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TEMPERATURE DEPENDENCE OF THE μ^+ HYPERFINE FIELD IN FERROMAGNETS*

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Abstract

The temperature dependences of the μ^+ hyperfine fields in Ni and in Fe were found to deviate from that of the saturation magnetization in opposite senses. Difference in the screening mechanism of conduction electrons around the μ^+ is considered, among several possible explanations.

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Since the first successful experiment in ferromagnets [1], the positive muon spin rotation method has been extensively used to study interstitial spin densities in magnetic materials. Recently, precise measurements of the temperature dependences of the local hyperfine fields felt by the μ^+ in Ni [2] and Fe [3] have shown different types of deviations from the temperature dependence of the saturation magnetization, both in sign and in magnitude. In this paper we present the experimental results as well as some trials at interpretation of the results.

With regard to the location and diffusion properties there is a significant difference between the μ^+ in Ni and μ^+ in Fe. Judging from hydrogen diffusion data, the μ^+ is expected to stay for its entire lifetime at specific octahedral sites in fcc Ni below room temperature [2]. On the contrary, the observed μ^+ spin relaxation in Fe can be interpreted as an evidence that the μ^+ is diffusing from one interstitial site (octahedral or tetrahedral) to another, even at 23 K [3].

The μ^+ local magnetic field (B_μ) observed as a precession frequency in a μ^+SR experiment at an external field below saturation can be decomposed into the Lorentz field ($4\pi M/3$), the dipolar field inside the Lorentz cavity (H_{dip}) and the contact field from the conduction electrons (H_{int}). The dipolar field H_{dip} is completely cancelled in Ni because of the crystal symmetry. In Fe we can also assume that $\langle H_{dip} \rangle \sim 0$, because the μ^+ diffuses rapidly through magnetically inequivalent interstitial sites. We introduce a term A(T) to characterize the deviation of the μ^+ hyperfine field from the macroscopic magnetization at finite temperatures: $H_{int}(T)/H_{int}(0) = A(T)M(T)/M(0)$. The experimental results of A(T) for μ^+ in Ni and Fe below 300 K are shown in fig. 1a. Also shown are the results of recent NMR experiments on the temperature dependence of the hyperfine field at ^{12}B nuclei in Ni. Like the μ^+, these nuclei occupy the octahedral interstitial sites in Ni [4]. For comparison, A(T) values at lattice sites taken from NMR experiments on ^{61}Ni in Ni [5] and ^{57}Fe in Fe [6] are shown in fig. 1b.

The following features are readily apparent in these two figures: (1) the deviation of the contact field at the interstitial probes in Ni has an opposite sign to that in Fe; (2) the hyperfine field at lattice sites deviates in the same manner in both Ni and Fe; and (3) the deviation

of the interstitial hyperfine field in Fe has the same sign and almost the same magnitude as that of lattice sites in Fe.

A rather straightforward conclusion drawn from these features is that the interstitial probe in Ni perturbs the host magnetic structure, producing an anomalous deviation of the interstitial fields from the magnetization, while that in Fe does not. This result seems to have relevance to the well-known impurity effects in Ni and Fe: while non-magnetic impurities like Al significantly affect the magnet structure of the neighbouring atoms in Ni, their effect in Fe is mainly simple dilution. According to Mott [7], this phenomenon can be explained by the difference of the screening mechanisms around the impurities. If we apply this theory to the interstitial impurities, the conduction electron screening around the μ^+ would originate from s-electrons in the case of Fe and from d-electrons in Ni.. Although the real mechanism is much more complicated, we might say that the d-electron screening is somewhat enhanced for Ni compared to for Fe. In the case of d-electron screening, contrary to the s-electron screening mechanism as predicted by Daniel-Friedel model [8], the conduction electron polarization induced by positively charged impurity is no longer proportional to the unperturbed spin densities because of exchange correlation in the d-band [9]. If one were to consider this effect correctly, one might find a qualitative explanation for the observed anomaly in A(T) for Ni.

It would be premature to rule out completely some additional mechanisms. One of those is the anomalous volume expansion effect which could arise if the field at the interstitial sites in Ni, in particular, were very sensitive to small changes in volume. The comparison mentioned above should be done at constant volume. Another effect would be the static distortion of the neighbouring lattice producing a local magnetic complex which results in a different type of temperature dependence, similarly as discussed for impurity nuclei in ferromagnets by Jaccarino *et al.* [10]. A third mechanism couid come from a change in the spatial average field seen by μ^+ as its position is broadened with increasing temperature.

Definitely, further studies either experimental or theoretical are required before we reach complete understanding of our results.

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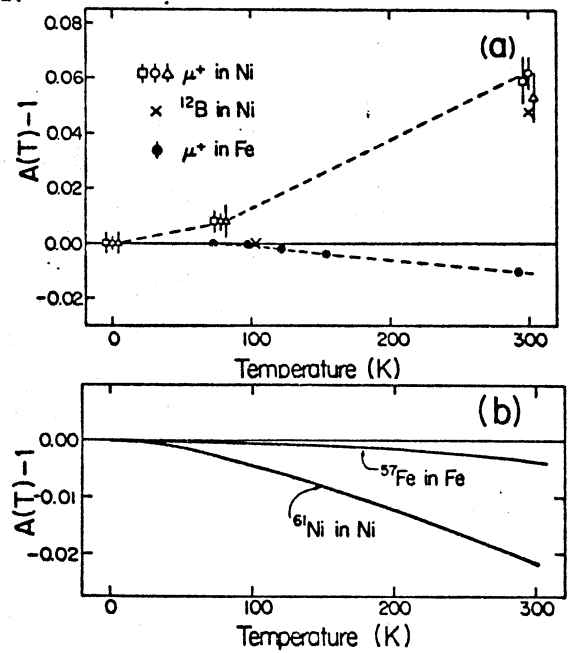

Fig. 1. (a) Temperature dependence of the reduced hyperfine field A(T) at interstitial sites in Ni and Fe observed by μ^+ and ^{12}B (constant pressure). The μ^+ experiments have been done at external fields of 0 G (squares), 153 G (circles) and 340 G (triangles) for Ni and 0 G for Fe. The A(T) value is normalized at 0.12 K for μ^+ in Ni, at 100 K for ^{12}B in Ni and at 73 K for μ^+ in Fe.

(b) Temperature dependence of the reduced hyperfine field A(T) at lattice sites in Ni and Fe (constant pressure). After converting to constant volume, A(T) for Ni becomes unity within 0.5% [5].