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# NEUTRON SCATTERING STUDY OF SPIN WAVES IN THE AMORPHOUS FERROMAGNET $(Fe_{0.3}Ni_{0.7})_{0.75}P_{0.16}B_{0.06}Al_{0.03}$

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## ABSTRACT

The neutron inelastic scattering technique has been used to measure the collective magnetic excitation spectrum in the ferromagnetic ($T_C \sim 255$ K) metallic glass $(Fe_{0.3}Ni_{0.7})_{0.75}P_{0.16}B_{0.06}Al_{0.03}$. In this system only the iron atoms appear to be magnetic, and the observation of relatively well-defined spin waves is striking in comparison with other amorphous systems where the spin waves rapidly broaden with decreasing iron concentration. The spin waves obey the conventional quadratic dispersion relation $E_{SW}=DQ^2$, with D=35meV-Å$^2$. Contributions from fourth and higher order terms in the dispersion relation are not in evidence for wave vectors in the region investigated ($Q \lesssim 0.25$ Å$^{-1}$).

## INTRODUCTION

Metallic glasses form a new class of materials which have interesting and technologically important magnetic and metallurgical properties. A variety of experimental techniques has recently been employed to investigate the magnetism of these systems, but it has proven difficult to achieve a consistent picture of the underlying microscopic magnetic properties.[1] We have therefore undertaken a systematic investigation of the amorphous ferromagnetic systems $(Fe\text{-}Co\text{-}Ni)_{0.75}P_{0.16}B_{0.06}Al_{0.03}$. The structure of these materials can be characterized as a dense random packing of spheres. They also have well-defined ferromagnetic transition temperatures.[2] Moreover, in the glasses containing Fe and Ni, the Ni atoms appear not to possess magnetic moments. Thus the magnetic properties of these alloys may be more easily understood since there is only one magnetic species present. In this note we wish to report our initial neutron scattering measurements for $(Fe_{0.3}Ni_{0.7})_{0.75}P_{0.16}B_{0.06}Al_{0.03}$. This relatively low magnetic concentration was chosen so that the ferromagnetic transition would be below room temperature, which offers several advantages. Firstly, the critical magnetic region is in an experimentally convenient temperature range which is well below the temperatures at which repacking and recrystallization occur. Secondly, the low transition temperature implies

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that the exchange energy is relatively small, so that the spin-wave energies are in a more accessible energy range for neutron scattering measurements.

## SAMPLES

The samples were made by the centrifugal spinning technique[3] in the form of ribbons 1 mm wide, 0.1 mm thick and 5 m long. The ribbons were then cut into strips 2 cm long and stacked together in the shape of a plate 2 x 2 $cm^2$. The total weight of the sample was 10 gm. A special isotope of boron ($^{11}B$) was used in the starting materials to avoid the high absorption cross section for neutrons of naturally occurring boron.

A diffraction pattern taken on the sample showed a broad peak in the scattering function S(Q) centered at 3.12 $Å^{-1}$, which corresponds closely to the position expected on the basis of dense random packing of spheres. No sharp peaks characteristic of a crystalline phase were observed, and no preferred directional or structural anisotropies were detected. To determine the magnetic transition temperature, the intensity of the elastic scattering was measured at $Q = 0.06$ $Å^{-1}$ as a function of temperature. The critical scattering was found to peak at $T \sim 255$ K, which we took to be the nominal value of the ferromagnetic transition temperature. This value is in good agreement with the value expected on the basis of bulk magnetization measurements[2] for this alloy concentration and is also consistent with magnetization measurements taken on this sample.

