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Spin-wave dynamics in Invar $Fe_{65}Ni_{35}$ studied by small-angle polarized neutron scattering

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Abstract Spin dynamics in $Fe_{65}Ni_{35}$ Invar alloy has been studied by left-right asymmetry of Small-Angle Polarized Neutron Scattering below $T_C = 485$K in external magnetic fields $H = 0.05 - 0.5$T inclined relative to the incident beam. The spin-wave stiffness D and the damping Γ were obtained by fitting the antisymmetrical contribution to scattering. The spin-wave stiffness extrapolated by $(T/T_C)^{5/2}$ law to $T = 0$K is $D_0 = 117 \pm 2$ meV·Å^2 which is somewhat smaller than the spin-wave stiffness obtained by triple-axis spectrometry, whereas the spin-wave stiffness extracted from magnetization measurements reads $D_0 = 80\,\text{meV}{\cdot}\text{Å}^2$. An abnormal behaviour of the spin-wave parameters for $H > 0.2$T is marked.

1 Introduction

Spin-wave (SW) dynamics in Invar systems has been intensively investigated in connection with the problem of so called 'hidden excitations' [1,2]. The idea of hidden excitations stems from the observation that conventional spin waves with the stiffness $D(T)$ can not explain the temperature variation of the magnetization $M(T)$. This idea was checked in a series of inelastic neutron scattering experiments with and without polarization analysis at a number of Invar and non Invar materials [3-7]. Various explanations had been proposed for this discrepancy, among them, e.g. was the coupling between the transverse and longitudinal fluctuations. However, all of them fail to close the problem, so far.

Usually, the spin excitations are studied by direct measurements of the energy transfers in triple-axis spectrometry [1-7] sensitive to momentum transfers $q > 0.05$Å^{-1}. Here, a somewhat different technique has been applied based on the analysis of the asymmetry of small-angle polarized neutron scattering (SAPNS) with the sample magnetized in the direction inclined relative to the incident beam. The left-right asymmetry in magnetic inelastic SAPNS arises when the magnetization direction of the sample is neither parallel nor transverse to the incident neutron wavevector. Apart from tripple-axis spectrometry, this method [9–12] measures the integral over energy transfers coming from the scattering on antisymmetrical spin correlations. The SW parameters can be extracted by comparison of the antisymmetrical contribution to scattering with a model function. This technique has no restriction on the measured momentum transfers and can be applied to study spin excitations for $k\theta$ even less than 0.05Å^{-1}.

2 Experimental

Spin dynamics in Invar $Fe_{65}Ni_{35}$ alloy has been studied below $T_C = 485$K in magnetic fields of 0.05–0.5T. The magnetization was measured with a SQUID magnetometer and a Faraday balance for temperatures from 4K to 550K in an applied magnetic field of 0.42T. The obtained result coincides with that of the previous studies [8].

Following the approach developed in [9-12] the magnetic scattering cross-section of polarized neutrons is given by:

$$\frac{d^2\sigma(\mathbf{P_0})}{d\Omega d\omega} = \frac{1}{2\pi} A_m^2 \frac{k^{'}}{k} \left|F(\mathbf{q})\right|^2 S(\mathbf{q},\omega,\mathbf{P_0}) \ , \qquad (1)$$

where A_m is the magnetic scattering length of the atom, $F(\mathbf{q})$ is the magnetic form factor, $\mathbf{P_0}$ is the primary neutron polarization, $\mathbf{q} = \mathbf{k}^{'} - \mathbf{k}$ and $\omega = E^{'} - E$ are the momentum and energy transfers, respectively. At $\mathbf{P_0} \parallel \mathbf{m}$, where $\mathbf{m} = \mathbf{M}/M$, the scattering function can be written as: $S = S_t + P_0 S_a$, where S_t and S_a are related to

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symmetrical (K_t) and antisymmetrical (K_a) contributions for the spin projections transverse to $\mathbf{m}$. At small scattering angles $\theta \ll 1$ and $q \ll k, k'$, one can put $F(\mathbf{q}) = 1$ and the integral of the antisymmetrical part of the cross-section in Eq.(1) over the energy transfer is given by:

$$\left(\frac{d\sigma}{d\Omega}\right)_a = 2P_0 A_m^2 \int d\omega (\mathbf{em})^2 K_a(\mathbf{q},\omega) \ , \qquad (2)$$

where $\mathbf{e} = \mathbf{q}/q$ and

$$(\mathbf{em})^2 = \frac{\theta_x^2 \sin^2\phi + \left(\frac{\omega}{2E}\right)\theta_x \sin 2\phi + \left(\frac{\omega}{2E}\right)^2 \cos^2\phi}{\theta^2 + \left(\frac{\omega}{2E}\right)^2} \ , \qquad (3)$$

