NUCLEAR SPECIFIC HEAT OF FeV *ALLOYS*

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The specific heat of FeV alloys containing 4.4 and 13.8 at.% vanadium is measured. H_{eff} at the vanadium nuclei in these alloys is found to be 78 ± 7 and 58 ± 4 kOe, respectively. An explanation is proposed for the observed strong dependence of H_{eff} on the composition of the alloys. An estimate $\bar{p}_V \approx -0.4\,\mu_B$ is obtained for the localized magnetic moment of the vanadium atom in the alloys.

THE nuclei of some elements introduced into a ferromagnetic metal matrix are acted on by a hyperfine interaction field (HIF) that sometimes reaches an intensity of several million oersteds.[1-3] In recent years these fields at the nuclei of impurity atoms have been measured by several methods (NMR, the Mössbauer method, γ-ray anisotropy and β-ray asymmetry of polarized nuclei, nuclear specific heat of alloys) in Fe, Co, and Ni matrices, but thus far no quantitative theory has been published. Further experimental investigation is needed.

The HIF field H_{eff} at a vanadium nucleus in an iron alloy containing 1 at.% V was measured in [4] by the NMR method. A negative [5] value of 87.3 ± 0.5 kOe was obtained. In [6] the specific heat of an iron-vanadium alloy containing 33 at.% V was investigated; the upper limit of the field at the V was determined from the nuclear component of the specific heat: $H_{eff} \leq 61$ kOe.[1)]

We have measured the nuclear specific heat of iron-vanadium alloys having two different concentrations of vanadium: I – 4.4 at.%, and II – 13.8 at.%. The samples were prepared by melting in an electromagnetic crucible.[7] The raw materials were electrolytic iron (Fe – 99.9%, Cr – 0.01%, Ni – 0.01%, Mn – 0.01%, plus C, S, and H_2) and 99.5% pure vanadium (V – 99.52%, Al – 0.01%, Si ≤ 0.01%, S – 0.01%, C – 0.17%, O_2 – 0.23%, N_2 – 0.01%). The samples were then vacuum-annealed for 48 hours at 750°C. The phase diagram of the FeV system [8] shows that the samples were disordered solid solutions of vanadium in iron and that they were ferromagnetic below 750°C.

The specific heat of the alloy was measured in the temperature range 0.03—0.15°K by means of a comparison with the specific heat of the cooling salt. The latter had been determined experimentally using a control alloy sample of known specific heat. The experimental technique has been described in [9], but the appratus used to measure the nuclear specific heat was somewhat modified. Pulsed heating of the salt was effected by a rf electromagnetic field (f = 2.8 Mc/sec) that induced most of the heat release in the salt; heating had previously been effected by a 2500-cps sonic field and most of the heat was released in the cold conductor. In this way we eliminated the previously observed overheating of the cold conductor relative to the cooling salt during the pulsed heating process and the resulting errors.

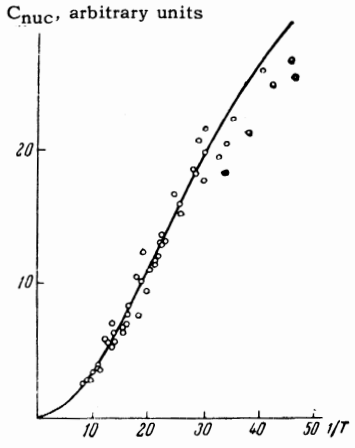
We used a cold conductor made of electrolytic copper, having a residual resistance at 4.2°K that was smaller by a factor of 30 than in the earlier experiments; the attainment of temperature equilibrium between the sample and the salt was thus somewhat accelerated. These improvements permitted measurements at lower temperatures. The accompanying figure shows results obtained with the control sample (99.70 wt.% Fe and 0.30 wt.% Co).

Since in the range 0.03—0.05°K the splitting of the cobalt nuclear levels in the alloy ($\mu H_{eff}/I$) was comparable to kT, to calculate the specific heat of the sample we used the complete formula

$$C_{nuc} = \alpha^2\left\{\frac{1}{\mathrm{sh}^2\alpha} - \frac{(2I+1)^2}{\mathrm{sh}^2[(2I+1)\alpha]}\right\}, \qquad \alpha = \mu H_{eff}/2kTI, \qquad (1)^*$$

[1)] At the 9th International Conference on Low Temperature Physics (Columbus, Ohio, 1964) Cameron et al. reported a field of 90 kOe obtained by measuring the anisotropy of γ radiation from V^{48} in an iron alloy.

*sh ≡ sinh.



C_{nuc} (1/T) for an FeCo alloy. The curve was calculated from (1) for a 289.7-kOe field at the Co nucleus.

where μ is the magnetic moment, I is the nuclear spin, and k is Boltzmann's constant. For $kT \gg \mu H_{eff}/I$, Eq. (1) becomes

$$C_{nuc} \approx {}^1/_3 I(I+1)(\mu H_{eff}/kTI)^2. \quad (2)$$

H_{eff} at the cobalt nucleus in the alloy was taken to be 289.7 kOe.[10] The experimental dependence $C_{nuc}(1/T)$ for the control sample is seen to agree with the calculated curve up to $1/T \approx 30$.

The specific heat measurements on the iron-vanadium samples yielded the following results: in alloy I (4.4 at.% V) the effective field at the vanadium nucleus was 78 ± 7 kOe; in alloy II (13.8 at.% V) the field was 58 ± 4 kOe. The observed strong dependence of the field on the composition of the alloy can be accounted for by a simple model, as follows. In a free vanadium atom having three electrons in the unfilled 3d shell and two electrons in the 4s shell the HIF at the nucleus is −315 kOe. The changed electron configuration of the vanadium atom in an alloy reduces the field at the nucleus to 90 kOe (with a negative sign). The state of the vanadium electron shell in an iron alloy can be determined from the concentration dependence of the mean magnetic moment per atom of the alloy. Nevitt and Aldred [11] give

$$\bar{p} = (2.218 - 3.232\,c)\,\mu_B, \quad (3)$$

where c is the atomic concentration of vanadium in the alloy.

The replacement of a single iron atom by a vanadium atom thus reduces the magnetic moment of the alloy by 3.2 μ_B. Assuming that at least a part of this effect results from the magnetic moment of the electron shell in the vanadium atom, oriented antiparallel to the magnetic moment of the iron atoms, we can represent H_{eff} at the vanadium nucleus in the alloy by

$$H_{eff}(c) = a_0 + \bar{b\mu}(c), \quad (4)$$

where a_0 is the contribution from the localized magnetic moment of the vanadium shell (which must be positive), and $\bar{b\mu}(c)$ is the contribution to the field coming from the vicinity of the vanadium atom in the alloy.

Using the values of H_{eff} for alloys containing 1 at.%,[4] 4.4% at.%, and 13.8 at.%, we obtain the most probable values of a_0 and $\bar{b\mu}(0)$:

$$a_0 \approx +50 \text{ kOe}, \quad \bar{b\mu}(0) \approx -140 \text{ kOe} \quad (5)$$

The field at a vanadium nucleus in the allo is therefore negative; this agrees with[5].

According to Watson and Freeman, the uncompensated d-shell spin of iron group atoms alone contributes ~ -130 kOe to the field at the nucleus. Utilizing this value, we estimate the mean localized magnetic moment of the vanadium shell in an alloy for $a_0 \approx +50$ kOe:

$$\bar{p}_V \approx -0.4\ \mu_B. \quad (6)$$

Improvement of the values of a_0 and $\bar{b\mu}(0)$ will require measurements on a larger number of alloy samples having different compositions. Such measurements are planned for a future date.

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