Study of spin waves in amorphous magnetic materials by polarized-neutron scattering

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A method for determining the spin-wave stiffness from the right-left asymmetry of the scattering of polarized neutrons is proposed. The values of the critical index of the spin-wave stiffness have been found in amorphous magnetic materials: $x = 0.36 \pm 0.025$ for 50Fe22Ni10Cr18P and $x = 0.31 \pm 0.02$ for 48Fe34Ni18P.

Spin waves in amorphous magnetic materials have recently become the subject of extensive experiments (Refs. 1 and 2, for example). The thrust of this research has been to study the effect of structural disorder on the propagation of low-frequency excitations at temperatures far from the Curie point (T_C). On the other hand, the spin-wave dynamics near T_C has not received adequate explicit study. In the two studies[3,4] of this question of which we are aware, it was found that the spin-wave

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stiffness D can be described satisfactorily as a function of the relative temperature $\tau = (T_C - T)/T_C$ by a power law, $D(\tau) = D_0\tau^x$, as in crystalline ferromagnets. In contrast with the ordered materials, however, where $x \approx 1/3$ is predicted theoretically, we would have $x = 0.5 \pm 0.1$ in amorphous magnetic materials, according to Ref. 3, or $x = 0.6 \pm 0.08$, according to Ref. 4. It is important to note not only the poor accuracy of the results found in Refs. 3 and 4 but also possible systematic errors in the determination of $D(\tau)$, stemming from the difficulties of applying the conventional methods[3,4] to the critical dynamics in amorphous magnetic materials. To see the sources of these difficulties, we recall that well-defined spin waves exist only if their wavelengths are large in comparison with the correlation radius $R_c(\tau)$ and if their energies are small in comparison with the scale energy of the critical fluctuations , $\Omega(\tau)$. It is thus necessary to measure a small energy transfer of the scattered neutrons, $\omega \ll \Omega$, at a small momentum transfer $q \ll R_c^{-1}$, with allowance for $\Omega \to 0$, $R_c \to \infty$ in the limit $T \to T_C$.

The method which we are proposing here makes use of the asymmetry of the small-angle scattering of polarized neutrons[5,6] and can be summarized as follows: In the experiments, we measure the difference in the intensities of the neutrons which are scattered through a small angle θ and which were originally polarized along the magnetization of the sample, and opposite to it, $\Delta I(\theta) = I(\theta,\mathbf{P}_0) - I(\theta - \mathbf{P}_0)$, where $\mathbf{P}_0$ is the initial polarization. This quantity is proportional to the sum of two terms, the first of which describes magnetic scattering, while the second describes an interference of magnetic and nuclear scattering[7,8]:

$$\Delta I(\theta) \sim A_m^2 \int d\omega \,\{(\mathbf{em})(\mathbf{eP_0})S^a_{q,\omega} + A_m \bar{\alpha} M(\mathbf{P_0 m_\perp})\phi_{q,\omega}\} \,. \qquad (1)$$

Here A_m is the amplitude of the magnetic scattering of the atom, $\bar{\alpha}$ is the expectation value of the nuclear amplitude, $\mathbf{e} = \mathbf{q}/q$, $\mathbf{m} = \mathbf{M}/M$, $\mathbf{M}$ is the magnetization of the sample, and $\mathbf{m}_\perp = \mathbf{m} - \mathbf{e}(\mathbf{em})$. Under the experimental conditions we have $(\mathbf{em})(\mathbf{eP}_0) = P_0(\mathbf{em})^2$ and $P_0 = (\mathbf{P}_0\mathbf{m})$. The function $S^a_{q,\omega}$ describes antisymmetric spin correlations, $S^a_{q,\omega} = m^a \epsilon^{\alpha\beta\gamma} \langle S^\beta_{q,\omega} S^\gamma_{-q,-\omega}\rangle$, and $\phi_{q,\omega}$ is the dynamic nuclear structure factor. In the spin-wave region with $\omega \ll T$, we have the following expression for $S^a_{q,\omega}$:

