double donor and simple donor scattering are examined. The experimental results best conform to scattering calculated for a simple singly charged donor impurity.

In addition, the donor ionization energies and the saturation values of $n(T)$ appear to be more satisfactorily understood in terms of a simple donor than a double donor (e.g., native defect). It, therefore, seems quite probable that the donor defect controlling the electrical properties of these zone-refined crystals is a residual simple impurity.

Magnetoresistance effects proportional to H^2 were readily observed. This was found due in part to contact effects which obscured both the magnitude and angular dependence of the true effect for CdTe. The magnitude for CdTe is, however, $<10^{-11}$ G^{-2} at 300°K. The uncertainty of the angular dependence must be removed before definitive conclusions concerning band structure can be drawn from this type of measurement.

ACKNOWLEDGMENTS

The authors employed instrumentation developed by H. H. Woodbury for the transport measurements and are indebted to him also for much helpful advice. We also thank Professor F. C. Brown for helpful discussions, Miss E. L. Kreiger who performed much of the computational work, and B. B. Binkowski and L. H. Esmann who ably assisted with sample preparation and measurement.

PHYSICAL REVIEW VOLUME 129, NUMBER 6 15 MARCH 1963

Knight Shifts in Niobium-Molybdenum Alloys

S. Alexander,* E. Corenzwit, B. T. Matthias,† R. G. Shulman, and B. J. Wyluda
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received 9 November 1962)

Measurements of the Knight shift of Nb^{93} in Nb-Mo alloys are reported. For alloys containing less than 40 at.% Mo, the shift is equal to the Nb metal shift of 0.83%. For higher Mo concentrations, the shift decreases linearly with concentration to a value of 0.57% at 95 at.% Mo. The possible meaning of these results and their relation to other measurements on these alloys are discussed.

We have measured the Knight shift (K_S) of Nb^{93} nuclei in alloys of Nb and Mo as a function of concentration. The results are shown in Fig. 1. It can be seen that the shift is constant within experimental accuracy up to about 40% Mo and is equal to the Nb metal shift of 0.83%. For higher Mo concentration K_S decreases linearly as the molydenum concentration is increased.

The resonance frequencies were determined from the position of the zero-slope point on the resonance line, i.e., from the point where the derivative changes sign. For high Nb concentration (above 30% Nb) the resonance lines were asymmetric with long tails towards high fields and about 30 G wide. At lower Nb concentrations the lines narrowed, becoming 2 G wide in the 5% Nb alloy. The shifts were measured by comparison with the Br^{79} nuclear resonance in water solution of KBr, assuming the nominal values of 1040.7 and 1066.7 cps/G for the gyromagnetic ratios of Nb^{93} and Br^{79}, respectively. From the intensity of the observed resonance lines it seems that one only sees the $\frac{1}{2}\rightarrow -\frac{1}{2}$ transition of the Nb nucleus.

The measurements were carried out on a Varian spectrometer. Most alloys were measured at room temperature in a field of 15 kOe. A number of alloys were, however, measured also at fields of 12 and 8 kOe. No significant changes in the fractional shift or in the linewidths were found at these fields (see Fig. 1). It, therefore, seems clear that quadrupole effects are not important either for the measured shift or for the linewidth. No temperature dependence of K_S was found down to 4°K.

Niobium-molybdenum alloys have been investigated extensively in recent years. Hulm *et al.*[1,2] have measured

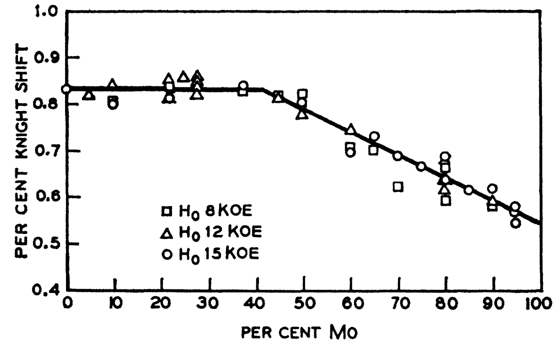

FIG. 1. The percentage Knight shift of Nb^{93} in Nb–Mo alloys as a function of Mo concentration. Measurements at 15, 12 and 8 kOe are included.

---

* Present address: The Weizmann Institute of Science, Rehovot, Israel.

† University of California, La Jolla, California.

[1] J. K. Hulm and R. D. Blaugher, Phys. Rev. **123**, 1569 (1961).

[2] J. K. Hulm, R. D. Blaugher, T. H. Geballe, and B. T. Matthias, Phys. Rev. Letters **7**, 302 (1961).

