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1. Introduction

Spin-echo small-angle neutron scattering (SESANS) is a novel method to determine the structure of materials in real space (Rekveldt, 1996; Bouwman et al., 2004a; Rekveldt et al., 2003, 2005). The method is based on the Larmor precession of polarized neutrons transmitted through two successive precession devices before and after the sample, which encodes the scattering angle into a net precession angle. The advantages of the method are the relatively high intensity of the beam, the large length scale $(10-10^4 \text{ nm})$ of correlations in the sample being studied (inaccessible for conventional SANS) and the fact that multiple scattering can be taken into account in an analytic way (Rekveldt et al., 2003). The principal difference of SESANS from conventional SANS is that it measures a real-space function. Until now, SESANS has been applied to non-magnetic systems only (Bouwman et al., 2004a); application to magnetic systems was considered to be difficult, if not impossible, due to depolarization of the beam at the very moment of scattering.

It is well known that a polarized beam becomes depolarized after transmission through a magnetic sample. Measuring the depolarization in a ferromagnetic sample is a well established technique to study large-scale magnetic inhomogeneities. According to works by Maleyev (Maleyev & Ruban, 1972; Maleyev, 1982), depolarization is the result of unresolved small-angle neutron scattering within the angular width Ψ of the neutron beam accepted by the detector. It is determined by the integral cross section of scattering σ_{Ψ} . Maleyev showed also that the degree of depolarization depends on the relative

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A novel real-space scattering technique, spin-echo small-angle neutron scattering for magnetic samples, is described. Previously, this method has been exploited for non-magnetic samples only, in order to measure the nuclear density correlation function. Magnetic scattering is different from nuclear scattering as in the former a partial neutron spin-flip that affects the phase accumulation of the Larmor precession occurs just at the moment of scattering. Because of this intrinsic property of magnetic scattering, one can use a magnetic sample as a flipper in the spin-echo technique. This enables the separation of the magnetic contribution from other sources of scattering. Particular features of the technique are pointed out. Some model examples are considered. The similarity and the differences of magnetic SESANS with respect to the technique of three-dimensional neutron depolarization are discussed. The theoretical description is proven by experiments.

orientation of the initial polarization \mathbf{P}_0 and the neutron wavevector \mathbf{k} , and on the magnetic anisotropy of the sample.

The technique was extended by applying three-dimensional polarization analysis to the transmitted beam (Rekveldt, 1973) and to the SANS (Okorokov *et al.*, 1978), *i.e.* the polarization of the transmitted, though partially scattered beam is successively analyzed along all three laboratory axes. This yields information on the average magnetic field in the system and on its magnetic texture. Further information is obtained by applying a domain model to the system. Thus, the obtained information is model-dependent and the method itself has all the disadvantages of an integral technique.

In this paper, we wish to show that we can resolve this smallangle scattering in magnetic systems, which leads to depolarization, by using the neutron spin-echo (NSE) technique. We must be aware that in NSE in a magnetic system, two processes will occur which certainly interfere: (i) the change of the neutron spin in the scattering process and (ii) the precession of the neutron spin to encode the scattering effects.

The main principles of NSE in magnetic systems for inelastic scattering were established by Mezei (1980, 2003). Two important cases were studied: 'paramagnetic NSE' and 'ferromagnetic NSE'. In 'paramagnetic NSE', the intrinsic feature that the neutron spin is flipped at the very moment of scattering was exploited. The scattering event operates as a spin flipper; hence, if one places a paramagnetic sample instead of a flipper between spin-echo arms, the magnetically scattered neutrons produce a spin-echo signal. We point out that without a flipper no signal from non-magnetic scattering would appear, accounting for the non-monochromaticity of real neutron beams. Indeed, even for a beam with $\Delta\lambda/\lambda = 0.01$, the statement holds due to the guide fields, which extend over the setup. Thus, the presence of a signal is unambiguous evidence of magnetic neutron scattering.