$$S^a_{q,\omega} = \frac{T}{2\omega} M\{\delta(\omega - \epsilon_q) + \delta(\omega + \epsilon_q)\}\,, \qquad (2a)$$

$$\epsilon_q^2 = \{Dq^2 + g\mu H_i\}\{Dq^2 + g\mu H_i + 4\pi g\mu M[1 - (\mathbf{em})^2]\}\,, \qquad (2b)$$

where ϵ_q is the energy of the spin wave, and H_i is the internal magnetic field. If $\theta \ll 1$ and $\omega \ll E$, where E is the energy of the incident neutrons, we have

$$(\mathbf{em})^2 = \frac{k^2}{2} q^{-2}\left\{\theta_x^2(1 - \cos 2\varphi) + \left(\frac{\omega}{2E}\right)^2 (1 + \cos 2\varphi) + \theta_x \frac{\omega}{2E}\sin 2\varphi\right\}. \qquad (3)$$

Here $q^2 = k^2[\theta^2 + (\omega/2E)^2]$, $\theta^2 = \theta_x^2 + \theta_y^2$, the x axis runs perpendicular to the momentum of the incident neutrons ($\mathbf{k}$) and lies in the plane defined by $\mathbf{e}$ and $\mathbf{m}$, and φ is the angle between $\mathbf{k}$ and $\mathbf{m}$. It follows from (1)–(3) that if the scattering is dominated by processes for which the condition $\omega \ll E$ holds, the scattering by spin waves can be separated experimentally from the contribution of the interference of magnetic and

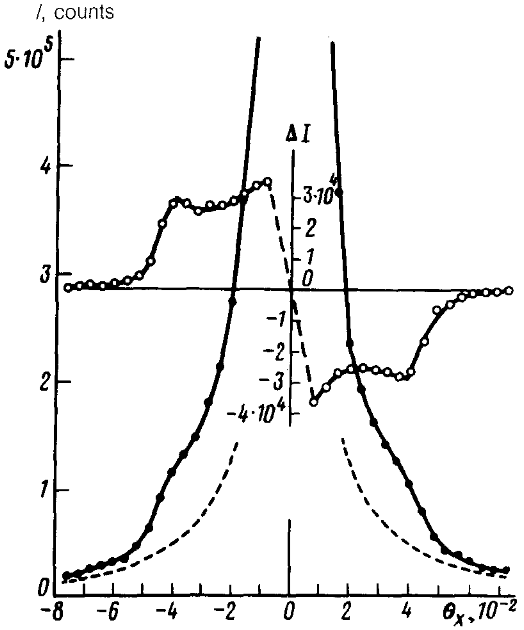

FIG. 1. The angular dependences $I(\theta_x)$ and $\Delta I(\theta_x)$. Dashed line—Profile of the direct beam.

nuclear scattering. For this purpose we need the measure $\Delta I(\theta_x)$ at scattering angles θ_x and $-\theta_x$ and form the difference $A(\theta_x) = \frac{1}{2}[\Delta I(\theta_x) - \Delta I(-\theta_x)]$. The quantity $A(\theta_x)$ is nonzero only at $\varphi \neq 0, \pi/2$, and the interference scattering does not contribute to it. In leading order in the parameter ω/E, the function $\phi_{q,\omega}$ is of even parity in ω, while the last term in (3), proportional to θ_x, is odd in ω. Consequently, the integral of their product over ω is zero. The function $S^a_{q,\omega}$, on the other hand, is not even in ω, so that the difference $A(\theta_x)$ is not zero. Substituting (3) and (2) into (1), we can easily calculate $\Delta I(\theta_x)$ and then $A(\theta_x)$. That is not our purpose here, however (corresponding calculations for the scattering cross section were carried out in Ref. 9). We simply note, that according to (2) and (3), a scattering by spin waves is

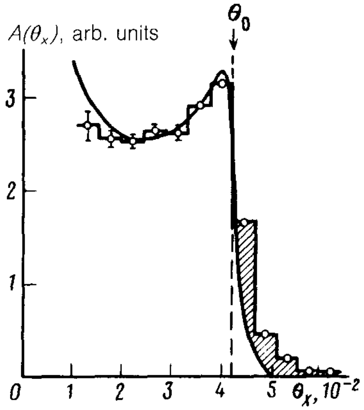

FIG. 2. The angular dependence $A(\theta_x)$. Solid line—Calculated with allowance for the angular resolution of the apparatus.

