Spin dynamics of the amorphous Invar alloy $Fe_{0.86}B_{0.14}$

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High-resolution neutron scattering studies have been made of the long wavelength spin excitations in a ribbon sample of amorphous $Fe_{0.86}B_{0.14}$, which exhibits Invar properties. Spin waves were observed in the wave vector range $0.05\ \text{Å}^{-1}<q<0.12\ \text{Å}^{-1}$ at temperatures between 300 K ($0.54\ T_c$) and 500 K ($0.90\ T_c$). The spin wave energies are well described by a dispersion relation $E = Dq^2 + \Delta$. The small energy gap Δ of ≈ 0.04 meV is attributed primarily to the dipole-dipole interaction. The stiffness constant renormalizes with temperature as $D = D(0)[1.0 - 0.86\,(T/T_c)^{5/2}]$ in the range of temperatures under study, with $D(0) = 132$ meV Å^2. This value of $D(0)$ is approximately twice as large as that calculated from the $T^{3/2}$ coefficient of the magnetization, a discrepancy common to many Invar materials. Plots of the intrinsic linewidths against q^4 and T^2 reveal that the data are consistent with the $\Gamma \propto q^4[T\ln(kT/E)]^2$ dependence predicted for a Heisenberg ferromagnet. There are no anomalies in the spin-wave lifetimes at long wavelengths which appear to relate to the Invar effect seen in the Fe_xB_{1-x} system.

INTRODUCTION

The amorphous alloy $Fe_{0.86}B_{0.14}$ has been shown to exhibit Invar characteristics[1] where the usual thermal contraction with decreasing temperature is compensated by a large positive magnetostriction as the spontaneous magnetization in the system develops. Previous studies of this alloy system[2,3] showed that conventional spin-wave excitations are found at small wave vectors for temperatures up to at least $0.90\ T_c$.

The spin-wave energies were found to obey the normal quadratic dispersion relation

$$E = \Delta + D(T)q^2 + ..., \tag{1}$$

where Δ is an effective anisotropy gap which originates in this alloy from the dipole interaction; D is the exchange stiffness constant and q is the magnon wave vector. The spin-wave stiffness constant exhibited a temperature dependence of the Dyson form

$$D(T) = D(0)[1 - a(T/T_c)^{5/2}] \tag{2}$$

in agreement with the two-magnon interaction theory of a Heisenberg ferromagnet. This $T^{5/2}$ dependence was observed over an unusually wide range of temperature, as found in other amorphous ferromagnets. The stiffness constant obtained from the neutron scattering measurements, however, was almost twice as large as that derived from the $T^{3/2}$ coefficient of the magnetization.[2,3] Such a discrepancy implies that additional excitations other than long wavelength spin waves are present and lead to the anomalously rapid decrease of the bulk magnetization with increasing temperature. Similar behavior has also been reported for other Invar systems, namely crystalline $Fe_{0.65}Ni_{0.35}$ and Fe_3Pt (Ref. 4), and is apparently an intrinsic dynamic property peculiar to the Invar state.

To further characterize possible effects of the Invar anomaly on the spin dynamics, we have carried out detailed measurements of the spin-wave energies and linewidths as a function of temperature and magnon wave vector. Conventional two-magnon interaction theory for a Heisenberg ferromagnet gives for the linewidth[5]

$$\Gamma \propto q^4\left[T\ln\left(\frac{kT}{E}\right)\right]^2, \tag{3}$$

and this relationship has been confirmed in a number of crystalline and amorphous alloys[6] which do not exhibit Invar properties.

SAMPLE PREPARATION AND EXPERIMENTAL DETAILS

A sample of $Fe_{0.86}B_{0.14}$ was prepared in ribbon form by the planar flow casting technique in vacuum. Boron enriched to 98.5% ^{11}B was used to reduce the neutron absorption. The ribbons were wound between two aluminum posts to produce a flat platelike sample which was placed in a vacuum furnace.

The neutron scattering measurements were taken on a triple axis spectrometer at the National Bureau of Standards Reactor. Pyrolitic graphite [PG(002)] crystals were used as monochromator and analyzer. The incident energy was fixed at 13.95 meV and a PG filter was placed just after the monochromator in order to suppress higher order wavelength contaminations. Soller slit collimators of 15′-12′-11′-25′ were used to produce a FWHM energy resolution of 0.35 meV at the elastic position.

