LETTER TO THE EDITORS

EXPERIMENTS ON LONG-RANGE ATTRACTIVE FORCES BETWEEN MACROSCOPIC OBJECTS

INTRODUCTION

In order to investigate the existence of long-range attractive forces, proposed by Kallmann and Willstätter (1), and worked out by Hamaker (2) and by Verwey and Overbeek (3) in the theory of the stability of hydrophobic colloids, experiments on direct measurements of these forces have been undertaken. Flat, highly polished glass and quartz plates were chosen as objects.

Starting from London's (4) basic equation, de Boer (5) and Hamaker (2) obtained for the force per square centimeter between two parallel flat plates at a distance d,

$$F = -\frac{A}{6\pi d^3}, \qquad [1]$$

where F = attractive force in dynes/cm.², d = distance in cm., and $A = \pi^2 q^2 \lambda$, in which q = number of atoms/cm.³ and λ is the London constant for the dispersion force between a pair of atoms.

The constant A is expected to be of the order of 10^{-13}–10^{-11} dyne-cm. but due to the complicated structure of glass and quartz an accurate calculation is impossible. If only the polarizability of the oxygen ions is taken into account, A is calculated at very near to 10^{-12}.

Casimir and Polder (6) have calculated that due to retardation effects the inverse third power law of Eq. [1] should change to an inverse fourth power at distances much larger than the wavelength to be associated with the dispersion forces.

EXPERIMENTS[1]

The two plates were carefully adjusted over an area of the order of 1 cm.². Newton interference colors were used to estimate the parallelism and the distance. One of the plates was attached to a fairly stiff spring. The force F was obtained by measuring the bending of this spring, using an electric capacity method, capable of measuring the bending with an accuracy of about 10 A.

The air pressure in the system was lowered to 0.04 mm. Hg. At this pressure the viscosity of the air was low enough to permit establishment of the equilibrium at the distances required (5000–15,000 A.) within a

[1] A preliminary note on the first experiments has been published in *Proc. Koninkl. Nederland. Akad. Wetenschap.* **54**, 387 (1951).

few seconds and high enough to damp vibrations of the plate. Water vapor was removed by flushing the system with dry air. In order to avoid spurious electrostatic effects the air inside the apparatus was made conducting by the presence of a radioactive preparation or by ionizing.

The major difficulties in the measurements were formed by obstacles between the plates, probably dust particles or small pieces of the gel-like surface layer of glass.

In all the experiments mentioned below, the two plates were free from each other except in the experiments at a distance of about 200 A., which could only be obtained by forcing the plates together by crushing or pushing away the dust particles between them.

A full description of the experimental setup will be given in a future publication.

RESULTS

Results of the measurements with one set of glass plates ($n_D = 1.5209$; $d_{15} = 2.556$) are assembled in Fig. 1. In the double logarithmic plot the best straight line leads to the force–distance relation

$$F = \frac{2.5 \times 10^{-12}}{6\pi d^{2.64}} \text{ dynes/cm.}^2 \qquad [2]$$

but the scattering of the points is so large, that an exponent of 3 cannot be ruled out. With this exponent the most probable value of A would be 3×10^{-11}. An exponent of 4 would not agree with our measurements.

Replacing of one of these glass plates by a crown glass plate of different origin ($n_D = 1.515$; $d_{15} = 2.55$) led to forces which were about two times larger.

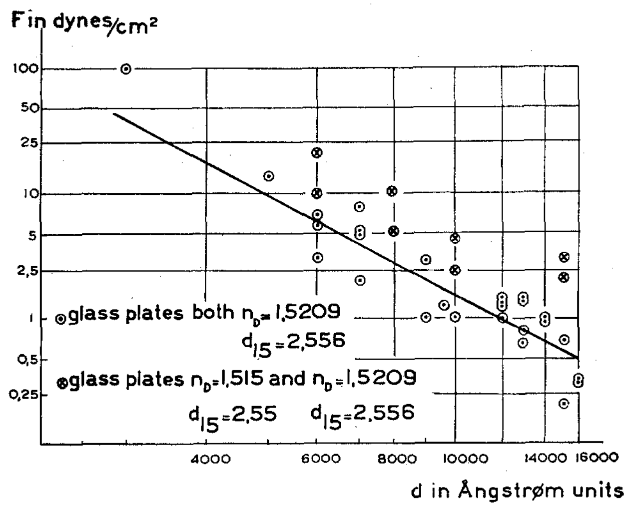

FIG. 1. Graph of force vs. distance. The force value at 3000 A. is not included in the line drawn in the figure.

A few measurements with two quartz plates gave the following results from which a value of A of about 3×10^{-11} is calculated, assuming the exponent to have the value of 3.

d A.	F dynes/cm.^{2}
12,000	0.7–2
16,000	0.2

Evaporating a thin layer of silver (100–200 A.) upon the plates did not materially change the attractive force at distances of about 6000 A. It has not yet been possible to obtain satisfactory measurements with thicker silver layers due to comparatively large obstacles between the plates in those cases.

With all the glass plates attractive forces of more than 10^5 dynes/cm.^{2} at a distance of about 200 A. have been found. In these experiments the force was measured which was just large enough to tear the plates apart. In these cases both the measuring of the force and that of the distance was relatively inaccurate, but the values obtained are in agreement with those found by Lord Rayleigh (7), and assuming again the inverse third-power law an A value of about 2×10^{-11} is found.

Conclusions

Attractive forces do exist between macroscopic objects. An origin by spurious electrostatic charges can be ruled out by the conductivity of the air, by the experiments with the silver layer, and by the reproducibility of the values. The dependence of the force on the distance is in accordance with the inverse third-power law following for the London forces although there is a tendency to a somewhat smaller power than three. An inverse fourth power predicted by Casimir and Polder for the retarded London force is not found in our experiments.

The absolute value of the forces measured is somewhat larger than that predicted on the most simple assumptions, but still within the range possible for London forces.

The experiments are being continued.

References

1. Kallmann, H., and Willstätter, M., *Naturwissenschaften* **20**, 952 (1932).
2. Hamaker, H. C., *Physica* **4**, 1058 (1937).
3. Verwey, E. J. W., and Overbeek, J. Th. G., Theory of the Stability of Lyophobic Colloids, Chap. 6. Elsevier, Amsterdam, 1948.
4. London, F., *Z. physik. Chem.* **B11**, 222 (1931).
5. de Boer, J. H., *Trans. Faraday Soc.* **32**, 21 (1936).
6. Casimir, H. B. G., and Polder, D., *Nature* **158**, 787 (1946); *Phys. Rev.* **73**, 360 (1948).
7. Rayleigh, J. W. S., *Proc. Roy. Soc.* (London) **A156**, 326 (1936).

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