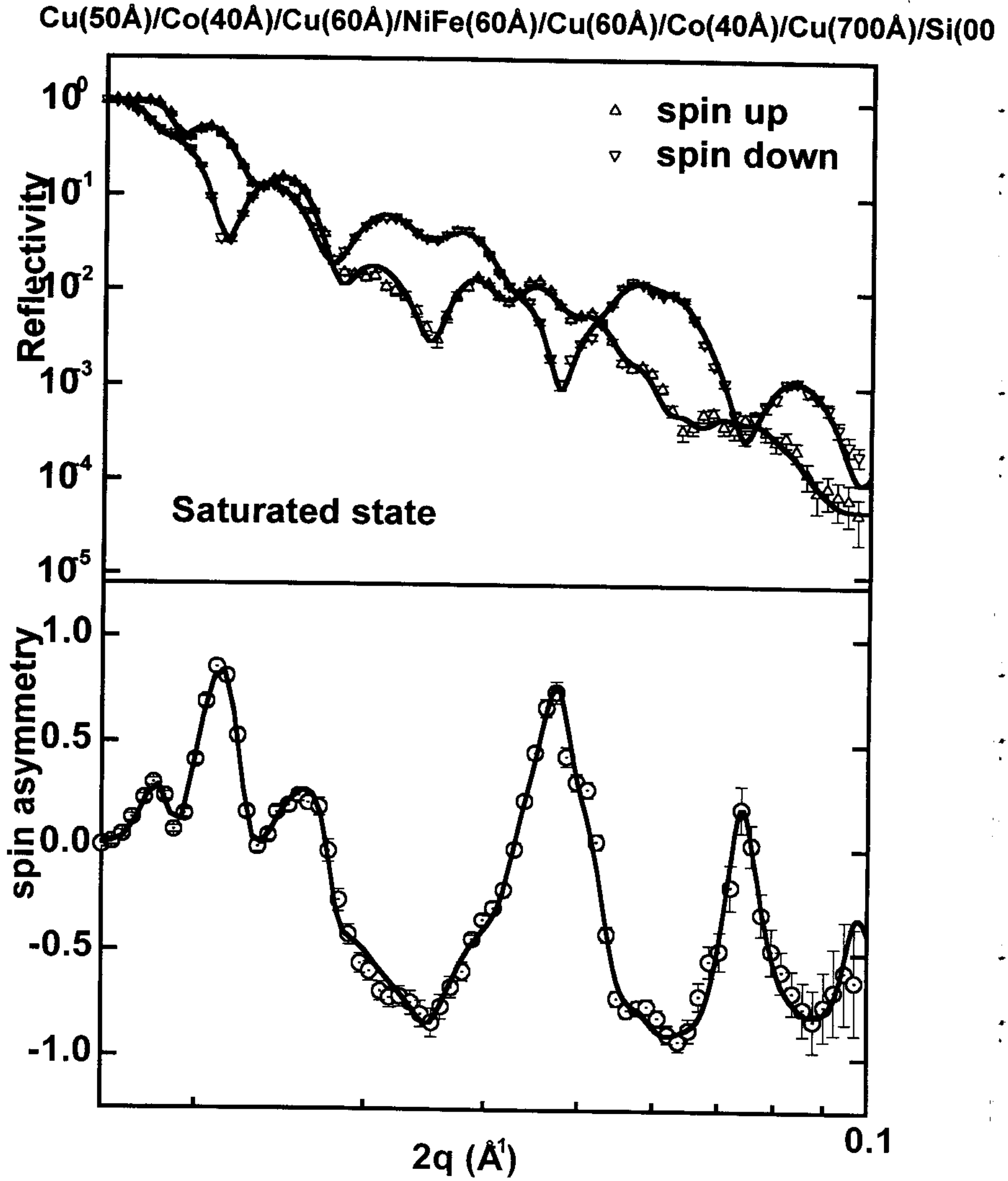


Neutron Potential at layer α

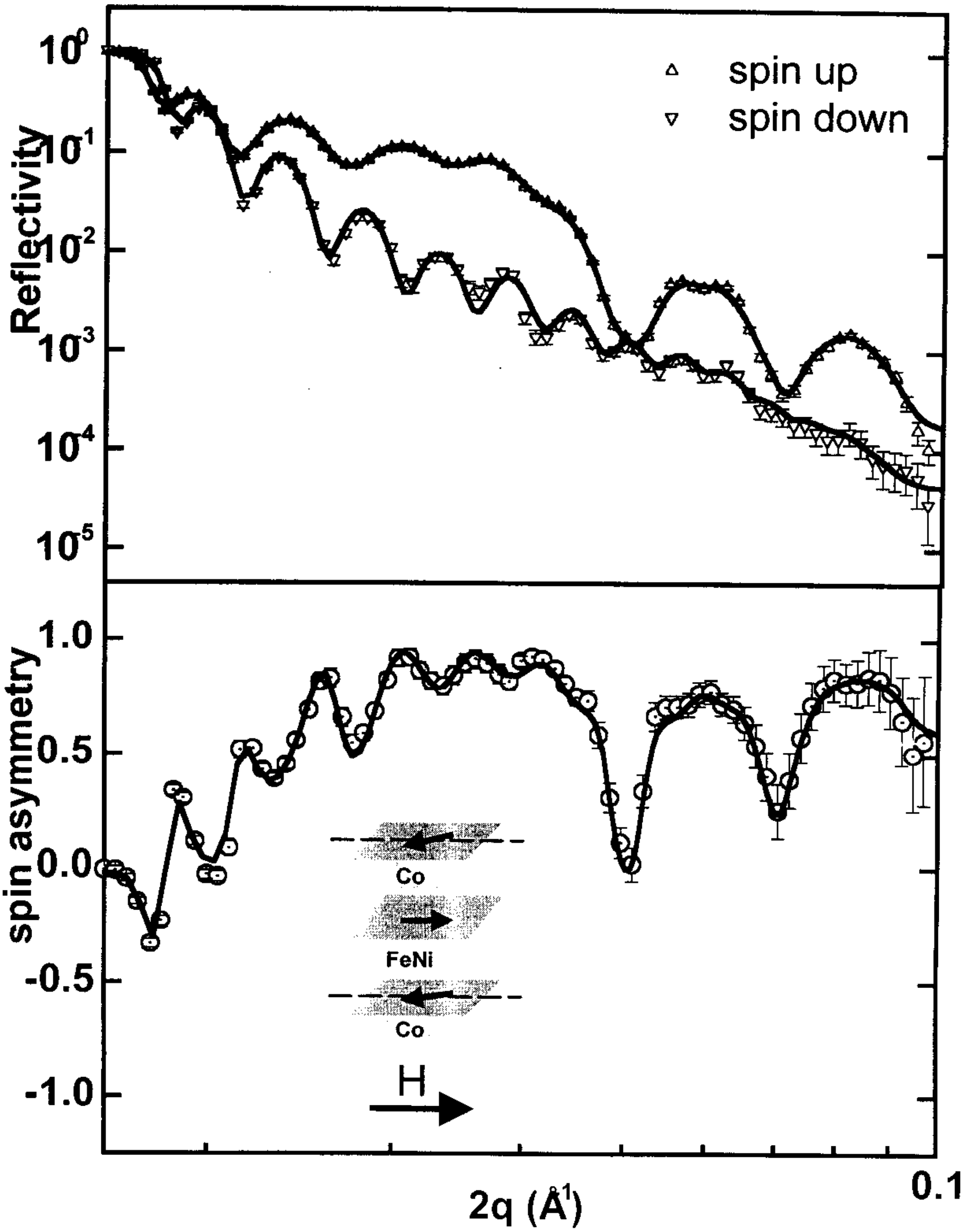
$$V_\alpha = (h^2/2\pi m_N)\, N_\alpha b_\alpha \pm \mu_0 \mu_N . M_s^\alpha \quad \text{(SI)}$$