RESULTS

The amorphous state required that measurements be taken near the forward (0, 0, 0) beam position. Wave vector

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transfers examined were in the range $0.05\ \text{Å}^{-1} \leqslant q \leqslant 0.12\ \text{Å}^{-1}$ and at temperatures ranging from 4–500 K (0.90 T_c). Well-defined spin waves were observed for temperatures above approximately 300 K (0.54 T_c). At lower temperatures the spin-wave energies were above the experimentally accessible range. In analyzing the data, spin-wave energies and damping information were obtained by convoluting the theoretical cross sections with the instrumental resolution. Three different theoretical cross sections corresponding to double Lorentzian, damped harmonic oscillator[7] and Halperin and Hohenberg[8] forms of the spectral weight function were used. After subtraction of the background scattering measured at 4 K, the data were least-squares fitted to the convoluted cross sections to obtain values of the spin-wave energies and linewidths. The results with all three spectral weight functions yielded a dispersion relation of the form of Eq. (1). Figure 1 shows the dispersion relations obtained for the double Lorentzian spectral weight function, which gave the best fit to the data. The gap $\Delta \sim 0.04$ meV shows only a slight temperature dependence and is consistent with the value 0.038 meV obtained from the Holstein–Primakoff treatment of a Heisenberg ferromagnet when the dipole-dipole interaction is included.[9]

The stiffness constant D renormalizes in accordance with Eq. (2) over the whole range of temperatures under study (see Fig. 2), with $D(0) = 132.5 \pm 0.7$ meV Å^{-2} and $a = 0.86 \pm 0.01$. For this nominal concentration values of 138 and 118 meV Å^2 have been previously reported for $D(0)$ in Refs. 2 and 3, respectively. These values are to be contrasted to $D_{\text{mag}} = 65$ meV Å^2 as calculated from the $T^{3/2}$ term in the low-T magnetization.[10] This discrepancy is a common signature to Invar alloys as discussed above.

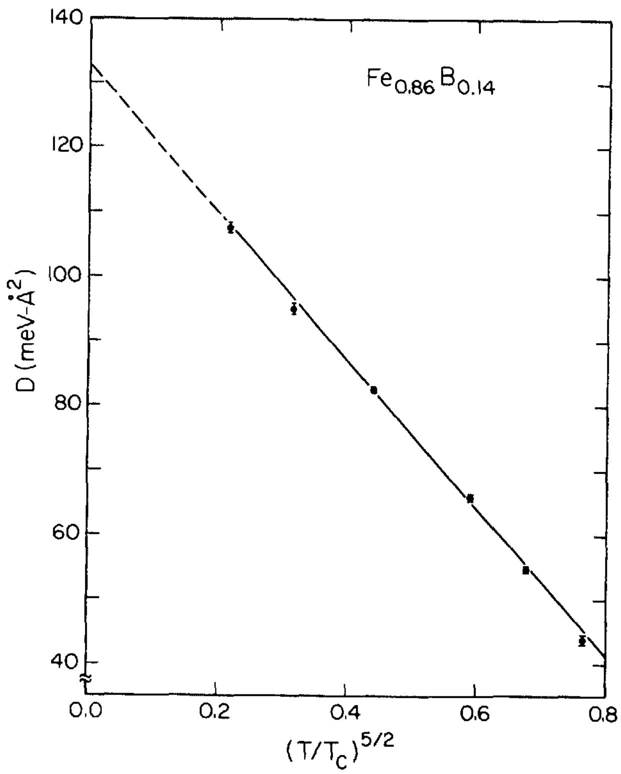

FIG. 2. The stiffness constant "D" plotted as a function of $(T/T_c)^{5/2}$ in the range of temperatures under study (0.54 T_c–0.90 T_c), showing the typical two-magnon form of renormalization.