In the case of 'ferromagnetic NSE', it is assumed that the sample depolarizes the neutron beam fully so that the information on the precession phase is lost. The same happens if a high magnetic field is applied at the sample because an uncontrolled and inhomogeneous amount of Larmor precession is added. Full depolarization may be avoided if one maintains the polarization component parallel to the field. The polarization component perpendicular to the field will be lost. This gives a 50% reduction of the amplitude. When the system depolarizes the beam anyway, a so-called 'intensity-modulated NSE' may be used: one polarization component is transformed into an intensity modulation by setting an additional analyzer just in front of the sample. This intensity modulation is not affected by the depolarization in the sample. The polarization is restored by a second polarizer just after the sample.

'Paramagnetic NSE' has been used to study the critical dynamics of ferromagnets near the phase transition temperature $T_{\rm C}$ (Mezei, 1982; Pappas *et al.*, 1998) and the complicated dynamics of spin glass systems (Mezei, 1983; Pappas *et al.*, 2003). Experiments with 'ferromagnetic NSE' have been performed in high magnetic fields up to 7 T in high- $T_{\rm C}$ superconductors (Boucher *et al.*, 1985).

For magnetic SESANS, the observation of the paramagnetic SE signal, *i.e.* the signal obtained from critical fluctuations of magnetization near $T_{\rm C}$, is hardly possible, owing to the fact that this signal is determined by a relatively small neutron cross section attributed to fluctuations on a large background of the transmitted beam (see Maleyev, 1982, for details). As shown below, magnetic SESANS can be applied to ferromagnetic samples. In this case, the depolarization caused by the ferromagnetic structure is not the factor to be avoided but the phenomenon under study. The magnitude of the SESANS signal is of the same order, or equal to the value of the depolarization. The SESANS experiment in a magnetic field is the subject of forthcoming papers.

This paper is organized as follows. The concept of SESANS for non-magnetic samples is presented in §2. In §3, we demonstrate how these principles and formulations can be



Figure 1

A single precession device preceded by the polarizer, a $\pi/2$ flipper to orient the polarization perpendicular to the field *B* in the precession device, followed by a second $\pi/2$ flipper, a second polarizer and the detector.

modified for magnetic SESANS. §4 gives examples of the expected SESANS signal for three models of magnetic systems: (i) a solution of ferromagnetic particles, and (ii) a layer of ferromagnetic domains on a substrate with domain magnetization parallel and (iii) perpendicular to the plane of the substrate. The first experimental results of magnetic SESANS are presented in §5.

2. Concept of SESANS

The principles of the SESANS technique are described in detail in a number of papers (Rekveldt, 1996, 2005). It is based on encoding the neutron fly direction through a precession device into a unique precession angle, when the device's front and end faces are inclined by an angle θ_0 towards its main axis (Fig. 1). The polarization after this device is determined by the precession angle φ :

$$P(\varphi) = P_0 \cos(\varphi) \tag{1}$$

with the precession angle

$$\varphi = c\lambda BL \frac{\sin\theta_0}{\sin(\theta_0 - \theta)} \simeq c\lambda BL(1 + \theta \cot\theta_0), \qquad (2)$$

where θ is the angle between the fly direction and the main axis, *B* is the magnetic field in the precession device, and *L* its length.

Two such devices in series with opposite magnetic fields (or parallel fields and a spin flipper in between) create the possibility to measure small-angle scattering of a sample positioned also in between. A sketch of the setup is given in Fig. 2.

According to equation (2), the net precession angle $\Delta \varphi$, after passing the two precession devices at transmission angles θ_1 and θ_2 , respectively, is given by

$$\Delta \varphi = \varphi_1 - \varphi_2 = c\lambda BL \cot \theta_0 (\theta_2 - \theta_1) = ZQ_z, \qquad (3)$$

with

$$Z = \frac{c\lambda^2 BL \cot \theta_0}{2\pi} \quad \text{and} \quad Q_z = \frac{2\pi}{\lambda} (\theta_2 - \theta_1). \tag{4}$$

Here Q_z is the momentum transfer of the scattering in the z direction. The quantity Z, which is complementary to Q_z , defines a length called the 'spin-echo length'. This length can be scanned by varying the quantities λ , B, L or θ_0 .