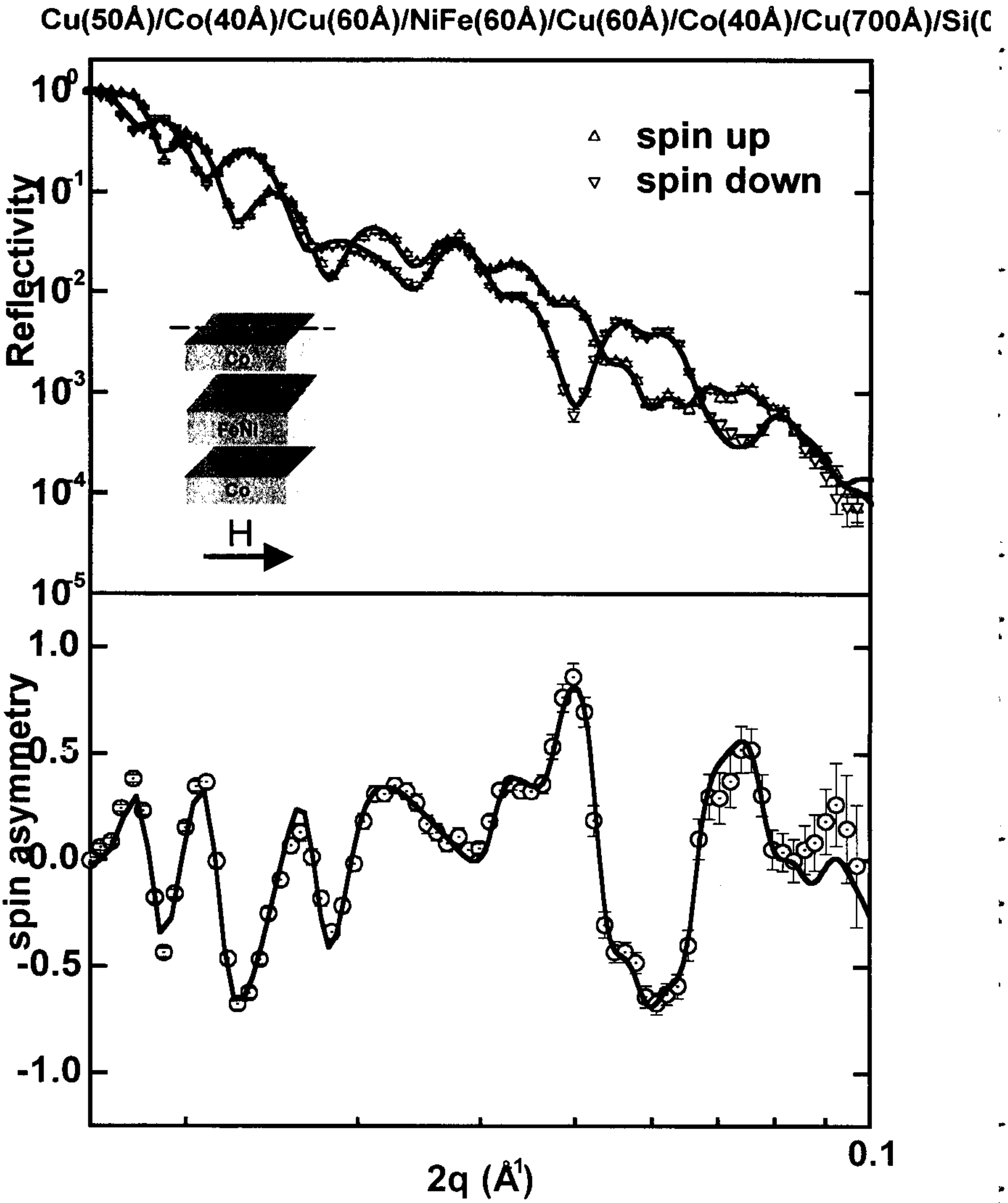
(m_N the neutron mass, N_α the atomic density of α, b_α the neutron scattering length, μ_N the neutron magnetic moment and M_s^α the magnetisation.)




Cu(50Å)/Co(40Å)/Cu(60Å)/NiFe(60Å)/Cu(60Å)/Co(40Å)/Cu(700Å)/Si(00
spin up
spin down
Reflectivity
Saturated state
spin asymmetry
2q (Å^{-1})
0.1

Cu(50Å)/Co(40Å)/Cu(60Å)/NiFe(60Å)/Cu(60Å)/Co(40Å)/Cu(700Å)/Si(00




Cu(50Å)/Co(40Å)/Cu(60Å)/NiFe(60Å)/Cu(60Å)/Co(40Å)/Cu(700Å)/Si(
Reflectivity
spin up
spin down
Co
FeNi
Co
H
spin asymmetry
2q (Å^{-1})
0.1