

ism between the alkali earth metals cannot be as close as superficially appears, because at atmospheric pressure calcium and strontium are face-centered cubic, whereas barium is body-centered. It is surprising that these simple cubic structures permit so many other forms.

Selenium is probably a mixture of amorphous and crystalline material. On the initial application of pressure it experiences some permanent change, but a single application apparently forces it into a more or less well-defined condition. The results obtained now agreed well in the common range with the former measurements to a pressure maximum of 50,000 kg/cm<sup>2</sup>. The very sharp drop

of compressibility of selenium in the neighborhood of 25,000 is to be noted. The curve of compression of selenium against pressure is quite different in character from that of all the other elements, dropping off with pressure at a much more rapid rate. The amorphous material doubtless functions more like a liquid than a crystalline solid.

As in all this work, I am indebted to the Carboloy Company for the Carboloy. I have received financial assistance from the Milton Fund of Harvard University, and the skillful assistance of my mechanic Mr. Charles Chase was essential.

AUGUST 15, 1941

PHYSICAL REVIEW

VOLUME 60

## Heat Transfer and Superfluidity of Helium II

P. L. KAPITZA

*Institute for Physical Problems, Academy of Sciences USSR, Moscow, USSR*

(Received June 23, 1941)

**I**N our recent researches, when studying the heat transfer of helium II in capillaries, we established the existence of a counter current in the liquid.<sup>1</sup> An analysis of the experimental results indicated that the transfer of heat into the kinetic energy of the current might take place in a thermodynamically reversible way. From these experiments it was suggested that the helium II flowing in thin films could be in a different energy state.

In the present experiments we studied the flow of helium through a narrow slit, about 10<sup>-5</sup> cm, obtained by means of two optically polished quartz disks in the same way as in the viscosimeter by the aid of which we originally established the superfluidity of helium II.<sup>2</sup> By making the helium flow through this slit under the influence of a temperature gradient in a container with a good heat insulation it was possible to show that the flowing helium has zero entropy. The difference of the heat content  $Q$ (cal./g of free helium and helium flowing through the slit

obtained at a number of temperatures is plotted by crosses in Fig. 1.

From a simple thermodynamic analysis of this phenomenon it follows that if the helium II is forced through a narrow channel under a pressure  $p$ ; then in the case of thermohydrodynamically reversible phenomena a temperature difference  $\Delta T$  will be caused which can be determined from the following expression.

$$p = A\rho Q(\Delta T/T), \quad (1)$$

where  $\rho$  is the density of the helium and  $A$  the mechanical heat equivalent.

By means of the same apparatus the existence of the temperature difference  $\Delta T$  was established and measured. In such a way we have an independent means of determining the value of  $Q$  from expression (1). On the curve in Fig. 1 these values of  $Q$  are plotted by circles. The coincidence of  $Q$  determined by two different methods shows that the thermohydrodynamic processes of helium II are reversible.

The reversibility of the thermohydrodynamical processes in helium II must evidently be attributed to the lack of the sources of energy

<sup>1</sup> P. L. Kapitza, *J. Exp. Theor. Phys.* **11**, 1 (1941); *J. Phys. USSR* **4**, 177 (1941).

<sup>2</sup> P. L. Kapitza, *Rec. Acad. Sci. USSR* [18] **28** (1938); *Nature* **74**, 141 (1937).

dissipation. This shows once more that helium II is a superfluid and a poor heat conductor.

The former experiments made to study the viscosity of helium II when flowing through narrow channels did not take into account the influence of a possible temperature difference which, according to Eq. (1) would cause an additional pressure. Therefore, all the data obtained when studying the possibility of a viscous flow of helium II through a slit or through capillaries must be revised. By taking into account this extra pressure, we found that the limit of a possible viscosity for helium II is less than  $10^{-11}$  poise. This is about 100 times less than the limit found with the same viscosimeter in our original experiments<sup>1</sup> and also much smaller than that established by other research workers.<sup>3</sup>

The reversibility of the thermohydrodynamic phenomena in helium II gives the research worker the possibility of establishing a method for attaining very low temperatures. As there are, at present, no experimental or theoretical reasons for supposing that helium II changes its thermohydrodynamical properties on approaching zero, this method for obtaining low temperatures—as distinguished from the magnetic method—will *a priori* permit us to approach as near to absolute zero as our technical means will permit.

This method is now being worked out by us, and in the preliminary experiments temperature drops of  $0.4^\circ\text{K}$  have already been easily obtained.

A possibility of helium II flowing with zero entropy has already been put forward in the theoretical views of London<sup>4</sup> and Tisza.<sup>5</sup> The

<sup>3</sup> J. F. Allen and A. D. Misener, Proc. Roy. Soc. **172**, 467 (1939).

<sup>4</sup> W. F. Giauque, J. W. Stout and R. E. Barieau, Phys. Rev. **54**, 147 (1938); J. Am. Chem. Soc. **61**, 654 (1939); H. London, Proc. Roy. Soc. **171**, 484 (1939).

<sup>5</sup> L. Tisza, Nature **141**, 913 (1938); Comptes rendus (Paris) **207**, 1035, 1186 (1938).

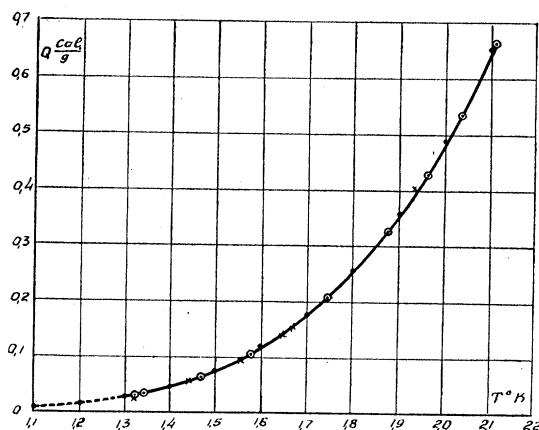


FIG. 1. Heat content of helium.

recently proposed theory of Landau<sup>6</sup> establishes a quantum basis for the phenomena of superfluidity and also permits us to make a qualitative calculation of the heat content of helium II at low temperatures. According to these theories

$$Q = ST, \quad (2)$$

where  $S$  is the entropy of helium II.

The results as calculated by Professor Landau from his theory are plotted by dots on the curve in Fig. 1 and coincide well with the independent experimental data from the experiments made to ascertain the values of  $Q$ . This theory also gives an interesting quantum interpretation of the counter current of helium observed during heat conductivity.

A detailed account of these experiments will be found in one of the next issues of the *Journal of Physics, USSR*.

<sup>6</sup> L. Landau, J. Phys. USSR, in press; Phys. Rev. **60**, 356 (1941) (this issue).