Reply to "Comment on 'Magnetism in $Au_{82.5}Fe_{17.5}$'"

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The description in the preceding Comment [Boumazouza *et al.*, Phys. Rev. B **39**, xxxx (1989)] of the Mössbauer-effect spectra for the $Fe_{0.65}Cr_{0.35}$-based amorphous alloy suggests the onset of the hyperfine field at 84 K, but it also shows clearly that at least down to 60 K the hyperfine field is not sufficiently well developed to indicate ferromagnetism. Even if this development to a six-line spectrum is completed below 60 K, the wide temperature range required for this development clearly indicates the presence of superparamagnetic fluctuations and the absence of ferromagnetism between 60 and 84 K. Hence, a clear-cut paramagnetic-to-ferromagnetic phase transition at 84 K, as implied in the Comment, appears not to be compatible with the data described. On the other hand, Boumazouza *et al.* are fully justified in calling attention to the apparently cooperative change at 84 K, even if it is not sufficiently extensive to result in ferromagnetism.

The "counterexample" of $(Fe_{0.65}Cr_{0.35})_{75}P_{15}C_{10}$ described in the Comment[1] is very interesting indeed. This amorphous spin-glass alloy shows $\sigma(T)$ behavior very similar to that of $Au_{82.5}Fe_{17.5}$ with a well-defined upper knee near 85 K in the large demagnetization-factor configuration but no upper knee at all when the demagnetization factor is small. Nevertheless, in contrast to the gold-iron alloys, the Mössbauer effect (ME) spectrum indicates a hyperfine field up to the temperature of the upper knee. This appears to be consistent with the position of the Comment that at 84 K a phase transition takes place from paramagnet to long-range ferromagnet.

However, as described in the Comment and shown in Fig. 3(b) (Ref. 1), the ME spectrum from 84 down to at least 60 K consists of a quadrupole doublet and the hyperfine field is indicated only by a pronounced broadening of the two lines of the doublet. This means that the transition of the ME spectrum from the paramagnetic to the six-line type extends over a temperature range of more than 30% of the presumed Curie temperature of 84 K, a very broad transition in contrast with the sharp transition at the Curie temperature of a normal ferromagnet. As shown by Rancourt and Daniels,[2] such ME spectra can result from superparamagnetic fluctuations. This interpretation of the ME spectrum implies that no "true phase transition" from paramagnet to long-range ferromagnet occurs at 84 K. In fact, the amorphous Fe-Cr–based alloy appears to be very similar to $Au_{82.5}Fe_{17.5}$ in regard to its quasisuperparamagnetic behavior. Borg, Lai, and Violet[3] published an ME spectrum for quenched $Au_{83.4}Fe_{16.6}$ at 65 K and this, as well as its temperature dependence, corresponds closely to the description in the Comment of the ME spectra for the amorphous Fe-Cr–based alloy. Here, too, the transition, as seen in the ME spectrum, is a very broad one, strongly suggesting superparamagnetic fluctuations.

Figure 3 of Ref. 2 shows calculated ME spectra to be expected for a superparamagnetic alloy in the presence of various applied fields. This offers further opportunities for checking the conclusion as to the quasisuperparamagnetic nature of the alloys discussed above.

A very interesting feature of the amorphous Fe-Cr–based alloy is the well-defined sharp maximum at 84 K in the small-angle neutron scattering versus temperature curve. It suggests some kind of a cooperative interaction between the fluctuating superparamagnetic moments, which is not sufficiently strong to change the quasisuperparamagnet into a ferromagnet. The large and quite sharp peak in the susceptibility versus temperature curves for the "reentrant" Au-Fe alloys observed by Sarkissian[4] suggests a similar "weak cooperative interaction effect" at about the temperature of the upper knee of $\chi(T)$ for these alloys as well. Because of the sharpness of these peaks, they also were originally interpreted as indications of the onset of long-range ferromagnetism. However, it was recognized later,[5] that there are no corresponding peaks in the magnetic specific heat versus temperature curves for $Au_{85}Fe_{15}$ and $Au_{82}Fe_{18}$, measured by Mirza and Loram.[6] As mentioned above, the ME spectrum of $Au_{83.4}Fe_{16.6}$ at 65 K (Ref. 3) clearly indicates superparamagnetic fluctuations well below Sarkissian's "Curie temperature." This explains the absence of an entropy change and of a transition into the long-range ferromagnetic phase at the so-called Curie temperature. It may be assumed that the gold alloys with 15 and 18 at.% Fe are also quasisuperparamagnetic and thus are also subject to such fluctuations. The interesting question as to the precise nature of the weak cooperative interaction effect, failing to result in ferromagnetism, suggested by the information available at present, still remains to be explored.

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[2] D. G. Rancourt and J. M. Daniels, Phys. Rev. B **29**, 2410 (1984).
[3] R. J. Borg, D. Y. F. Lai, and C. E. Violet, Phys. Rev. B **5**, 1035 (1972).
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[6] K. A. Mirza and J. W. Loram, J. Phys. F **15**, 439 (1985).