## RESULTS AND DISCUSSION

The neutron scattering experiments were performed on a triple-axis spectrometer at the Brookhaven High Flux Beam Reactor. Pyrolytic graphite crystals were used as both monochromator and analyzer. A fixed incident neutron energy of 14.8 meV was employed for the measurements with $Q \lesssim 0.20$ $Å^{-1}$, with horizontal collimation before and after the monochromator and analyzer respectively of 20 minutes full width at half maximum (denoted 20'-20'-20'-20') or a combination of 20 and 10 minutes, in this case 20'-10'-10'-20'. For Q in the range 0.20 to 0.25 $Å^{-1}$ we used incident neutron energies of 40.5 meV and 10'-10'-10'-10' collimation. A pyrolytic graphite filter was placed before the monochromator to suppress higher order wavelengths in the incident beam.

The measurements of the inelastic scattering spectra were taken by fixing the magnitude of the momentum transfer Q and varying the energy transfer E. Some typical measurements are shown in Fig. 1. The peak centered at zero energy transfer, whose width is instrumental in origin, has a magnetic contribution but is

primarily due to scattering from the cryostat and elastic nuclear scattering from the sample. The peaks on either side are due to the creation ($E > 0$) and annihilation ($E < 0$) of collective magnetic excitations in the system. These relatively well-defined spin waves are striking in comparison with other amorphous systems studied where the spin waves rapidly broaden with decreasing iron concentration[4,5] and become overdamped at magnetic concentrations considerably higher than in the present system.

With increasing Q the excitations shift to higher energies and broaden. The observed peak intensities of these excitations are also seen to decrease rapidly with increasing Q. Firstly, this is due to the decrease in the thermal population of the spin-wave states with increasing energy. In addition, the line widths are rapidly increasing, and since for this energy and temperature range the integrated intensity in a constant Q scan is

$$\int I(E)dE \approx \Gamma/E \qquad (1)$$

the peak intensity decreases as the line widths increase. Thus with increasing Q the signal-to-noise ratios become rapidly less favorable.

The spin-wave energies, corrected for instrumental resolution, are shown in Fig. 2. Over this wave vector range the data are seen to obey

$$E_{sw} = DQ^2 \qquad (2)$$

very closely. The slope of the line yields a value for the spin-wave stiffness constant D of $(35 \pm 3)$meV-$A^2$. The error bars in the figure represent one standard deviation.

To obtain some information about the line widths of the spin-wave excitations, we performed least-squares fits of the inelastic portion of the spectra to a dispersion relation of the form of Eq.(2), with the spectral weight function[6] taken to be of the Lorentzian form

$$F(Q,E) = \frac{1}{\pi}\left\{\frac{\Gamma(Q)}{\Gamma(Q)^2 + (E - E_{sw}(Q))^2}\right\}. \qquad (3)$$

The solid curves in Figs. 1 and 3 are the results of these least-squares fits. For the data in Fig. 1 we obtained values for the line widths $\Gamma$ (HWHM) of 0.06, 0.23, and 0.45 meV at $Q = 0.14$, 0.16, and 0.18 $A^{-1}$ respectively. The ratios of the line widths to the excitation energies for these values of Q are then $\Gamma/E_{sw} = 0.09$, 0.26, and 0.40. Thus as Q increases the

spin waves become rapidly broader relative to their energies.

Fig. 3 shows data at 100 K and 220 K. These measurements were taken with somewhat better resolution than those in Fig. 1. At the lower temperature the widths of the spin waves at $Q = 0.12\ \text{Å}^{-1}$ are much smaller than the instrumental resolution, whereas for $Q = 0.16\ \text{Å}^{-1}$ we find $\Gamma = 0.23$ meV. At 220 K the spin waves have obviously broadened and renormalized to lower energies. From the least-squares fits we obtain $D = 22$ meV-Å$^2$ for the spin-wave stiffness parameter, and $\Gamma = 0.05$ meV and $\Gamma = 0.31$ meV for the spin-wave line widths(HWHM) at $Q = 0.12$ and $0.16\ \text{Å}^{-1}$ respectively. Note also that the scattering at $E = 0$ increases in intensity with increasing temperature, and this increase cannot be attributed simply to an overlapping of the elastic and inelastic contributions to the scattering. We would also like to point out that there appears to be some additional inelastic scattering at the higher values of Q in the region between the spin-wave peak and the resolution limited $E = 0$ peak. Thus the description of the magnetic states may be more complicated than simply well-defined spin-wave states with a quadratic dispersion curve as given by Eq.(2). This could be the source of the difference found in some systems between the value of the spin-wave stiffness constant as determined by bulk magnetization measurements using conventional spin-wave analysis, and the value for D as determined by identifying the peak in the neutron scattering cross section with the spin-wave energy.[5] Clearly, further work will be needed in order to properly characterize the nature of this scattering. Further measurements are in progress.


