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LETTER TO THE EDITOR

Superconductivity in zinc at high pressure

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Abstract. The variation of the superconducting critical temperature, T_c, with pressure in ^{67}Zn has been studied making use of a recent experimental study on the pressure-dependent Lamb–Mössbauer factor in the range 0–5.8 GPa at 4.2 K. It is found that the critical temperature decreases with pressure. At 5.8 GPa the value of T_c ($\simeq$0.123 K) is about 1/6.8 of that at ambient pressure. The variation of T_c with pressure can easily be measured.

Recently, measured values of the Lamb–Mössbauer factor in ^{67}Zn at different pressures, in the range 0–5.8 GPa at 4.2 K, have been reported (Potzel *et al* 1989). The Lamb–Mössbauer factor, f_{LMF}, is found to increase significantly with reduced volume. At 5.8 GPa the increase over the value at ambient pressure is almost three times. Thus the mean square displacement of a zinc atom in its crystal decreases substantially with increase in pressure. This decrease is, essentially, due to the change in the phonon frequency distribution function, particularly that of low-energy phonons, brought about by the application of pressure on the zinc crystal. The pressure-dependent change in the phonon frequency distribution function would therefore affect the electron–phonon interaction and hence superconductivity. In the present Letter we study the effect of pressure on the superconducting transition temperature, T_c, in zinc.

Zinc is a well known strongly coupled superconductor (McMillan 1968). A recent experimental value of T_c in ^{67}Zn is 835 ± 20 mK (Obenhuber *et al* 1987) at ambient pressure. The superconducting transition temperature in zinc is well described by the following equation of McMillan (Tewari 1983, Allen and Dynes 1975, McMillan 1968) which is an outcome of the basic Eliashberg theory of strongly coupled superconductors:

$$T_c = (\langle\omega\rangle/1.2)\exp\{[-1.04(1+\lambda)]/[\lambda - \mu^*(1+0.62\lambda)]\} \tag{1}$$

where

$$\lambda = 2\int \alpha^2(\omega)F(\omega)\,\mathrm{d}\omega/\omega = \eta/M\langle\omega^2\rangle \tag{2}$$

is the electron–phonon mass enhancement factor; $F(\omega)$ is the phonon frequency distribution function; $\alpha^2(\omega)$ is the electron–phonon coupling constant; M is the ionic mass; η is a purely electronic factor, and $\langle\omega\rangle$, $\langle\omega^2\rangle$ are suitable averages (Tewari 1983, McMillan 1968) and μ^* is the electron–electron Coulomb interaction.

Making use of the constancy of the electron–phonon coupling constant with phonon frequencies (Tewari 1983, Gomersall and Gyorffy 1974, McMillan 1968, Schrieffer *et al*

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1963), one can put the expression (1) for $\mu^* = 0$ in terms of Mössbauer effect parameters in the following form:

$$T_c = -0.295\left(\frac{E_R}{\hbar \ln f}\right) \exp\left[\frac{1.04M\langle\omega\rangle'}{\eta}\left(\frac{E_R}{\hbar \ln f}\right)\right] \tag{3}$$

where $E_R = E_\gamma^2/2mc^2$ is the recoil energy when a γ-ray of energy E_γ is emitted from the nucleus of mass m, c is speed of light,

$$\langle\omega\rangle' = \int \alpha^2(\omega)F(\omega)\omega \, \mathrm{d}\omega \Big/ \int \alpha^2(\omega)F(\omega)\,\mathrm{d}\omega \tag{4}$$

and $f = f_{LMF}$ at 0 K. The expression for f (Hanks 1961) at low temperatures, $T \ll \theta_D$, with the variation of pressure is given as

$$\ln f_{LMF}(V_2) = (-3E_R/2k_B\theta_2)[1 + 6.6(T/\theta_2)^2] \tag{5}$$

where

$$\theta_2 = \theta_1/[1 - \gamma(\Delta V/V_0)] = \theta_D(p) \tag{6}$$

where θ_1 is the Debye temperature at ambient pressure i.e. $\theta_D(p = 0)$;

$$\Delta V = V_0 - V_2$$

where V_0 is the volume at ambient pressure; V_2 is the volume at finite pressure; and γ is the Grüneisen constant. When the compressibility K is independent of pressure, which is not the case in zinc (McWhan 1965), the expression (6) reduces to the following form:

$$\theta_2 = \theta_1/(1 - K\gamma p). \tag{7}$$

For $\mu^* \neq 0$, the expression for T_c can be obtained making use of expression (3).

One can now study the variation of T_c with pressure using expression (3) and its modified form for $\mu^* \neq 0$ in conjunction with the measured values of f_{LMF} near $T = 0$ K at different pressures. Potzel *et al* (1989) reported the measured values of f_{LMF} at ambient pressure, 2.2, 3.8 and 5.8 GPa which are plotted in figure 1(*a*). Because of the low temperature, $T = 4.2$ K, used in the experiment, the Debye approximation to the phonon frequency distribution function is used to explain the pressure-dependent f_{LMF}. It is found that the mean value of f_{LMF} could be reproduced by $\theta_D = 232$ K at ambient pressure while $\theta_D = 287$ K explained the value at 5.8 GPa. If one uses the measured mean values of f_{LMF} with the corresponding Debye distribution function to evaluate T_c using the modified form of equation (3) for $\mu^* = 0.12$, one gets the variation of T_c with pressure as shown by curve I in figure 1(*b*) (the measured values of f_{LMF} for different pressures at 4.2 K are very close (less than about 1%) to the corresponding value of f_{LMF} at 0 K). Here we have assumed that η, the electronic parameter, is not changing with pressure. However η does change with pressure because of the reduction in the volume of the crystal with pressure. Assuming the free-electron model for zinc (McMillan 1968), one can take η to be varying as $\eta_{k_F}(k_F'/k_F)^5$ where k_F' is the value of the Fermi wavevector at finite pressure and k_F is that at the ambient pressure i.e. $p = 0$. Using the pressure-dependent values of η thus calculated, the pressure-dependent T_c is computed and is shown by curve II in figure 1(*b*). The critical temperature is therefore found to decrease with increase in pressure. This is so because, with the increase in pressure, the number of low-energy phonons decreases sharply, resulting in the reduction of the value

