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DIFFUSION OF POSITIVE MUONS IN SOME CUBIC METALS

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ABSTRACT

In Cu and Nb, positive muons "freeze in" at temperatures below 90 K and 60 K, respectively, whereas in Al they show high mobility all over the range 1-700 K. The possible spatial extension of the muons and the effects of strong electrical field gradients at neighbouring nuclei are discussed.

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Great efforts have been spent on experimental studies of the diffusion of light elements in metals. The positive muon, which in this context can be looked upon as a light isotope of hydrogen ($m_\mu/m_p \approx 1/9$), has become a new probe for studies of metallic properties. Gurevich et al. [1] studied diffusion of muons in Cu as a function of temperature down to 77 K and recently extended the measurements down to 30 K [2]. The method used, muon spin rotation (μSR) has been reviewed recently by Brewer et al. [3].

In metals having nuclei with large magnetic moments, the nuclear dipole fields will cause a spread of the Larmor precession frequencies of muons placed in an external, homogeneous field. If the muons are mobile this frequency distribution depends on the volume sampled during their lifetime (motional narrowing). For classical diffusion the relation between jump time τ_c of the particle and the line width $\Delta\nu$ in a frequency spectrum is approximately given by [4]

$$\tau_c^{-1} = \frac{2(\ln 2)^{\frac{1}{2}} \Delta\nu}{\tan \frac{\pi}{2} (\Delta B/\Delta B_0)^2} , \tag{1}$$

where ΔB is the line width observed and ΔB_0 is the static line width

$$\overline{\Delta B_0^2} = \frac{1}{3} \gamma_I^2 \hbar^2 \, I(I + 1) \sum_{\substack{\text{all} \\ \text{space}}} \frac{(1 - 3 \cos^2 \Theta)^2}{r^6} \tag{2}$$

caused by the nuclear dipoles which also precess in the external magnetic field.

In this letter we report the measurements of line widths for muons in Cu(f.c.c.), Al(f.c.c.) and Nb(b.c.c.) at low temperatures. The experimental data were fitted to Gaussian or Lorentzian line shapes. The results presented in Fig. 1 are fitted to a Gaussian line shape.

The line width of the Fourier transform of the precession signal observed at low temperatures in a single crystal of Cu with an external magnetic field of 350 G applied approximately parallel to the [111] direction is $0.193 \pm 0.010\ \mu\text{sec}^{-1}$. A possible explanation of this value for the dipolar broadening is that the muon occupies a finite volume around an interstitial point rather than being confined to a point-like octahedral or tetrahedral interstitial position, for which calculations give line widths of 0.07 and 0.31 μsec^{-1}, respectively. The muon might also cause electric field gradients (EFG) at the Cu nuclei similar to those produced by dilute substitutional impurities in Cu [5], in which case Eq. (2) would not apply. If neighbouring nuclei are affected by strong EFG's it is possible to explain the practically constant line width observed at 1.7 K for different orientations of the crystal with respect to the external magnetic field [6] and also the preliminary results reported by Schenck et al. [7], who find effects due to crystal orientation in applied fields above 2 kG.

In polycrystal Cu we find the line width at low temperatures to be 0.23 ± 0.03 μsec^{-1}. This result is in reasonable agreement with the measurements of Grebinnik et al. [2].

For Al a narrow line was observed at all temperatures of investigation. The difference between the behaviour of muons in Al and Cu is surprising, but a more efficient screening of the ionic potentials by the conduction electrons in Al would allow for the higher mobility.

Niobium shows the same behaviour as Cu, i.e. the muons are "frozen in" at low temperatures. The static line width observed in Nb below 60 K is 0.285 ± 0.015 μsec^{-1}, compared with a computed value for a fixed interstitial position of 0.34-0.37 μsec^{-1} depending on site. Experiments with single crystals of Nb are being performed at present to find out whether the effects of electric field gradients are important in this case. The line width observed here contradicts the high mobility suggested by Fiory et al. [8] in their investigation of the superconducting state.

We observe a distinct transition to the superconducting state between 10 K and 8 K with a sharp decrease in initial asymmetry of the precession signal. Muons in the bulk of the Nb sample below the transition temperature do not contribute to the precession signal (a remaining small signal observed at 8 K and 1 K is fully explained as resulting from muons stopping in the cryostat walls).