where ϕ is the angle between the applied magnetic field and the incident momentum $\mathbf{k}$, and θ_x is the scattering angle in $\mathbf{k}-\mathbf{H}$ plane. As $K_a(\mathbf{q},\omega)$ is an odd function of ω for $\omega \ll T$, the integral (2) is not equal to zero only if $\phi \neq 0$ or $90°$. The integral reaches a maximum at $\phi = 45°$. Moreover, it is antisymmetrical with respect to the scattering angle component θ_x in the $\mathbf{m}-\mathbf{k}$ plane. This makes it possible to determine the antisymmetrical contribution by:

$$\Delta I_a(\theta) = \frac{1}{4}\left\{ \Big[I(P_0,\theta) - I(-P_0,\theta) \Big] - \right.$$
$$\left. - \Big[I(P_0,-\theta) - I(-P_0,-\theta) \Big] \right\} . \qquad (4)$$

This fraction of measured intensities was fitted by Eq.(2) with K_a inferred in the framework of isotropic Heisenberg model and renormalized by dipolar forces [11,12] and with collimation taken into account. As a result, a set of SW parameters has been determined such as the stiffness D, the damping factor Γ_0 in SW damping accepted in the form $\Gamma_q = \Gamma_0 \epsilon_q$ which is in accord with the results of the early experiments [1,2]. We put the Landé factor in the Zeeman term $g = 2$.

The SAPNS experiments were carried out at the SANS-2 scattering facility of FRG-1 research reactor in Geesthacht (Germany). A polarized beam of neutrons with an initial polarization of $P_0 = 0.9$, the neutron wavelength $\lambda = 5.6$Å$(\Delta\lambda/\lambda = 0.1)$ and a divergence of 1.0 mrad was used. The scattered neutrons were detected by a 128×128 position sensitive detector with an angular range of ± 60mrad. The sample was magnetized parallel to its long dimension by an electromagnet. The external magnetic field was applied at an angle of $\phi = 45°$ with respect to the incident beam.

3 Results

Fig.1 shows the twice-antisymmetrical part (4) of scattering in the $\mathbf{k}-\mathbf{H}$ plane ΔI_a as a function of the scattering angle θ_x for the magnetic fields $H = 70$ and 350 mT at $T = 300$K. The solid line represents the theoretical model [11,12] calculated with the SW parameters obtained from the fit. The scattering is concentrated mostly within the cut-off angle θ_C that depends on the magnetic field as [13]: $\theta_C(H)^2 = \theta_0^2 - g\mu H\theta_0/E$, and θ_0 is inversely proportional to the SW stiffness D. In the vicinity of the cut-off angle the scattering is smeared by the SW damping Γ_q.

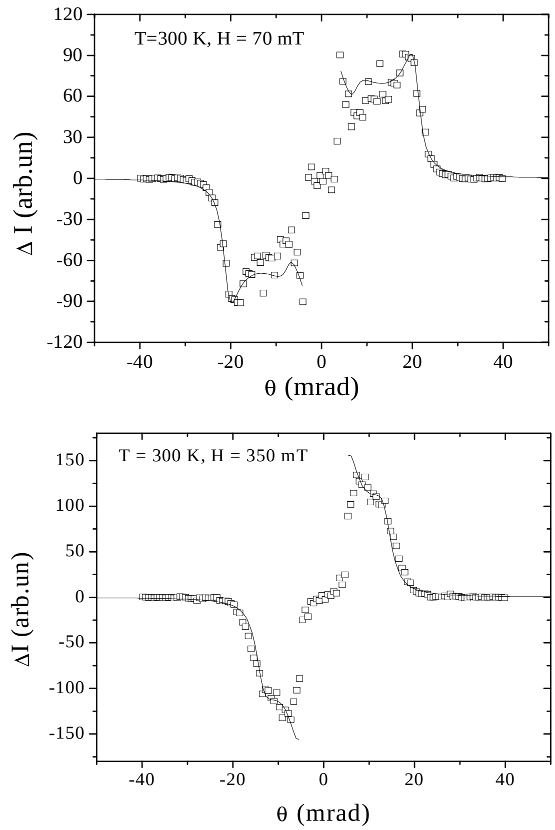

Fig. 1 The antisymmetric part of SAPNS ΔI_a for magnetic fields of $H = 70$ and 350 mT at $T = 300$ K.

