Temperature and Pressure Dependence of the Elastic Constants of Ammonium Bromide*

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The adiabatic elastic constants of single-crystal ammonium bromide have been measured as functions of temperature and pressure by a pulse-superposition technique. The values at 1 atm and 300°K are: $c_{11} = 3.414$, $C' = (c_{11} - c_{12})/2 = 1.316$, and $c_{44} = 0.722$, in units of 10^{11} dyn cm^{-2}. Measurements of c_{11} and C' were not made below the lambda transition at 234.5°K because of a sudden increase in attenuation; c_{44} was not attenuated in this manner and was measured from 105° to 320°K. The elastic constants were measured as functions of pressure between 0 and 12 kbar at constant temperatures which ranged from 255° to 315°K. In this region, which is far from the lambda line, disordered ammonium bromide behaves like a normal CsCl-type crystal.

INTRODUCTION

A LAMBDA transition at 234.5°K in crystalline ammonium bromide was first discovered from heat-capacity measurements.[1] This transition is now established as an order–disorder transition involving the relative orientations of adjacent ammonium ions. However, there are important differences between the ordering process in NH$_4$Br and that in NH$_4$Cl, which undergoes a cooperative order–disorder transition at about the same temperature (242.8°K). X-ray,[2] neutron-diffraction,[3] Raman,[4] and infrared[5] investigations show that above their critical temperatures both NH$_4$Br and NH$_4$Cl have a CsCl-type cubic structure with the tetrahedral ammonium ions oriented at random with respect to the two equivalent positions in the cubic cell (hydrogen atoms pointing toward nearest-neighbor halide ions). Hettich[6] observed that ammonium bromide does not become piezoelectric below the lambda point but does exhibit double refraction. This result and the low-temperature Raman spectrum led Menzies and Mills[4] to suggest that the ammonium ions in two adjacent unit cells were antiparallel (have opposite orientations relative to the crystallographic axes). Low-temperature x-ray studies[7] have shown that the crystal

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[3] H. A. Levy and S. W. Peterson, Phys. Rev. **83**, 1270 (1951); **86**, 766 (1952); J. Am. Chem. Soc. **75**, 1536 (1952).
[4] A. C. Menzies and H. R. Mills, Proc. Roy. Soc. (London) **A148**, 407 (1935); R. S. Krishnan, Proc. Indian Acad. Sci. **26A**, 432 (1947); **27A**, 321 (1948).
[5] E. L. Wagner and D. F. Hornig, J. Chem. Phys. **18**, 296 (1950); J. Chem. Phys. **18**, 305 (1950).
[6] A. Hettich and A. Schleede, Z. Physik **50**, 249 (1928); A. Hettich, Z. Physik. Chem. **A168**, 353 (1934).
[7] J. A. A. Ketelaar, Nature **134**, 250 (1934); J. Weigle and H. Saini, Helv. Phys. Acta **9**, 515 (1936); V. Hovi, K. Heiskanen, and M. Varteva, Ann. Acad. Sci. Fenn. Ser. A. VI, No. 144, 1–12 (1964).

structure of NH$_4$Br becomes tetragonal below the transition, and the neutron-diffraction work[3] establishes the location of the hydrogen atoms and confirms that this phase is ordered. The tetragonal unit cell, as shown in Fig. 1, contains two molecules of ammonium bromide.
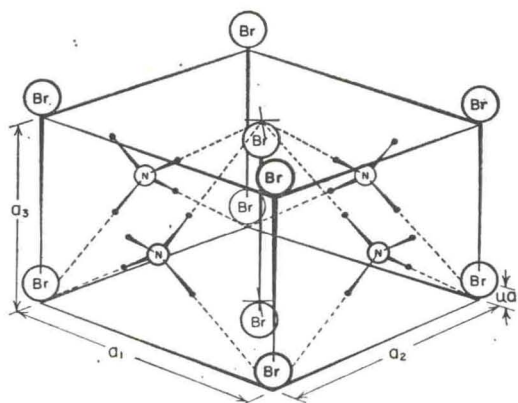

Fig. 1. Unit cell for γ-phase (ordered tetragonal) ammonium bromide. [From E. L. Wagner and D. F. Hornig, J. Chem. Phys. **18**, 305 (1950).]

The ammonium ions are antiparallel ordered in the $a_1 - a_2$ plane and parallel ordered along the a_3 or tetragonal axis. The antiparallel ordering of ammonium ions is stabilized by the bromide ions which are displaced along the tetragonal axis alternately in positive and negative directions with respect to the $a_1 - a_2$ plane by ua_3 where $u = 0.02$. The tetragonal distortion is very slight, amounting to an extension of the a_3 axis by only 0.3% relative to the a_1 and a_2 axes.[7] In contrast, the low-temperature ordered phase in ammonium chloride is cubic (CsCl type), and all the ammonium ions are parallel (have same relative orientation with respect to crystallographic axes).

