Dispersion Forces between Fused Silica Objects at Distances between 25 and 350 nm

BY G. C. J. ROUWELER AND J. Th. G. OVERBEEK

Van 't Hoff Laboratory, University of Utrecht, Netherlands

Received 29*th December*, 1970

Direct measurements of dispersion forces between a fused silica lens and a fused silica flat plate were carried out for a range of separations between 25 and 350 nm. At separations greater than 50 nm, retarded dispersion forces were observed, while at shorter distances a transition towards unretarded dispersion forces was detected. The value of the retarded Hamaker constant for fused silica was 1.05×10^{-19} erg cm, about twice the value predicted by the Lifshitz theory.

During the past fifteen years several authors reported direct measurements of dispersion forces. Most of them described only experiments in which retarded forces were found.[1-5] The objects chosen for measurement were polished dielectrics or metals for which separations smaller than 90 nm could not be achieved because of surface roughness. Tabor and Winterton [6] succeeded in measuring dispersion forces in the distance range of 5-30 nm by using molecularly smooth mica surfaces. They found good agreement with Lifshitz' theory,[7] the unretarded dispersion forces operating at distances below 10 nm and retarded dispersion forces above 20 nm. Wittmann and Splittgerber [8] measured dispersion forces between fused silica objects, which were cleaned in a special manner. They reported 5 measurements lying in the distance range between 20 and 100 nm.

We have succeeded in extending the range of our measurements of dispersion forces down to about 25 nm with a carefully selected set of a fused silica sphere and a flat plate.

EXPERIMENTAL

PROCEDURE

The measurements were carried out in vacuum with a precision balance used also by Van Silfhout.[4] We improved the measurement of the gap width between the plates by using a binocular microscope, specially modified for reflectometric measurements (fig. 1). A parallel beam of white light was directed towards the gap. The Newton rings in the gap could be observed visually with the eyepiece. The intensity of the light reflected from the very middle of the rings was measured with a photomultiplier after passing through an appropriate monochromatic filter. The distance d between the plates then could be calculated from the Rayleigh equation with an accuracy of about 1 nm for the greater part of the distance range:

$$I = I_0 \frac{2R_s\{1-\cos(4\pi\, d \cos\phi/\lambda)\}}{1+R_s^2-2R_s\cos(4\pi\, d\cos\phi/\lambda)}. \tag{1}$$

I is the intensity of the reflected light, I_0 that of the incoming beam, R_s the reflectivity of the vacuum-fused silica surface, λ the wavelength of the monochromatic filter used and ϕ the angle of refraction here being 6°.

The deflection of the balance arm was measured as a change in the capacity of a condenser fixed to this arm (fig. 1). The condenser was connected to a sensitive capacity bridge, which was used slightly out of balance. The signal of the zero-point detector of this bridge was fed to a two-pen recorder, on which the signal of the photomultiplier was also recorded. With this balance, forces as small as 0.5×10^{-3} dyn could be detected. However, for measuring at shorter distances, stiffer leaf springs (*a* in fig. 1) had to be mounted, which increased the detection limit to 12×10^{-3} dyn. This had to be done to prevent the plates from collapsing at the shorter distances.

