# MAGNON-DRAG THERMOPOWER IN IRON*

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Results of measurements on the thermoelectric power of pure nickel, pure iron, and four dilute iron alloys are presented. They strongly suggest that, in iron, magnon drag is dominant over a wide temperature range, and provide the first indication of this mechanism in a ferromagnetic metal.

Several years ago Bailyn[1] suggested that in ferromagnetic metals one might expect a "magnon-drag" effect analogous to the phonon-drag phenomenon which has been observed in all pure metals whose thermoelectric properties have been studied.[2] We here report results of thermopower measurements on pure iron, pure nickel, and several dilute iron alloys which, we believe, can only be interpreted in terms of magnon drag in iron.

Figures 1 and 2 summarize our results. The nickel data are in excellent agreement with the results published by Greig and Harrison.[3] Our data on pure iron agree with the work of Kolomoets and Vedenikov[4] who restricted their measurements to temperatures above 300°K.

The curve of thermopower, $S$, versus temperature for nickel shows evidence of a relatively weak phonon-drag peak near 50°K. That the deviation from the approximately linear relationship in this temperature range is probably due to phonon drag is indicated by the following: (1) As in similar observations with other metals,[5] there is a substantial decrease of this contribution as a result of cold work without significant change in the diffusion thermopower $S_d$. (2) The temperature at which this presumed phonon-drag contribution attains its maximum falls, as it does for many metals,[2] near $\Theta_D/5$, where $\Theta_D$ is the Debye temperature.

The thermopower of iron exhibits a very large peak near 200°K and two anomalies at high temperatures, namely, a slope discontinuity at the Curie temperature and a discontinuity at the $\alpha$-$\gamma$ phase transition. The fact that the peak in $S$ appears at a relatively high temperature
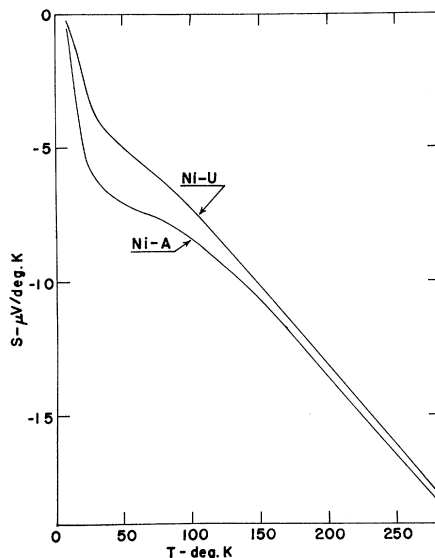


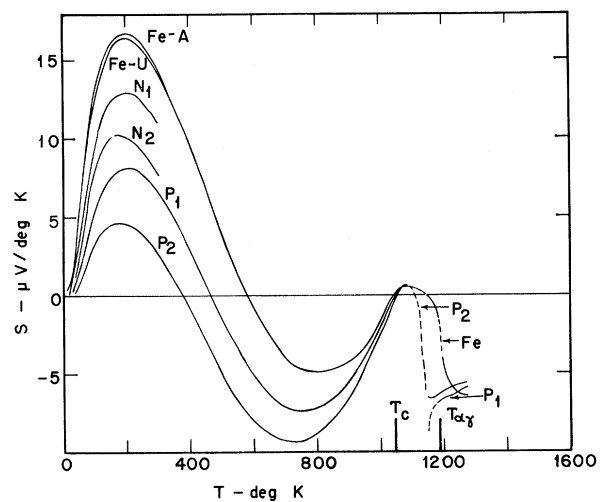FIG. 1. Thermopower of nickel: $A$, annealed; $U$, unannealed.



FIG. 2. Thermopower of iron and iron alloys: Fe-$A$, annealed iron; Fe-$U$, unannealed iron; $N_1$, Fe-0.6 at.% Ni alloy; $N_2$, Fe-1.45 at.% Ni; $P_1$, Fe-1 at.% Pt; $P_2$, Fe-2 at.% Pt.

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suggested to us that phonon drag may not be the dominant mechanism here. More conclusive evidence against phonon drag is the fact that the difference in $S$ between hard-drawn and well-annealed iron is barely perceptible, in sharp contrast to nickel and other metals.

Earlier work on copper[6] demonstrated that phonon drag could be completely quenched by the addition of as little as $\frac{1}{2}$ at.% gold. This reduction is the result of scattering of phonons by the much heavier gold atoms. We therefore measured $S$ of two Fe-Pt alloy wires containing 1 and 2 at.% Pt. We selected Pt rather than Au as the solvent in view of the very limited $\alpha$-phase region of the Fe-Au system.[7]

The results clearly demonstrate that while the addition of Pt reduced the peak, the decrease is an order of magnitude less than expected for phonon drag. Next, we measured $S$ of two Fe-Ni wires containing 0.6 and 1.45% Ni. A comparable reduction of the peak was again observed.

These results can be understood if it is assumed that magnon drag rather than phonon drag is principally responsible for the large peak in $S$ of iron near 200°K. Since coldwork is not expected to inhibit significantly the mean free path of magnons, there should now be no substantial difference between $S$ of annealed and unannealed iron. The effect of Pt and Ni as solutes in Fe is then to be interpreted in terms of (1) a modification of $S_d$ and (2) a reduction of magnon drag as a result of scattering of spin waves by the defects in the magnetic lattice. The strength of this scattering depends principally on the difference of the magnetic moments of Fe and the solute atom and of the exchange coupling between Fe-Fe and Fe-Pt (or Fe-Ni).[8] Unfortunately, these quantities are not well known; however, it is not unreasonable that Pt should present a somewhat larger perturbation in the magnetic lattice of Fe than does Ni.

Finally, we may note here that at low temperatures phonon drag, $S_g$, and magnon drag, $S_m$, should be proportional to their specific heat contributions. Hence, $S_g \propto T^3$ and $S_m \propto T^{3/2}$. We find that over the range 15°K$< T <$ 70°K, $S = \alpha T + \beta T^{3/2}$ with $\beta = 0.016 \pm 0.0005$ $\mu$V (°K)$^{5/2}$ and $\alpha = -0.01 \pm 0.003$ $\mu$V/(°K)$^2$.

The negative value of $\alpha$ is consistent with the negative thermopower of Fe between 700 and 900°K, where magnon drag is presumably negligible as a result of magnon-magnon and magnon-phonon scattering[9] and the onset of the Curie anomaly is not yet pronounced. A relation of the form $S = \alpha'T + \beta'T^3$ does not fit the data over any significant temperature range.

The presence of magnon drag in Fe and its absence in Ni are consistent with the view[10-12] that the behavior, expecially as it relates to transport properties, of iron is best described in terms of spin-disorder scattering of conduction electrons whereas $s$-$d$ scattering seems more appropriate for nickel.

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