The thermal expansion data also show a marked difference between NH$_4$Br and NH$_4$Cl. In NH$_4$Cl, the lattice undergoes an anomalous contraction[8] when

[8] Y. Sakamoto, J. Sci. Hiroshima Univ. **A18**, 95 (1954).

ordering occurs on cooling the crystal below the lambda temperature. In NH_4Br the situation is reversed; on cooling there is an anomalous lattice expansion[9] as the bromide crystal undergoes the transition to the ordered tetragonal form. These volume changes associated with changes in ordering make it easy to follow the transition temperatures as a function of applied pressure. Stevenson[10] has obtained the phase diagrams of ammonium chloride, bromide and iodide. His phase diagram for ammonium bromide is reproduced in Fig. 2. (The region encompassed by the sloping lines labeled V_1 to V_{17} in this figure indicates the region of the phase diagram studied in the present investigation.) The β, γ, and δ phases correspond to the structures disordered cubic (CsCl), antiparallel ordered tetragonal and parallel ordered cubic (CsCl), respectively. An α phase corresponding to a disordered NaCl-type cubic structure occurs at high temperatures but is not shown here. There is also a very pronounced hysteresis associated with the γ–δ order–order transition at 1 atm, which is not shown in this figure.

The present paper reports on a variety of ultrasonic velocity measurements which have been made on single-crystal ammonium bromide. Both longitudinal and transverse waves were studied over a wide range of pressure (0 to 12 kbar) at several constant temperatures in the range 255°–315°K. These data all pertain to the disordered phase away from any transition line, and should provide a clear example of the "normal" behavior of a CsCl-type ammonium halide free from any effects due to ordering. Velocity measurements have also been made as a function of temperature at 1 atm, although data could be obtained below the lambda temperature (234.5°K) only for the transverse wave associated with c_{44}.

This investigation is closely related to previous studies[11,12] of the elastic constants of ammonium chloride as functions of temperature and pressure. These studies show that the shear elastic constants for ammonium chloride (especially c_{44}) varied almost linearly with the volume. Since the volumes of ammonium chloride and bromide vary in an opposite manner at the lambda temperature, we would expect that c_{44} should also vary in an opposite manner. For ammonium chloride, c_{44} increases markedly as the temperature is lowered through the transition; therefore c_{44} for the bromide would be expected to decrease.

The results presented below are given in terms of the variation of the three adiabatic elastic constants c_{11}, c_{44}, C', which can be obtained directly from the experimental sound velocities. Third-order elastic constants

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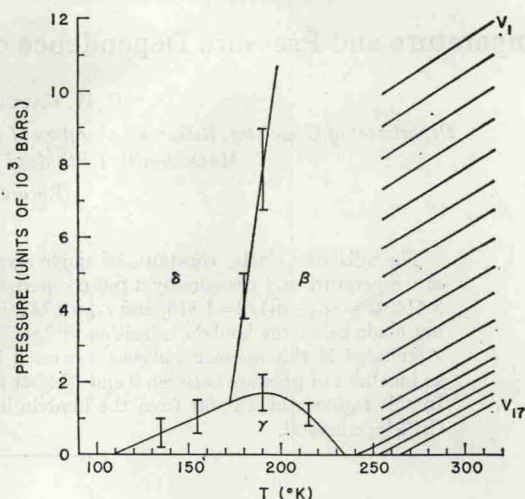
FIG. 2. Phase diagram for NH_4Br. The β phase corresponds to a disordered, CsCl-type cubic phase; the γ phase to an (antiparallel) ordered tetragonal phase; the δ phase to a (parallel) ordered, CsCl-type cubic phase. The vertical bars represent transition points as determined by the static volume measurements of Stevenson (Ref. 10). The set of sloping lines labeled V_1 through V_{17} represent isochores at various volumes.

are not used, and for pressures above 1 atm the quantities c_{11}, c_{44}, and C' are "effective" elastic constants.[13] The relations between the ultrasonic velocities and the elastic constants of a cubic crystal are well known:

Propagation in the [100] direction

$$c_{11} = \rho U_l{}^2, \tag{1}$$

$$c_{44} = \rho U_t{}^2, \tag{2}$$

where ρ is the mass density of the crystal, U_l is the velocity of the longitudinal sound wave, and U_t is the velocity of a transverse wave polarized in any direction perpendicular to the [100] axis.

Propagation in the [110] direction

$$C' = (c_{11} - c_{12})/2 = \rho U_{t'}{}^2, \tag{3}$$

$$c_{11} + c_{44} - C' = \rho U_{l'}{}^2, \tag{4}$$

where $U_{l'}$ is the velocity of the longitudinal wave and $U_{t'}$ is the velocity of a transverse wave polarized perpendicular to the [001] axis. Values of $U_{l'}$ were measured only at 1 atm from 250° to 300°K as a check on the internal consistency of the data.

Since the crystal structure of ammonium bromide changes from cubic to tetragonal below the β–γ lambda transition, one must consider the effect of this symmetry change on the elastic constants of a crystalline sample. The tetragonal axis a_3 is now not equivalent to the other axes, and therefore $c_{33} \neq c_{11}$, $c_{13} \neq c_{12}$, and $c_{66} \neq c_{44}$ in the low-temperature phase. Since data were obtained

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