A thermodynamic analysis[22] of the large change in dE/dT at the superconducting transition indicates a quadratic dependence of T_c on stress of magnitude

$$\frac{d^2T_c}{d\sigma^2} \simeq (2.8 \pm 1.5) \times 10^{-21} \text{ K cm}^4 \text{ dyn}^{-2}$$

at zero stress. This initial curvature, if extrapolated to high stresses (ignoring higher-order terms), would lead to a positive deviation of T_c from linear behavior, amounting to ~0.14 K at 10 kbar for uniaxial stresses parallel to the basal plane. Sambongi[28] has recently observed $d^2T_c/d\sigma^2 > 0$ for stresses perpendicular to the basal plane. Although a negative curvature appears to be present in the pressure results of Smith *et al.*,[29] an accurate determination is not possible. In any case, the sign of d^2Tc/dp^2 cannot be determined from the two uniaxial stress results given above, but also involves additional terms of the form $d^2T_c/d\sigma_i d\sigma_j$. The tendency of T_c to saturate at high pressures may be related to a pressure-induced shift in a CCDW or ICDW transition toward the superconducting T_c.

V. CONCLUSIONS

The CDW instabilities in the two-dimensional layered transition-metal dichalcogenides lead to unusual static and dynamic elastic effects. We have presented low-frequency modulus and internal-friction measurements in the 2*H* polytype of $TaSe_2$ and $NbSe_2$ which exhibit anomalous behavior near the CCDW and ICDW transitions. The coupling between the CDW instabilities and the lattice is found to be an order of magnitude larger at the commensurate CDW transition in $TaSe_2$ as compared to the ICDW transition in $TaSe_2$ or $NbSe_2$. The CCDW transformation in $TaSe_2$ near 90 K exhibits large elastic hysteresis (~5 K), which is characteristic of a first-order transition. On the other hand, the ICDW transitions in $TaSe_2$ and $NbSe_2$ show very little if any hysteresis and appear to be second order. If these incommensurate transitions are first order, they have only a weak first-order character as compared with the commensurate transformation.

Information concerning the dynamic properties of these CDW transitions was obtained from sound dispersion and attenuation measurements. At all the CDW transitions, the internal-friction maximum of a given frequency is at a temperature below the corresponding modulus minimum. Furthermore, the first-overtone internal friction associated with the transition is always comparable or smaller than that of the fundamental. This feature is inconsistent with simple relaxation processes where $Q^{-1} \propto \omega$ in the hydrodynamic limit.

We have shown that the vibrating-reed technique is a sensitive method for detecting and investigating the CDW transitions in the layered dichalcogenides. A more complete understanding of the thermodynamic properties of these transitions will come about as precision specific-heat and expansivity data become available to correlate with the elastic measurements. It is clear that any detailed theory of these CDW instabilities must explain the anomalous elastic properties.

ACKNOWLEDGMENTS

We wish to thank G. F. Brennert and W. A. Royer for technical assistance.

---

[1] F. R. Gamble, J. H. Osiecki, M. Cais, R. Pisharody, F. J. Di Salvo, and T. H. Geballe, Science 174, 493 (1971).

[2] J. A. Wilson and A. D. Yoffe, Adv. Phys. 18, 193 (1969).

[3] J. Edwards and R. F. Frindt, J. Phys. Chem. Solids 32, 2217 (1971).

[4] J. A. Wilson, F. J. Di Salvo, and S. Mahajan, Phys. Rev. Lett. 32, 882 (1974); Adv. Phys. 24, 117 (1975); and P. M. Williams, G. S. Parry, and C. B. Scruby, Philos. Mag. 29, 695 (1974).

[5] A. H. Thompson, Phys. Rev. Lett. 34, 520 (1975).

[6] M. Barmatz, H. J. Leamy, and H. S. Chen, Rev. Sci. Instrum. 42, 885 (1971).

[7] C. Herring, in *Magnetism*, edited by G. T. Rado and H. Suhl (Academic, New York, 1966), Vol. IV, p. 340.

[8] D. E. Moncton, J. D. Axe, and F. J. Di Salvo, Phys. Rev. Lett. 34, 734 (1975).

[9] W. L. McMillan, Phys. Rev. B 12, 1187 (1975); and unpublished.

[10] A. W. Overhauser, Phys. Rev. 167, 691 (1968).

[11] F. J. Di Salvo, J. A. Wilson, B. G. Bagley, and J. V. Waszczak, Phys. Rev. B 12, 2220 (1975).

[12] D. E. Moncton and J. D. Axe (private communication).

[13] H. N. S. Lee, M. Garcia, H. McKinzie, and A. Wold, J. Solid State Chem. 1, 190 (1970).

[14] R. K. Quinn, R. Simmons, and J. Banewicz, J. Phys. Chem. 70, 230 (1966).

[15] M. Barmatz, in *Proceedings of the 1974 IEEE Ultrasonics Symposium* (IEEE, New York, 1974), No. 74, p. 461.

[16] M. Barmatz and H. S. Chen, Phys. Rev. B 9, 4073 (1974).

[17] See, Harald Schäfer, *Chemical Transport Reactions* (Academic, New York, 1964).

[18] P. M. Morse, *Vibration and Sound* (McGraw-Hill, New York, 1948), 2nd ed., p. 151.

[19] M. Barmatz, L. R. Testardi, A. F. Garito, and A. J. Heeger, Solid State Commun. 15, 1299 (1974).

[20] See, for example, M. Barmatz and B. Golding, Phys. Rev. B 9, 3064 (1974).

[21] B. G. Bagley, F. J. Di Salvo, H. E. Bair, and E. M. Vogel (unpublished).

[22] L. R. Testardi, Phys. Rev. B (to be published).

[23] R. D. Williams and I. Rudnick, Phys. Rev. Lett. 25, 276 (1970).

[24] See, for example, B. Golding and M. Barmatz, Phys. Rev. Lett. 23, 223 (1969); and B. Golding, *ibid.* 34, 1102 (1975).

[25] J. M. E. Harper, T. H. Geballe, F. J. Di Salvo, Phys. Lett. A 54, 27 (1975).

[26] E. Revolinsky, E. P. Lautenschlager, and C. H. Armitage, Solid State Commun. 1, 59 (1963).

[27] A. J. Bevolo and H. R. Shanks, J. Appl. Phys. 45, 4644 (1974).

[28] T. Sambongi, J. Low Temp. Phys. 18, 139 (1975).

[29] T. F. Smith, R. N. Shelton, and R. E. Schwall, J. Phys. F 4, 2009 (1974).