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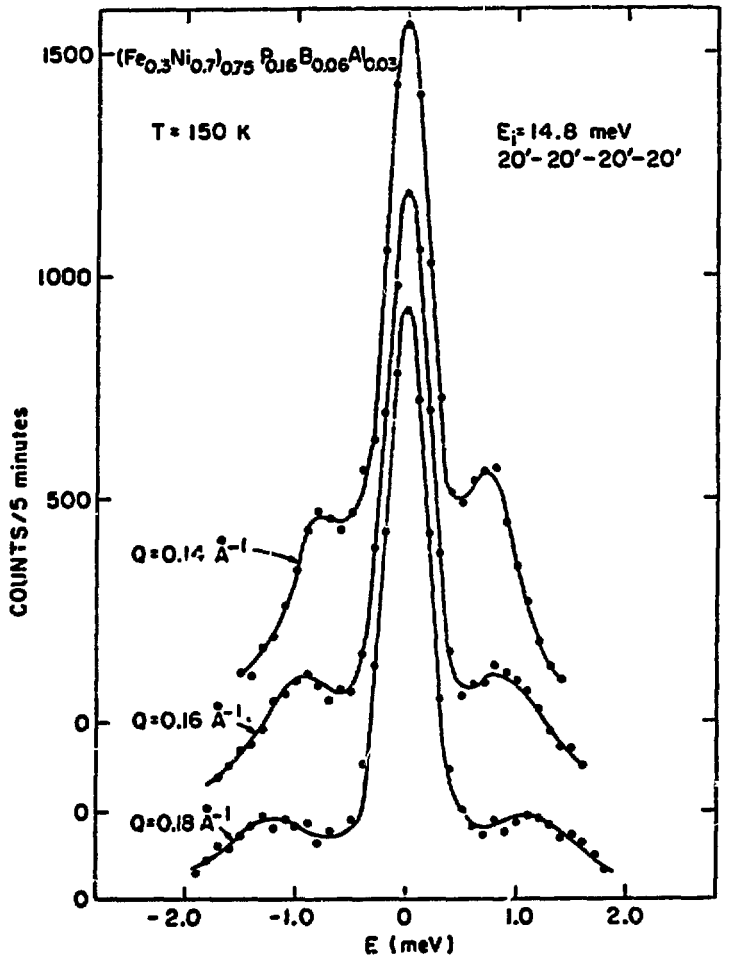


Fig. 1. Constant-Q scans at several values of Q below the ferromagnetic transition temperature. The peak centered at E = 0, which is limited in width by the instrumental resolution, has a magnetic contribution but is primarily due to nuclear elastic scattering and scattering from the cryostat. The peaks on each side are the spin-wave excitations. The solid curves are the least-squares fits as explained in the text.