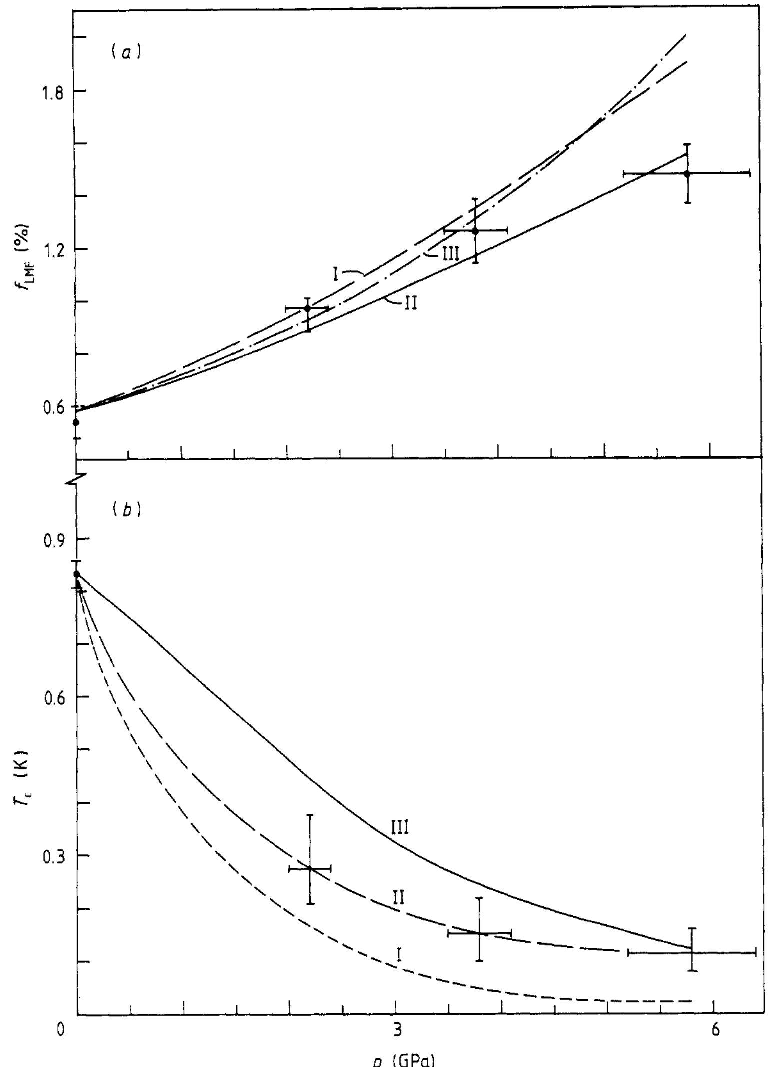

Figure 1. (*a*) Variation of Lamb–Mössbauer factor, f_{LMF}, with pressure in ^{67}Zn at 4.2 K. ● represents experimental results (Potzel *et al* 1989) with associated errors; curve I (———), values of f_{LMF} calculated using expression (5) with Grüneisen constant $\gamma = 3.0$; curve II (———), as curve I but with $\gamma = 2.5$; curve III (—·—·), as curve II but taking compressibility as being independent of pressure. (*b*) Variation of superconducting critical temperature, T_c, with pressure in ^{67}Zn for $\mu^* = 0.12$. Curve I (- - - -) represents the variation of calculated values of T_c with p using the measured values of the Lamb–Mössbauer factor and taking η to be constant with pressure; curve II (— — —), as curve I, but now η is varying with pressure. ┼ are not experimental results, but represent the variation in T_c corresponding to the experimental errors in f_{LMF} shown in figure 1(*a*); curve III (———), values of T_c calculated using the values of f corresponding to curve II of figure 1(*a*) and for η varying with pressure. ● denotes the experimental value of T_c at ambient pressure.

of λ, as is also evident from expression (2). When η is varied, λ increases and therefore T_c becomes larger.

Using expression (5), $\theta_D(p = 0) = 235$ K and $\gamma = 3$, the same value as that used by Potzel *et al* (1989), the f_{LMF} at various pressures is calculated and is shown by curve I in figure 1(a). While the calculated values lie within experimental error up to 3.8 GPa, the one at 5.8 GPa is quite large in comparison with the corresponding experimental value. However, we find that the value of $\gamma = 2.5$ yields the pressure-dependent values of f_{LMF} which lie within the experimental errors at all the pressures, as shown by curve II in figure 1(a). (Also shown in figure 1(a) by curve III are the results obtained for f_{LMF} using expression (5) with (7).) It may be noted that $\gamma = 3$ is rather a high value for zinc, which in fact has two values of γ: γ parallel to the c axis, $\gamma_c = 1.65$; and γ perpendicular to the c axis, $\gamma_a = 2.77$ (Barron and Munn 1967). Using the f_{LMF} at 0 K calculated from curve II in figure 1(a) and the corresponding θ_{D}, T_{c} has been calculated at various pressures and its variation is shown by curve III in figure 1(b) for η variable. As in the earlier study, we find that T_{c} decreases with increase in pressure.

From our study we conclude that the superconducting critical temperature in zinc decreases with increase in pressure up to 5.8 GPa. This decrease in T_{c} can easily be measured.

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