Fig.2 shows the SW stiffness D and the damping factor Γ_0 as functions of temperature for the magnetic field $H = 70$mT. The SW stiffness obeys a $(T/T_C)^{5/2}$ dependence in the temperature range up to $0.9\,T_C$ with the extrapolated value $D_0 = 117$meV·Å^2 at $T = 0$K. This value is by a factor of 0.82 lower than that obtained by triple-axis spectrometry [1,2]. At the same time, the quantity which would explain the variation of the magnetization measurements, is $D_0 = 80\,$meV·Å^2. Thus, our observation does not remove the problem of 'hidden excitations' for the Invar under study.

The SW damping factor shows a weak temperature dependence at $T < 400$K and then increases at $T > 400$K as the temperature approaches T_C. This behavior of Γ_0 is very similar to that of the thermal expansion coefficient and therefore the growth of Γ_0 with tempera-

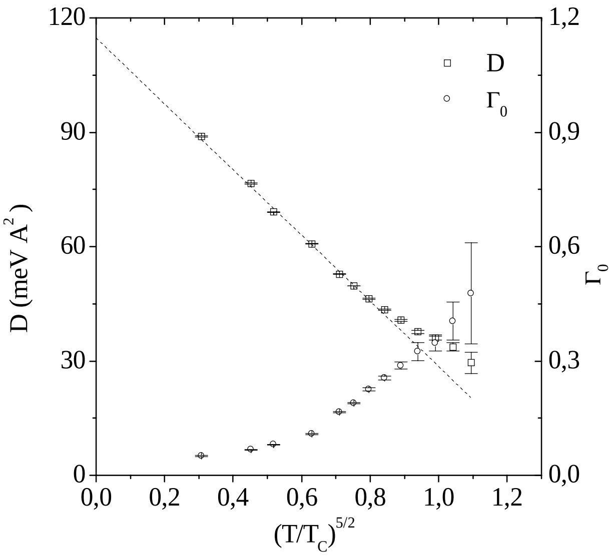

Fig. 2 The temperature dependence of (a) the spin-wave stiffness D and (b) the spin wave damping Γ_0.

ture can be related to the spin-lattice interaction in this temperature range.

Fig.3 represents the magnetic field dependence of θ_C^2 (a) and the spin wave stiffness D (b). As seen from this figure, the experimental data for θ_C^2 for $H > 0.2$T do not obey the linear behavior while such behaviour is observed for $H < 0.2$T in accordance to the prediction of the theory for ordinary ferromagnets [13]. A similar behavior of $\theta_C^2(H)$ has been observed at all temperatures measured. The SW stiffness obtained from the fit is nearly constant for $H < 0.2$T and decreases linearly with increasing the field for $H > 0.2$T. The damping factor Γ_0 shows a similar behavior as the spin wave stiffness does. However, such abnormal behavior for $H > 0.2$T is observed neither in our magnetization measurements nor in neutron scattering experiments elsewhere. We tend to consider such behavior at $H > 0.2T$ as that having non-spin wave origin. At the moment, we are not ready to offer a reliable and comprehensive explanation for this phenomenon, therefore, further investigations are needed.

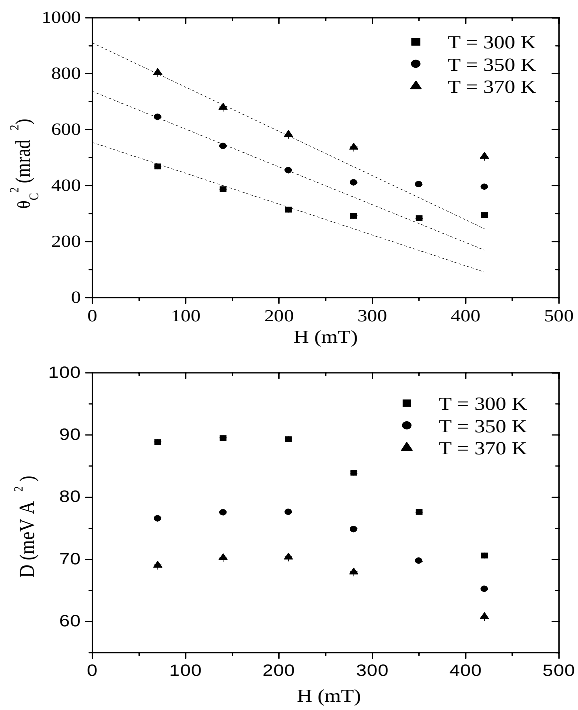

Fig. 3 The magnetic field dependence of (a) the square of the cut-off angle θ_C^2, and the spin-wave stiffness D (b).

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