The spin-wave data have also been analyzed for the temperature and wave vector dependence of the intrinsic

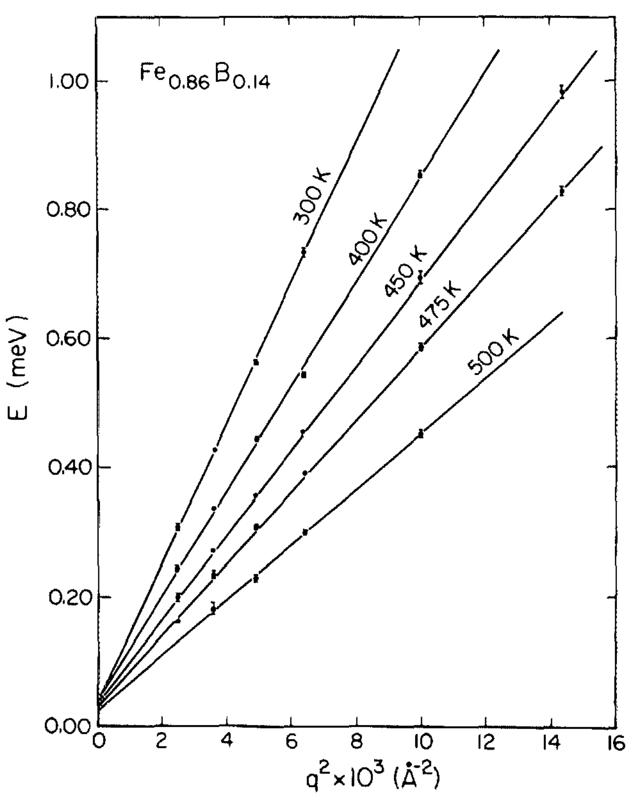

FIG. 1. Spin-wave dispersion relations for the $Fe_{0.86}B_{0.14}$ amorphous system for several temperatures. The spectral weight function used in the analysis was a double Lorentzian.

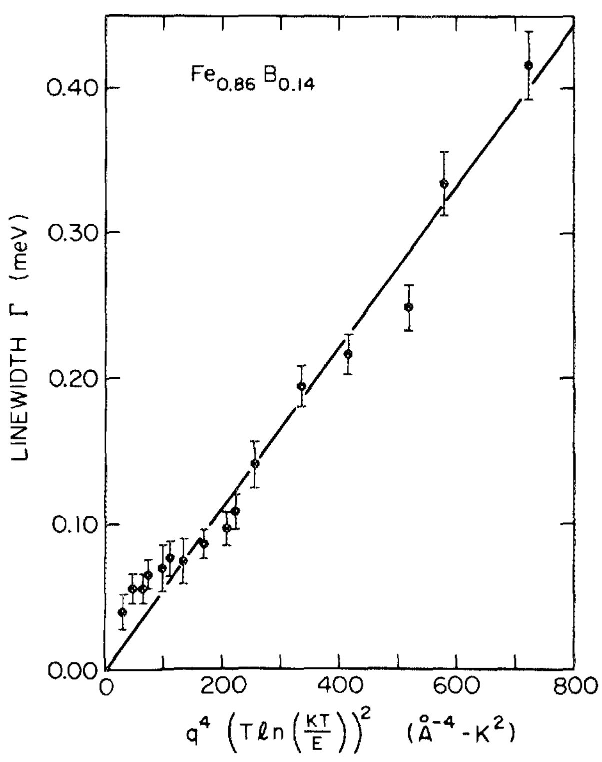

FIG. 3. The dependence of the intrinsic spin-wave linewidths on the quantity $q^4[T\ln(kT/E)]^2$ as predicted from the two-magnon interaction theory for a Heisenberg ferromagnet.

