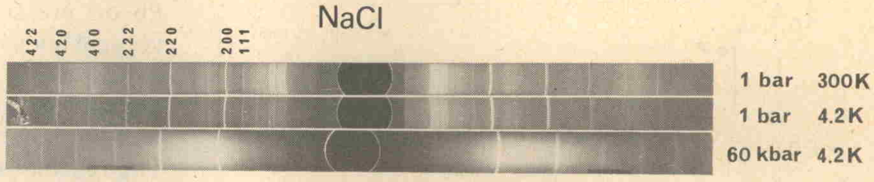

FIG. 5. Powder patterns of NaCl under various conditions. Five diffraction lines inside NaCl 111 line emanate from "amorphous" boron cell material.

tion of the pressure. The calibration at room temperature can not be adopted directly at low temperature because of thermal contraction and changes in elastic constants of the sample and the pressure transmitting material. For this purpose, as a conventional manometer, the pressure dependence of the superconducting transition temperature, $T_c(P)$ of metals has been frequently used. Investigations of $T_c(P)$ of metals such as Pb, Sn, and In, have been carried out.[4] In these studies, however, only indirect methods have been used for the determination of the pressure.

At elevated temperature the equation of state for alkali halides such as NaCl and CsCl was calculated by Decker,[5,6] and has been used as the most reliable scale of pressure. In this study, $T_c(P)$ of Pb has been determined by referring to the equation of state for NaCl. In other words, the lattice parameter of NaCl under high pressure was measured at low temperature by use of the above mentioned x-ray camera.

A. Pressure determination at low temperature

Decker's calculation of the equation of state for NaCl at elevated temperature is based on the vibrational Mie–Grüneisen equation of state,

$$P = -\frac{d\Phi(V)}{dV} + \frac{\gamma_E}{V} E_v(V,T),$$

where P is the pressure, $\Phi(V)$ the potential energy due to the static lattice, $E_v(V,T)$ the energy due to the lattice vibrations including the zero-point vibrations, V the volume, and T the temperature. γ_E is the Grüneisen parameter, but is not identical with γ defined by the Grüneisen rule.[7,8] At low temperature, γ_E is a function of both volume and temperature. Therefore, Decker's assumption that the Grüneisen parameter is a function of volume only is not valid at low temperature. However, Pautamo's calculation of γ_E for NaCl at atmospheric pressure indicates that γ_E varies much less with temperature than γ.[8] The difference between γ_E and γ_D (suffix D means the parameter used in Decker's calculation) is much smaller than that between γ_E and γ. It is difficult to calculate theoretical values of γ_E at low temperature under pressure. The use of γ_D instead of γ_E has a direct bearing on the term $(\gamma_E/V)E_v$ in Mie–Grüneisen equation. Assuming that the difference between γ_E and γ_D at atmospheric pressure holds equally at high pressure, the pressure obtained by extension of Decker's calculation using γ_D is low by the amount of 0.6 kilobar at 100 kilobar and 4.2 K compared with that obtained by using γ_E. This amount is almost negligible, when considering the uncertainty in pressure determination, ±1 kilobar, resulting from the uncertainty in the present measurement of V/V_0 for NaCl. Then Decker's calculation extended to 4.2 K was adopted as a reasonable scale in the present study. The differences in the pressures at 4.2 K and neighboring temperatures are entirely negligible.

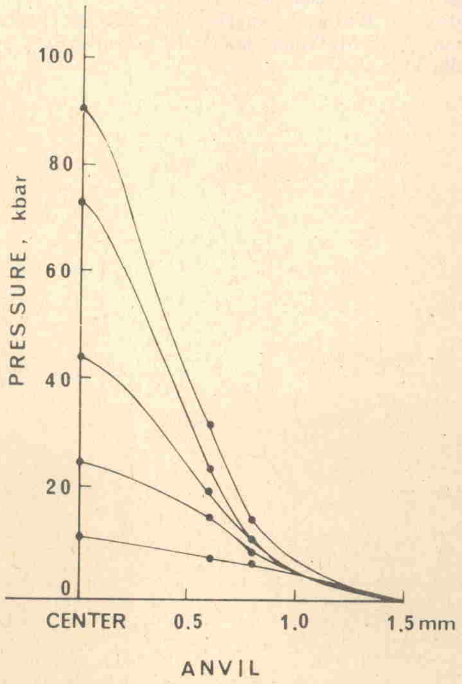

FIG. 6. Radial pressure distribution in the boron–epoxy cell with 3.0-mm diam at room temperature.