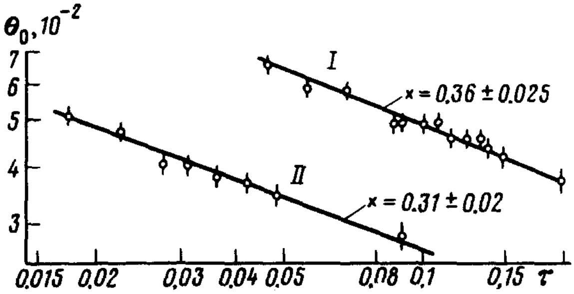

FIG. 3. The dependence $\theta_0(\tau)$ for samples I and II.

possible at angles $\theta \leqslant \theta_0$, where θ_0 is determined by the region in which solutions of the dispersion relations exist, $\omega = \pm \epsilon_q(\omega)$. In the simplest case, with $Dk^2\theta_0^2 \gg g\mu H_i$ and $Dk^2\theta_0^2 \gg 4\pi g\mu M$, we find $\theta_0 = E/Dk^2$ from (2b) and (3), where we have $D = D_0\tau^x$ at $(T - T_C) \ll T_C$. Under our experimental conditions, both of these inequalities hold. Furthermore, the measurements are carried out at the specially selected angle $\varphi = 45°$, at which we have $\theta_0 = E/Dk^2$, according to our analysis, even if the latter of these inequalities does not hold. Consequently, by determining the angle θ_0 at which $A(\theta_x)$ falls off sharply we can find the values of $D(\tau)$. Figures 1 and 2 show examples of the angular dependence of the scattering intensity $I(\theta_x)$, of the polarization asymmetry $\Delta I(\theta_x)$, and of the left-right asymmetry $A(\theta_x)$.

The samples in our experiments, with dimensions of $1 \times 10 \times 50$ mm, are fabricated from pieces of tapes of the metallic glasses 50Fe22Ni10Cr18P (I) and 48Fe34Ni18P (II), with a thickness of 30 μm. The measurements are carried out in a beam of neutrons with an average wavelength $\bar{\lambda} = 8.8$ Å ($\Delta\lambda/\lambda = 30\%$) in the momentum-transfer interval $0.02 \lesssim q \lesssim 0.05$ Å^{-1} and in the interval $\omega \lesssim 2 \times 10^{-4}$ eV of effective energy transfer.

It can be seen from Fig. 2 that the limiting angle θ_0 from the dependence $A(\theta_x)$ is determined within an error which does not exceed the angular resolution of the apparatus, $\Delta\theta_x = 4 \times 10^{-3}$. The sharp decrease in $A(\theta_x)$ at $\theta_x > \theta_0$ is evidence that the conditions for the applicability of the spin-wave approximation hold well: At $\theta_x > \theta_0$, scattering is possible (the hatched region in Fig. 2) only by virtue of the finite lifetime of the magnons. This scattering increases as τ decreases because of an increase of the damping of spin waves toward T_C.

Figure 3 shows the temperature dependence $\theta_0(\tau)$. Analysis of these results by the method of least squares yields a spin-wave stiffness $x = 0.36 \pm 0.025$, $D_0 = 94 \pm 9$ meV·Å^2, and $T_C = 355$ K for sample I; for sample II we find $x = 0.31 \pm 0.02$, $D_0 = 160 \pm 12$ meV·Å^2, and $T_C = 577$ K.

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