Birnbaum and Flynn [9] have suggested a tunnelling state for H and D in Nb including 4 tetrahedral and 4 triangular interstitial sites centred around an unoccupied octahedral site. Such a state for a muon might account for the observed reduction of line width in Nb compared to the theoretical value for a single interstitial point. A preliminary calculation of the activation energy E_a for classical diffusion of muons in Nb from the observed line widths above 60 K yields $E_a = 0.04 \pm 0.01$ eV.

In addition, we have studied the metals tantalum, lithium, sodium and lead at 77 K and 300 K. No significant line broadenings were found at these temperatures. The experiments were performed at the 600 MeV Synchro-cyclotron at CERN, Geneva, using a beam of positive muons from pions decaying in flight. A continuous flow ^{4}He cryostat [10] was used in the low temperature measurements.

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<u>Figure captions</u>

Fig. 1a : The observed line width σ for a single crystal of Cu with the external field parallel to the [111] direction. B_0 = 350 G.

Fig. 1b : The observed line width σ for a polycrystalline Nb sample. B_0 = 350 G.

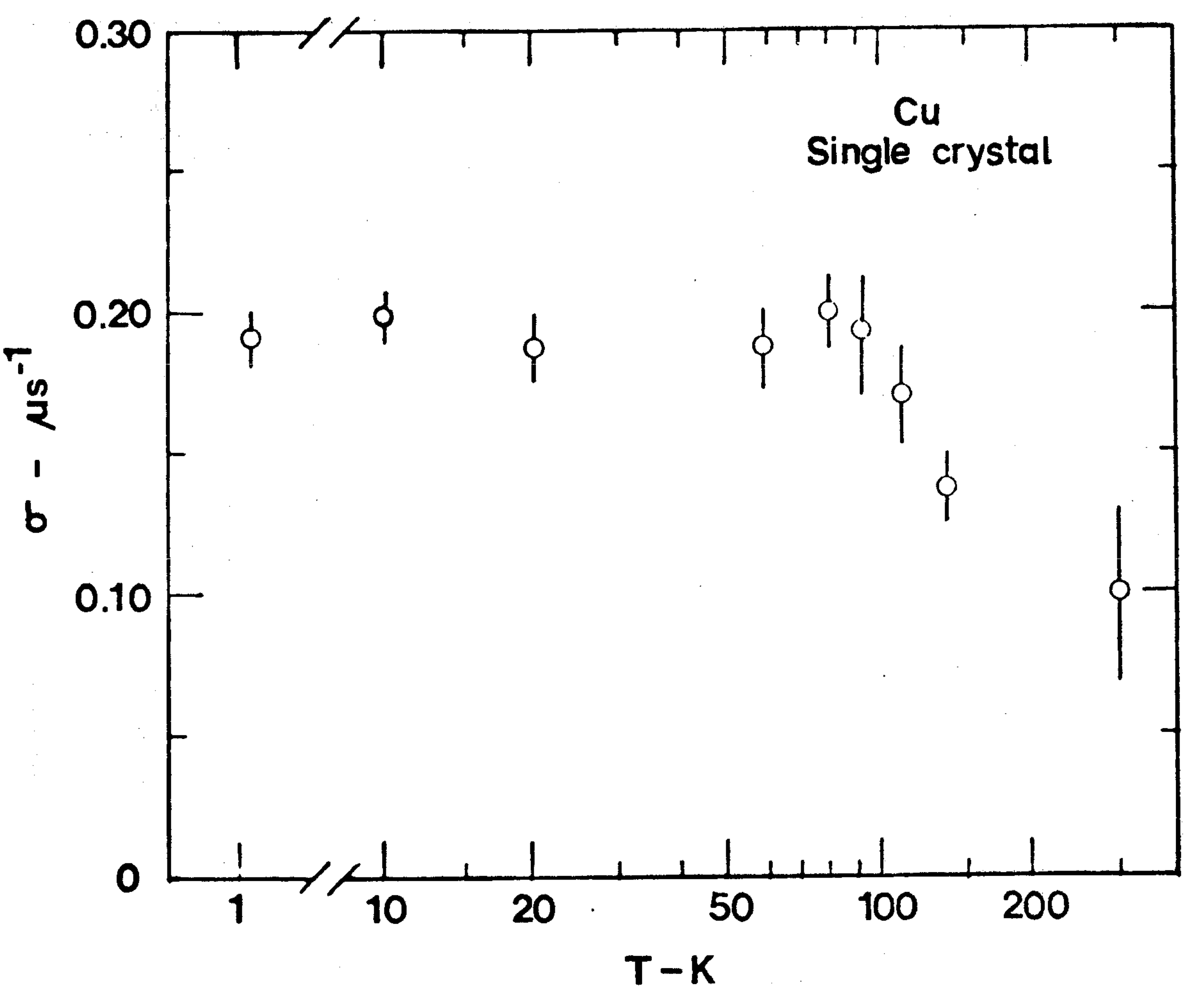

Fig. 1

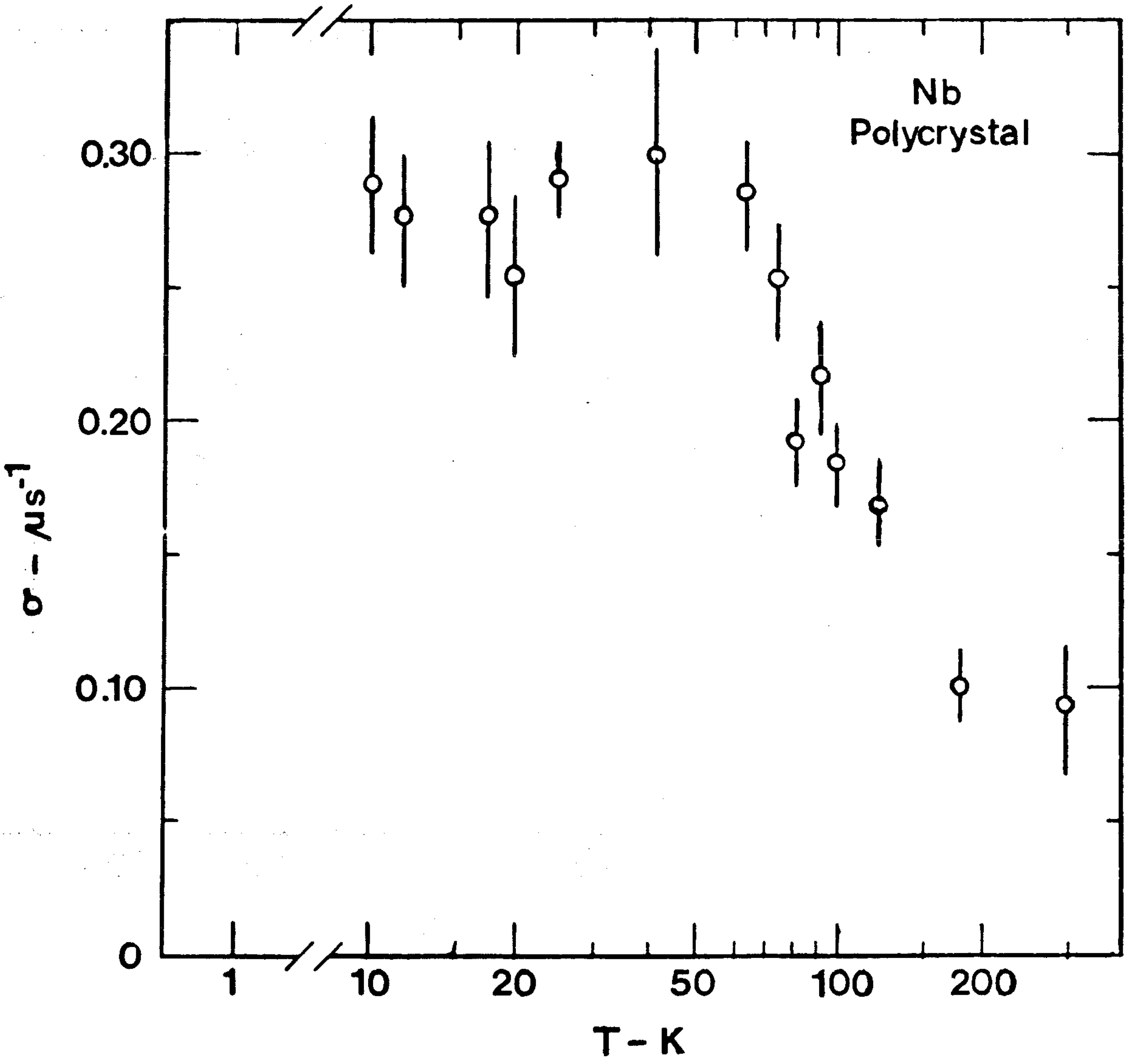

Fig. 2