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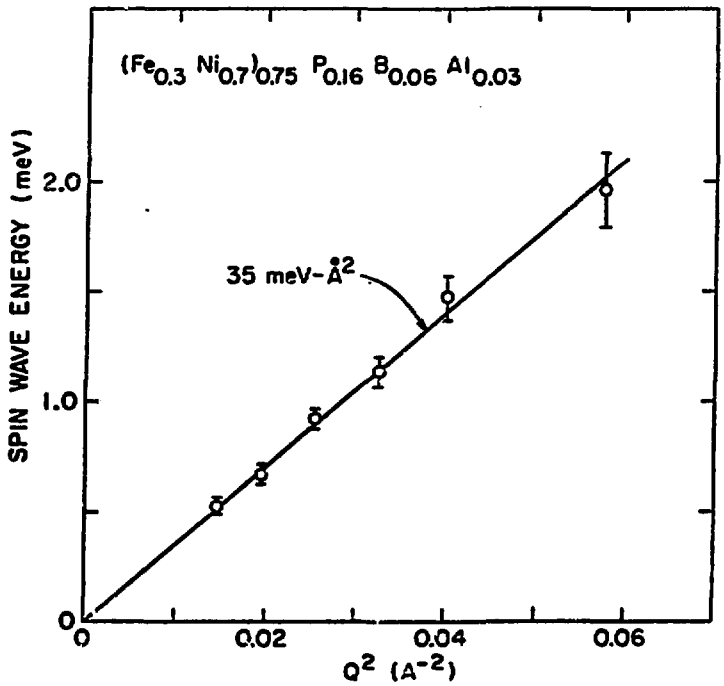


Fig. 2. The spin-wave energy at low temperatures plotted against $Q^2$, showing that the spin waves obey a quadratic dispersion relation over this wave vector range.

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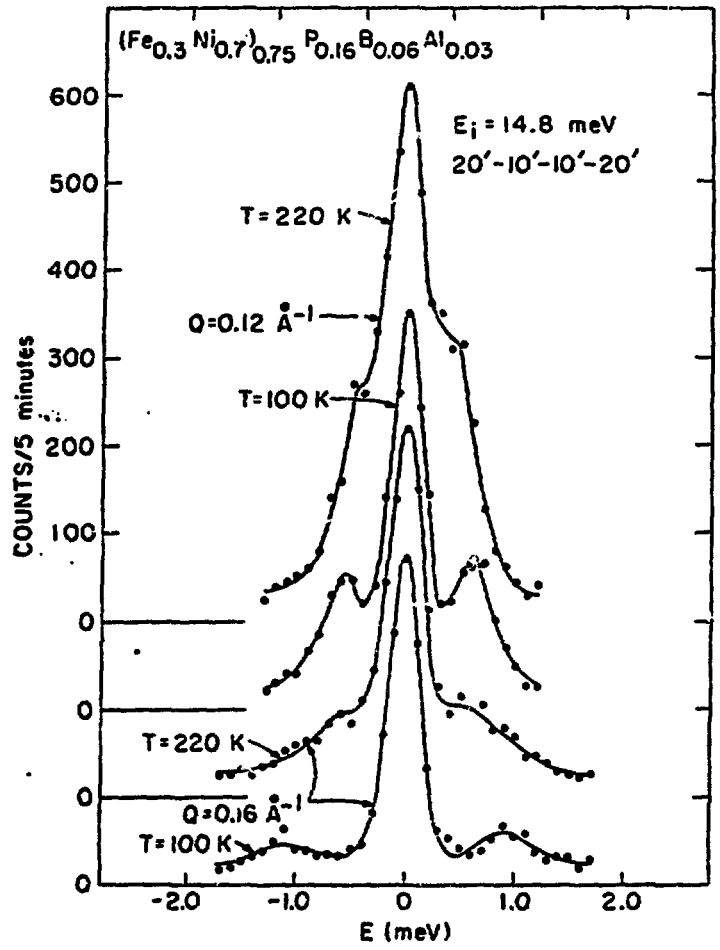


Fig. 3. Constant-Q scans at Q = 0.12 Å$^{-1}$ and Q = 0.16 Å$^{-1}$ at 100 and 220 K. The spin waves have broadened and renormalized to lower energies at the higher temperature. The solid curves are the least-squares fits to the data as explained in the text.

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