## Law of Force between Two He Atoms

During the last few years a number of papers<sup>1</sup> have appeared dealing with the energy of interaction of two He atoms as they are brought closer and closer together. The purpose of the present Letter is to point out that the law of force obtained by the most recent quantum theoretical considerations agrees surprisingly well with that found by Lennard-Jones<sup>2</sup> from classical considerations on the viscosity and equation of state of helium gas. Classically it is found that for fairly large internuclear distances a force of attraction prevails, but that at distance of 2.5 angstroms or less, a very strong repulsive force dominates the situation. These two types of force receive their interpretation in the quantum theory as electrostatic polar attraction, and repulsion due mostly to electron exchange. The polar attraction has been calculated by Slater and Kirkwood<sup>1</sup> taking account only of the dipole-dipole interaction. This calculation was



improved by Margenau,<sup>1</sup> who introduced the correction for the dipole-quadrupole and quadrupole-quadrupole interactions. The modification engendered by these other terms is considerable. The force of repulsion, or valence force, is known from the work of Slater.<sup>1</sup> Combining the results of Margenau and Slater, the mutual potential energy of two He atoms, distance  $\rho$  apart, is

$$V(\rho) = [7.7e^{-2.43\rho} - 0.68(1+7.9/\rho^{2} + 30/\rho^{4})/\rho^{6}] \times 10^{-10} \text{ ergs},$$

 $\rho$  being measured in terms of  $a_0$ , the radius of the first Bohr orbit for *H*. If the terms in  $1/\rho^8$  and  $1/\rho^{10}$  are omitted, the energy of inter-

action as calculated by Slater and Kirkwood is obtained.

Lennard-Jones<sup>2</sup> has found that in order to fit the experimental data on the variation of viscosity of He with temperature and on the equation of state

 $V(\rho) = 1.78 \times 10^{-6} / \rho^{13} - 6.21 \times 10^{-13} / \rho^4$  ergs. The figure shows the variation of  $V(\rho)$  with  $\rho$  for the three laws. It is surprising how closely the curves follow each other. The agreement is not good at large internuclear distances and it is in this region that the quantum theoretical calculations are most accurate, and are therefore to be preferred. At smaller internuclear separations, however, the reverse situation may very well apply, since the influence of the higher poles increases very rapidly as  $\rho$  decreases and these have been taken into account only approximately. Moreover, in this region the valence term may not be accurate although it is probably fairly near the truth.

There have been several attempts to estimate the second virial coefficient of He. Although it is not difficult to make approximate calculations which agree well with the experimental values, an exact theoretical treatment is lacking. The method used up to the present is a semi-classical one in which classical statistics are assumed for the translational energies of the atoms but for the internal motions quantum statistics are employed. Calculations along these lines have given good agreement with experiment as far as the second virial coefficient is concerned. One can use a similar procedure to obtain the coefficient of viscosity. For this calculation the weak attractive field of He is not of much importance. Since the quantum theoretical law of force agrees well with that of Lennard-Jones at those values of  $\rho$  where  $V(\rho)$  is about equal to the mean thermal energy of the molecules, it must also give a good value for the viscosity. The detailed calculations are rather laborious and it hardly seems worth while to make them until the law of interaction is known with greater accuracy.

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<sup>1</sup> J. C. Slater, Phys. Rev. **32**, 349 (1928); J. C. Slater and J. G. Kirkwood *ibid*. **37**, 682 (1931); H. Margenau, *ibid*. **38**, 747 (1931). <sup>2</sup> J. E. Jones, Proc. Roy. Soc. **107**, 157

<sup>2</sup> J. E. Jones, Proc. Roy. Soc. **107**, 15 (1925).