Figure 2

Full spin-echo setup with two precession devices with opposite magnetic fields that cancel the precession angles of the passing neutron spins without a sample between the devices. When the sample is present, the transmission direction changes and the net precession angle departs from zero. Precessions along different paths are indicated in the upper part.

The final polarization measured in the detector behind the analyzer is written as

$$P_{\rm m}I_{\rm m} = P_0I_{\rm ns} + P_{\rm s} * I_{\rm s} \tag{5}$$

where $P_{\rm m}$ and $I_{\rm m}$ are the measured polarization and the intensity of the transmitted beam, while P_0 and $I_{\rm ns}$ are the corresponding parameters of the non-scattered part of the beam. The term $P_{\rm s} * I_{\rm s}$ is a convolution of the cross section $d\sigma/d\Omega(Q)$ (probability of scattering) and polarization $P_{\rm s}$ of the beam scattered at a certain angle θ , corresponding to momentum transfer Q:

$$P_{\rm s} * I_{\rm s} = I_0 x \frac{1}{k_0^2} \int \mathrm{d}Q_y \, \mathrm{d}Q_z \, P_{\rm s}(Q_z) \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega(Q)},\tag{6}$$

where x is the sample thickness, $P_s(Q_z) = P_0 \cos(Q_z Z)$, I_0 is the incident beam intensity, k_0 is the wavevector magnitude of the incident beam, and

$$\sigma = \frac{1}{k_0^2} \int \mathrm{d}Q_y \,\mathrm{d}Q_z \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(Q) \tag{7}$$

is the total cross section. In the single-scattering approximation ($\sigma x \ll 1$), we have $I_{ns} = I_0(1 - \sigma x)$ and $I_m = I_0$, so the measured polarization [equation (5)] becomes

$$P_{\rm m} = P_0(1 - \sigma x) + P_0 x \left(\frac{1}{k_0}\right)^2 \int \mathrm{d}Q_y \,\mathrm{d}Q_z \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega(Q)} \cos(Q_z Z_1).$$
(8)

In the single-scattering approximation, we can arrive at the scattering by a sample of arbitrary thickness by rewriting equation (8) for a very thin sample of thickness dx as

$$\frac{(P_{\rm m} - P_0)}{P_0} \rightarrow \frac{\mathrm{d}P}{P} = -\mathrm{d}x \bigg[\sigma - \frac{1}{k_0^2} \int \mathrm{d}Q_y \,\mathrm{d}Q_z \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega(Q)} \cos(Q_z Z) \bigg],$$
(9)

showing that the change of the polarization dP/P_0 due to the scattering is proportional to dx. After integrating equation (9) over the thickness of the sample from 0 to l, we have

$$\frac{P_{\rm m}(l,Z)}{P_0} = \exp\left\{-l\sigma \left[1 - \frac{1}{\sigma k_0^2} \int \mathrm{d}Q_y \,\mathrm{d}Q_z \,\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega(Q)} \cos(Q_z Z)\right]\right\}.\tag{10}$$

As was shown by Krouglov *et al.* (2003*a*), the second term in the argument of the exponent is the projection of the spatial pair correlation function along the propagation axis of the neutron beam. So the measured quantity $P_{\rm m}$ can be finally converted into the so-called SESANS correlation function G(Z), which for isotropic samples is

$$G(Z) = \int \mathrm{d}x \langle \rho(r)\rho(r+Z) \rangle = \frac{1}{k_0^2} \int \mathrm{d}Q_y \,\mathrm{d}Q_z \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega(Q)} \cos(Q_z Z),$$
(11)

where $\rho(r)$ is the scattering potential at point *r*.