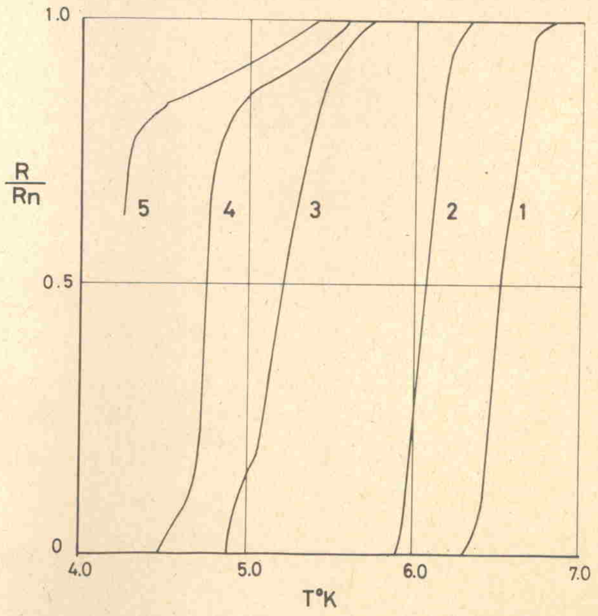

FIG. 7. Curves of the superconducing transition in Pb at various pressures P (kilobar): 1—7.0, 2—24.7, 3—36.0, 4—43.4, 5—53.2.

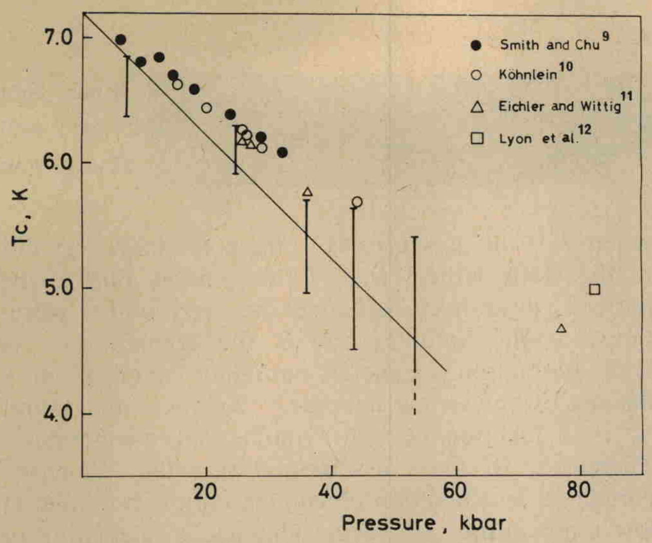

FIG. 8. Plot of $T_c(P)$ for Pb. Vertical lines indicate the result of the present work.

B. Experimental and results

In addition to the lattice parameter measurements of NaCl at 4.2 K, the electrical resistance of Pb was measured on spontaneous warming in order to determine the transition temperature. A wire made of Pb was imbedded vertically in the NaCl powder contained in the boron–epoxy disk. The electrical resistance was measured across the anvils with a double bridge. Temperature was measured with a germanium resistor attached to the lower anvil. The warming rate was 0.8 K/h up to 5.6 K, and 6.5 K/h above 5.6 K.

Figure 7 indicates the dependence of the relative electrical resistance of Pb on temperature under various pressure. Curve 5 for 53.2 kilobar shows the result above 4.2 K. The curves become less steep as the pressure increases. This is mainly attributed to the gradient of pressure throughout the sample. Figure 8 shows the dependence of the transition temperature of Pb on pressure, which is obtained from Fig 7. The vertical lines indicate the probable ranges of the present experimental result. Data by Smith *et al.* and the data quoted by them[4] are also plotted in this figure. The present values are significantly lower than the others. The reason for this is not clear, but may be due to the difference in methods for the pressure determination at low temperature. Smith and Chu's measurement[9] was based on the change of $T_c(P)$ of a Sn manometer, and Köhnlein's[10] was made using a strain-gauge technique. Eichler and Wittig[11] measured T_c at the transition points in Bi and Tl. In the case of Bridgman anvils used by all of them, a pressure gradient along the anvil at low temperature may be different from that at room temperature because of the decrease in plasticity of the pressure medium. A detailed redetermination in a hydrostatic environment seems to be necessary.

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