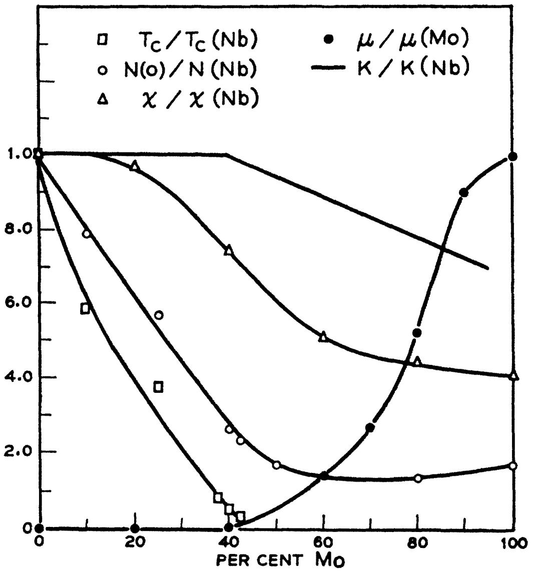

FIG. 2. The density of states (reference 5) [$N(0)$], superconducting transition temperature (T_c),[1,2] magnetic susceptibility (χ), (reference 3) Fe localized moment (μ), (references 3 and 4) and Nb^{93} Knight shift of Nb–Mo alloys. All quantities are relative to the value for metallic Nb except for the localized moments which are normalized for Mo.

the superconducting transition temperature of the alloys and have found that the transition temperature decreases rapidly as Mo is added to Nb and superconductivity seems to disappear somewhere between 40 and 50% Mo. Matthias *et al.*[3] and Clogston *et al.*[4] have shown that iron impurities form localized moments in alloys containing more than 40% molybdenum. They have also measured the magnetic susceptibility of the alloys. Those results together with our Knight-shift measurements are shown in Fig. 2. All these observables change rapidly with composition around 50% Mo.

On the Nb-rich side there is a very rapid change in the density of states as determined by specific heat measurements.[5] This change is only partially reflected in the magnetic susceptibility and does not appear at all in the Knight shift. It seems reasonable to assume that the density of states is determined by *d* electrons with small hyperfine interactions.[6] In the analogous third row vanadium-chromium alloys Barnes and Graham[7] and Drain[8] also found the *d*-electron contribution to the shift to be rather small. For high Cr concentrations (above 70%) the V^{51} shift decreased linearly.[7,8] This is similar to the change we find above 40% Mo. In our case this can certainly not be regarded as a low-concentration effect but it must reflect the electronic state of the alloy.

The 30% change in the shift in the Mo-rich alloys is quite large and would require an equally large change in the *s*-electron density which is unlikely. We have seen that the *d* states near Nb have a small effect and, therefore, it seems improbable that a change in the *d*-electron contribution can account for the observed change in K_S.

One possible explanation of the decreasing shift is a change of *d*-electron character. Asdente and Friedel[9] have shown that the *d* states on the molybdenum side are antibonding states and, therefore, more localized. These states should have a larger hyperfine interaction than the itinerant Nb states. The decrease in K_S could then be attributed to an increase in the density of these antibonding *d* states with their negative hyperfine interactions.

Alternatively, the change in K_S might come from a change in the orbital paramagnetism corresponding to the paramagnetic term in the chemical shift.[10,11] One would then expect to find a contribution to the susceptibility which is linear in the Mo concentration (above 40% Mo). Within the accuracy of the susceptibility measurements a linear term is possible. If additional measurements confirm the existence of the linear term in the susceptibility it would strengthen the possibility that the change in the shift is indeed of orbital origin. The fact that K_S is found to be constant over such a wide range may then be due to a compensation between the change in orbital paramagnetism and in the *d*-electron contribution.

---

[3] B. T. Matthias, M. Peter, H. J. Williams, A. M. Clogston, E. Corenzwit, and R. C. Sherwood, Phys. Rev. Letters **5**, 542, (1960).

[4] A. M. Clogston, B. T. Matthias, M. Peter, H. J. Williams. E. Corenzwit, and R. C. Sherwood, Phys. Rev. **125**, 541 (1962).

[5] F. J. Morin and J. P. Maita, Phys. Rev. **129**, 000 (1963).

[6] V. Heine, Phys. Rev. **107**, 1002 (1957); J. H. Wood and G. W. Pratt, *ibid.* **107**, 995 (1957).

[7] R. G. Barnes and T. P. Graham, Phys. Rev. Letters **8**, 248 (1962).

[8] L. E. Drain, J. Phys. Radium (to be published).

[9] M. Asdente and J. Friedel, Phys. Rev. **124**, 384 (1961).

[10] N. F. Ramsey, Phys. Rev. **86**, 243 (1952).

[11] A. M. Clogston, A. C. Gossard, V. Jaccarino, and Y. Yafet, Phys. Rev. Letters **9**, 262 (1962).