The central feature to be taken into account in magnetic SESANS is the change of the polarization at the very point of scattering. For ferromagnetic samples, the polarization \mathbf{P}_{s} of the scattered neutrons is given by (Izyumov & Ozerov, 1970)

$$\mathbf{P}_{\rm s} = 2\mathbf{m}_{\perp}(\mathbf{m}_{\perp} \cdot \mathbf{P}_0) - \mathbf{P}_0, \qquad (12)$$

where $\mathbf{m}_{\perp} = \mathbf{m} - (\mathbf{m} \cdot \hat{\mathbf{q}})\hat{\mathbf{q}}$, in which $\hat{\mathbf{q}}$ is the unit scattering vector and **m** is the unit magnetization vector, and \mathbf{P}_0 is the polarization just before the scattering. The last equation shows that for neutrons scattered at $\mathbf{q} \perp \mathbf{m}$, the polarization component parallel to the local magnetization $P_{0\parallel}$ remains unchanged in the scattering process, while the component perpendicular to it, $P_{0\perp}$, changes its sign. In this case, there is in principle no polarization loss (at least in the single-scattering approximation) as occurs in the paramagnetic scattering, where $\mathbf{P}_{s} = -\hat{\mathbf{q}}(\hat{\mathbf{q}} \cdot \mathbf{P}_{0})$. The polarization in the SE technique is always a vector rotating in the plane perpendicular to the guide magnetic field and hence it can be set in a position desired by the experimentalist. The local magnetization in the sample is a vector with an arbitrary direction. The consideration of all nine possibilities (three components of magnetization \times three precession planes of polarization) is very similar to the three-dimensional analysis of the depolarization (Rekveldt, 1973). Such a consideration is beyond the scope of this paper and we restrict ourselves to the demonstration of magnetic SESANS in its simplest form. The full three-dimensional analysis for magnetic SESANS will be published elsewhere.

Thus, for ferromagnetic scattering it is easy to find experimental conditions by which the polarization is fully flipped in the scattering process. For example, we consider the situation when the local magnetization is directed along the propagation axis x and the polarization is in the plane (xz) (Fig. 2). As a consequence, to observe the NSE signal, a flipper between the spin-echo arms is not needed. Therefore, by switching on or off the flipper, one can separate the magnetic scattering from other contributions, in particular, from the nuclear one and from the unscattered beam.

Then we can rewrite equation (8) for magnetic SESANS as

$$I_{\rm m}P_{\rm m} = P_0 I_0 \cos(\varphi_1 + \varphi_2)(1 - \sigma x) - \frac{I_0 P_0 x}{k_0^2} \int \mathrm{d}Q_y \, \mathrm{d}Q_z \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega(Q)} \cos(\varphi_2 - \varphi_1).$$
(13)

The first term is the non-scattered part of the beam. The precessions in both precession devices add, so no NSE will be produced. Since $\int d\lambda \rho_{\lambda}(\lambda) \cos[\varphi_1(\lambda) + \varphi_2(\lambda)] = 0$, this term vanishes. Here ρ_{λ} is the spectral density of the neutron beam. It should be noticed that the neutron beam is not monochromatic, as occurs in reality.

Considering the second term: after the flipping action of the magnetic scattering, the term $\cos(\varphi_2 - \varphi_1)$ is in echo for the neutrons magnetically scattered forward. Finally, equation (13) can be rewritten as

$$I_{\rm m}P_{\rm m} = -\frac{I_0 P_0 x}{k_0^2} \int \mathrm{d}Q_y \,\mathrm{d}Q_z \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega(Q)} \cos(Q_z Z)$$

= $-I_0 P_0 x \sigma G(Z),$ (14)

where we used equation (3) to express $\varphi_1 - \varphi_2$ in Z, with the G(Z) function given as

$$G(Z) = \int dx \langle \rho_{\rm m}(r)\rho_{\rm m}(r+Z) \rangle$$

= $\frac{1}{\sigma k_0^2} \int dQ_y dQ_z \frac{d\sigma}{d\Omega(Q)} \cos(Q_z Z),$ (15)

where $\rho_{\rm m}(r)$ is the magnetic scattering potential.