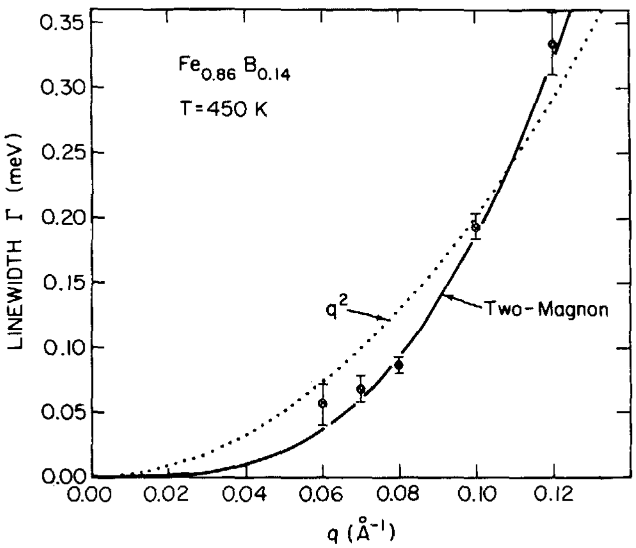

FIG. 4. The intrinsic spin-wave linewidths as a function of q at a fixed temperature ($T = 450$ K) for the $Fe_{0.86}B_{0.14}$ amorphous system. The solid line is the result from the fit to Eq. (3) for the Heisenberg linewidth broadening showing clearly the $q^4 \ln^2(kT/E)$ dependence in contrast to a q^2 dependence[3,4] as given by the dotted line.

linewidths (Γ). The results have been compared to the form of Eq. (3) in Fig. 3 where the intrinsic linewidths (Γ—full width at half maximum) have been plotted vs $q^4[T\ln(kT/E)]^2$. It is evident from this figure that the linewidth data are consistent with this theoretical form, derived from the two-magnon interaction theory of a Heisenberg ferromagnet.[5] The slight departures from this functional relation in the vicinity of the origin of Fig. 3 correspond to temperatures lower than 400 K where the intrinsic line broadening is considerably smaller than the instrumental resolution.

Previous results for the Invar alloys $Fe_{0.65}Ni_{0.35}$ and Fe_3Pt (Ref. 4) reported linewidths which obeyed the empirical form

$$\Gamma = (\Gamma_0 + CT^{\alpha})q^2, \tag{4}$$

where $0 < \alpha < 1$, and this same behavior has also been reported for amorphous $Fe_{0.86}B_{0.14}$.[3] In contrast to these results, our linewidths are found to be consistent with the conventional Heisenberg form [Eq. (3)]. In particular, our linewidth data do not show a q^2 dependence at any temperature examined, as shown for example in Fig. 4. Here the linewidths at $T = 450$ K ($0.81\ T_c$) are plotted as a function of q and compared to Eq. (3) (solid line) and to a q^2 dependence (dotted line). In summary we find no anomalies in the long wavelength magnon lifetimes which result from the Invar effect in the Fe_xB_{1-x} alloy system.

ACKNOWLEDGMENT

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[1]K. Fukamichi, H. Hiroyoshi, M. Kikuchi, and T. Masumoto, J. Magn. Magn. Mater. **10**, 294 (1979).
[2]J. J. Rhyne, G. E. Fish, and J. W. Lynn, J. Appl. Phys. **53**, 2316 (1982).
[3]Y. Ishikawa, K. Yamada, K. Tajima, and K. Fukamichi, J. Phys. Soc. Jpn. **50**, 1958 (1981).
[4]S. Onodera, Y. Ishikawa, and K. Tajima, J. Phys. Soc. Jpn. **50**, 1513 (1981); Y. Ishikawa, S. Onodera, and T. Tajima, J. Magn. Magn. Mater. **10**, 183 (1979).
[5]A. B. Harris, Phys. Rev. **175**, 674 (1968); V. G. Vaks, A. I. Larkin, and S. A. Pikin, Sov. Phys. JETP **26**, 647 (1968).
[6]See for example, J. D. Axe, G. Shirane, T. Mizoguchi, and Y. Yamauchi, Phys. Rev. B **15**, 2763 (1977); J. A. Tarvin, G. Shirane, R. J. Birgeneau, and H. S. Chen, Phys. Rev. B **17**, 241 (1978).
[7]See for example, R. A. Cowley, W. J. L. Buyers, P. Martel, and R. W. H. Stevenson, J. Phys. C **6**, 2997 (1973).
[8]B. J. Halperin and P. C. Hohenberg, Phys. Rev. **188**, 898 (1969).
[9]T. Holstein and H. Primakoff, Phys. Rev. **58**, 1098 (1940).
[10]R. Hasegawa and R. Ray, Phys. Rev. B **20**, 211 (1979).