For multiple scattering, one should realise that for magnetic scattering, the second scattering event reverses the polarization. In this case, the term describing that the neutron is scattered twice must be subtracted from the single-scattering process. Accounting for double, triple, *etc.* scattering, we rewrite equation (14) as

$$P_{\rm m} = P_0 G(Z) \left[x\sigma - \frac{(x\sigma)^2}{2} + \frac{(x\sigma)^3}{2 \cdot 3} - \dots \right]$$
$$= P_0 G(Z)(x\sigma) \exp(-x\sigma). \tag{16}$$

Thus the measured polarization P_m is proportional to the function G(Z) and multiple scattering now appears as the factor $\exp(-x\sigma)$. Equation (16) shows that the amplitude of the NSE signal is a function of the normalized thickness $x\sigma = x/l_f$ of the sample: $F(x\sigma) = (x\sigma)\exp(-x\sigma)$. This function is plotted in Fig. 3. Its maximum occurs at $x\sigma = 1$ and is equal to 1/e. It is the absolute maximum of the NSE signal which can be reached in magnetic SESANS.

For magnetic scattering, it is rather simple to normalize the amount of scattering. According to Maleyev (Maleyev & Ruban, 1972; Maleyev, 1982) the depolarization of the transmitted beam, which is not in spin-echo mode, is a measure for the total magnetic cross section:



Figure 3

The amplitude of the spin-echo signal is a function of the thickness x of the sample normalized by the mean free path $l_f = 1/\sigma$: $F(x\sigma) = (x\sigma)\exp(-x\sigma)$.

where the initial polarization \mathbf{P}_0 is parallel to the incident beam.

4. Model systems

4.1. Spherical magnetic particles

We consider the scattering from a system of ferromagnetic spherical non-interacting single domain (*i.e.* uniformly magnetized) particles with radius R, as, for example, in a ferrofluid. The correlation function of such a particle is known analytically and its projection according to the SESANS technique, G(Z), has been calculated by Krouglov *et al.* (2003*b*). In full analogy with the result given by Krouglov *et al.*, it reads

$$G(Z) = l\sigma G_0(Z), \tag{18}$$

where the function $G_0(\xi)$ is given by



Figure 4

Polarization as a function of spin-echo length Z: (a) for a system of magnetic spherical Ni particles with radius 500 nm, volume concentration 30% and sample thickness 1 mm; (b) for a system of cylindrical domains with radius 500 nm and length 10^4 nm, oriented along the neutron beam.

$$G_{0}(\xi) = \left[1 - \left(\frac{\xi}{2}\right)^{2}\right]^{1/2} \left(1 + \frac{1}{8}\xi^{2}\right) + \frac{1}{2}\xi^{2}\left[1 - \left(\frac{\xi}{4}\right)^{2}\right] \ln\left[\frac{\xi}{2 + (4 - \xi^{2})^{1/2}}\right], \quad (19)$$

in which $\xi = Z/R$ for $0 < \xi < 2$, and *l* is the thickness of the sample. The total scattering probability is:

$$\sigma = \frac{3}{2} \phi_{\rm V} \rho_p^2 \lambda^2 R, \qquad (20)$$

where ϕ_V is the volume concentration, λ is the neutron wavelength, and $\rho_p = Np$ is the magnetic scattering potential (with N the number of atoms per unit volume and p the magnetic scattering length).

Using equations (16), (18)–(20), we calculated the possible polarization signal from a solution (30%) of Ni particles ($Np = 1.46 \times 10^{-4} \text{ nm}^{-2}$) with R = 500 nm for $\lambda = 0.2 \text{ nm}$ and sample thickness l = 1 mm. The result is shown in Fig. 4(*a*).

4.2. Ferromagnetic layer on a substrate

We consider two cases: (i) 'easy plane', *i.e.* the magnetization vector is in the plane; and (ii) 'hard plane', *i.e.* the magnetization vector is perpendicular to it.

In *easy plane* we suppose a magnetic domain structure consisting of strips, magnetized parallel or antiparallel to the in-plane easy axis. The thickness of a strip is equal to the ferromagnetic layer thickness; its length is much longer than the thickness. This is a quasi-periodic one-dimensional structure like a grating. If we orient these strips with their length parallel to y, their width d_z in the gradient precession direction (sensitive direction, z) and their thickness d_x parallel to the neutron beam, we can calculate the scattering cross section for this structure in analogy to Bouwman *et al.* (2004*b*). The total scattering fraction is

$$\sigma l = l \frac{1}{k_0^2} \int dQ_y \, dQ_z \frac{d\sigma(Q_y, Q_z)}{d\Omega} = (nd_x d_y d_z) (2\rho_p \lambda d_x)^2$$
$$\equiv \phi_V (2\rho_p \lambda d_x), \tag{21}$$

where *n* is the domain density and again ρ_p is the magnetic scattering length density and ϕ_V the volume fraction. For G(Z) of such a one-dimensional structure, one expects to find the autocorrelation function of the density profile along the



Figure 5

Schematic drawing of the SESANS setup at IRI TU Delft. MC: monochromator crystal. P: polarizer. R1, R2, R3 and R4: polarization rotators. M1, M2, M3 and M4: electromagnets. S: sample position. A: analyzer. D: detector. The system consisting of M1 and M2 is the first arm of a spin-echo setup; M3 and M4 represent its second arm.

sensitive direction. For this model, it is the autocorrelation function of a rectangular domain, which has a triangular shape with a base width twice the width of a domain.

The hard plane model is a stack of cylinders with radius R and length l oriented perpendicular to the plane, *i.e.* a twodimensional structure. The correlation function of such a long particle (oriented by its long dimension along the incident beam) can be given analytically and the corresponding projection of this function in the SESANS technique is a product of this function and the normalized thickness $l\sigma$:

$$G(Z) = l\sigma G_0(Z), \tag{22}$$

where

$$G_0(\xi) = \frac{1}{\pi} \{2 \arccos(\xi) - \sin[2 \arccos(\xi)]\}, \qquad (23)$$

in which $\xi = Z/(2R)$ for $0 < \xi < 2$. The total scattering probability is given by

$$\sigma = \frac{\pi}{2} \phi_{\rm V} \rho^2 \lambda^2 l, \qquad (24)$$

where again ϕ_V is the volume concentration and ρ_p the magnetic scattering potential. Equations (22)–(24) are derived in the approximation of non-interacting particles, *i.e.* $r \leq R$. This approximation fails for the real system, naturally, where neighbouring domains are correlated in the range $r \geq R$; it remains valid for $r \leq R$.

Using equations (16), (22)–(24), we calculated the possible signal from a hypothetical ferromagnetic Ni layer ($Np = 1.46 \times 10^{-4} \text{ nm}^{-2}$) with thickness 10^4 nm and domain size 1000 nm; $\lambda = 0.2$ nm. The result is shown in Fig. 4(*b*), where the polarization is plotted as a function of spin-echo length, *Z*. Fig. 4 demonstrates that the correlation functions of the spherical particle and the cylinder-like particle are different and this difference could be clearly detected in the SESANS experiment.

5. Experiment

To illustrate the possibilities that SESANS presents for the investigation of magnetic materials, we applied this technique to study a ferromagnetic Ni layer, of 15 μ m thickness, on a copper substrate. The domain structure of the sample corresponds to the hard-plane model described in §4. The magnetization in the domains is directed perpendicular to the layer; the domain length coincides with the thickness of the layer (15 μ m); the width ('spaghetti' thickness) is of order of 3 μ m. This structure was named a 'spaghetti' domain structure. The magnetic structure of such a Ni layer had been studied long ago by neutron depolarization analysis (Kraan & Rekveldt, 1977), which was repeated for this particular sample. The 'spaghetti' domain structure describes the neutron depolarization results as a function of transmission angle very well.

We used the SESANS instrument at IRI in Delft (Rekveldt *et al.*, 2005), shown schematically in Fig. 5. A set of six pyrolytic graphite monochromators (MC) selects a beam with $\lambda = 0.21$ nm and $\Delta\lambda/\lambda = 0.01$ from a polychromatic beam from the

2 MW reactor. The polarizer P and the analyzer A before the ³He detector D, are sets of supermirrors. The adiabatic $\pi/2$ rotators R1 and R4 turn the polarization from the orientation parallel to the field in the polarizer and analyzer, into the plane perpendicular to the magnetic field in the electromagnets M1-M4. The basic components that create the triangular precession regions are 9 µm thick permalloy films deposited on silicon wafers, positioned at $\theta_0 = 5.5^\circ$ to the neutron beam at the centre of the rectangular poles of these electromagnets. Their fields are set and controlled by software to values usually between 0.5 and 130 mT. The sample S is mounted between the two SE arms. Two $\pi/2$ -rotators of polarization, R2 and R3, are installed around the sample position in order to set the polarization into the (xz) plane. Two large Helmholz coils are mounted around both arms as guide fields of 2 mT to maintain the polarization. All parts are mounted on an aluminium table to avoid magnetic disturbance of the surroundings of the neutron path.

Fig. 6(a) shows the polarization measured as a function of the parameter Z for the 'nuclear' mode. In this mode, the magnetic field reverses between magnets M2 and M3 by using a field stepper and the nuclear SESANS correlation function is measured. We see no variation of P, demonstrating the absence of nuclear inhomogeneities in the sample. Due to



Figure 6

Polarization measured as a function of the spin-echo length Z for the 'nuclear' (a) and 'magnetic' (b) modes (see the text for details).

magnetic scattering, the level of the polarization is equally suppressed for all Z. According to equation (17), this depolarization gives the total magnetic scattering.

Fig. 6(b) shows the polarization for the 'magnetic' mode. For this mode, the sign of the field was not actually reversed, but we arranged an adiabatic transition between M2 and M3 that compensates the action of the field reversal. The polarization shows a damped oscillating behaviour as a function of Z with a minimum at $Z = 3 \ \mu m$ and a maximum at $Z = 6 \ \mu m$. This implies the presence of correlations between neighbouring domains with characteristic size 3 µm. The linear character of the dependence P(Z) at small $Z(<2 \mu m)$ confirms the calculation made for the hard-plane model in §4.2. For comparison, we also plot the polarization in the 'magnetic' mode without sample. As expected, it is close to zero because the precessions in both arms add, since the spin flip during a magnetic scattering event is absent. For the beam with $\Delta \lambda / \lambda =$ 0.01, the condition that the total phase $\varphi_1 + \varphi_2 > 100\pi$ must be fulfilled for full suppression of the SE signal. This inequality holds even for the guide field between the magnets, of the order of 2 mT, which extends over the entire setup (length 5 m). This guide field produces one sense of precession and is strong enough to make the SE signal vanish. The question arises: is there a possibility that the observed signal in the 'magnetic mode' is actually due to the fact that the ferromagnetic Ni film is acting as an (imperfect) spin flipper? We estimated the possible precession of the polarization of a neutron beam with wavelength 0.2 nm inside a Ni layer of thickness 15 µm: $\Delta \varphi \simeq 0.1$, which is much less than π necessary for the spin flip. Thus, we conclude that this ferromagnetic film does not act as an imperfect spin flipper, but we are dealing with magnetic scattering at very small angles.

Finally, the measured polarization with the sample is higher than without it: this is a direct proof of the validity of equation (12) and the concept of magnetic SESANS. Similar curves were observed in non-magnetic SESANS experiments with dense colloids (Krouglov *et al.*, 2003*b*), where the correlation between particles becomes important.

6. Conclusion

In this paper we have reviewed the SESANS technique and pointed out that the projection of the pair correlation function along the beam axis is obtained with this technique. We have demonstrated that SESANS, hitherto applied to numerous non-magnetic systems, can also be applied to magnetic samples. We are helped by fact that the polarization is flipped in the magnetic scattering process, which eliminates the need for the usual π flipper to observe spin echo. Hence, by taking measurements with and without a flipper from the same sample, magnetic and nuclear modes of scattering can be separated in a trivial way. The formalism for magnetic SESANS is similar to that for non-magnetic SESANS, except for the correction for multiple scattering. As an example, we studied a Ni layer electrodeposited on copper, which had previously been characterized by three-dimensional depolarization analysis.

Comparison of this new technique with the well known depolarization analysis suggests that the new technique gives information that is complementary to neutron depolarization. The new technique gives the profile of the pair correlation function and one of its characteristics, a magnetic correlation length. This information is model independent and does not rely on knowledge of the magnetization (as a function of temperature) of the system, as in depolarization analysis. This presents new possibilities for the investigation of magnetic phase transitions.

In summary, the old idea to resolve magnetic scattering within the direct beam is nowadays realisable.

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