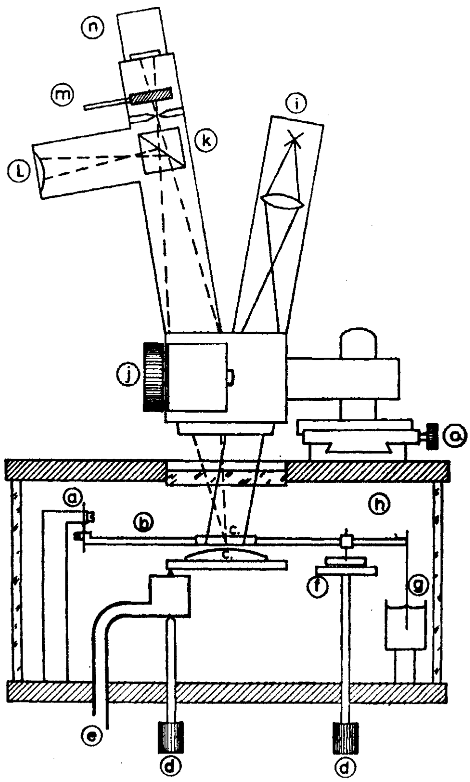


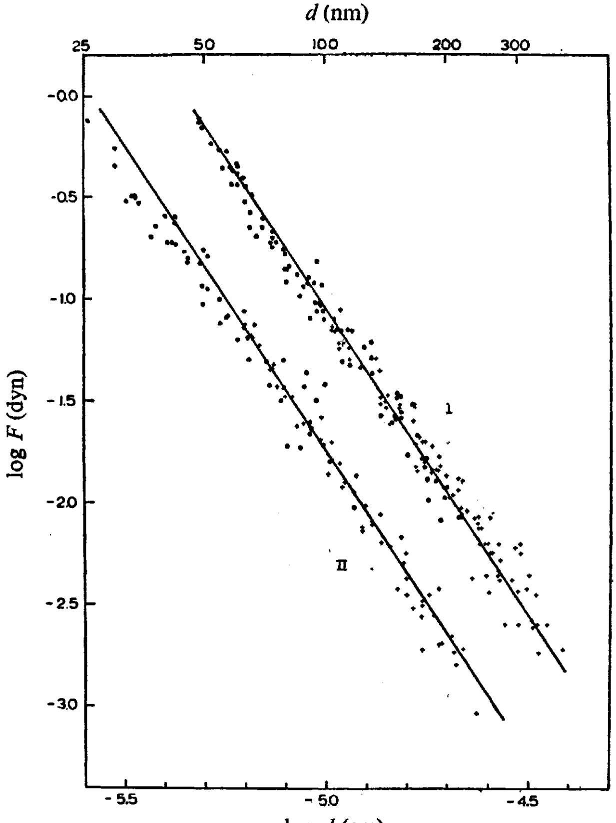
FIG. 1.—Schematic outline of the balance and the reflectometer. The counterweight at the balance arm has been omitted: the dimensions of the vacuum chamber are about twice as large compared to the other objects. (*a*) leafspring; (*b*) balance arm; (*c*) fused silica plate; (*d*) micrometer screw; (*e*) pressure device for distance adjustment; (*f*) capacity proximator; (*g*) damping device; (*h*) vacuum chamber; (*i*) microscope lamp; (*j*) magnification selector; (*k*) beamsplitter; (*l*) eye piece (*m*) interchangeable monochromatic filter; (*n*) photomultiplier; (*o*) table with cross feeds.

Two sets of carefully selected, very smoothly polished, fused silica objects were used. The first set consisted of a flat plate and a plano-convex lens, radius of curvature 413.5 cm; the spherical surface was directed towards the flat plate. The second set contained similar parts, the lens radius now being 83.75 cm. Before mounting the plates in the apparatus, the plates were carefully examined with a phase-contrast microscope. Only surfaces absolutely free of pits or scratches were selected. In a separate study the surface topography of some of the plates was inspected with Tolansky optics; no surface irregularities were found. Electron microscope examination of platinum-carbon replicas revealed the presence of a grainy structure mounting to a maximal height of about 5 nm; no wave-like aberrations of surface smoothness were detected. The deviations from the ideal surface topography are believed to have only a minor influence on the value of the retarded Hamaker constant.

After thoroughly cleaning the surfaces with isopropanol to remove surface contaminants and dust particles, the plates were mounted in the apparatus. When a vacuum of 10^{-2} Torr was reached, a few drops of water were introduced into the apparatus. This caused the formation of a thin conducting film of water, which removed all static electricity. After 15 min the apparatus was evacuated to a final pressure between 10^{-4} and 10^{-5} Torr. Very small separations could be achieved only when the plates were held for at least 6 h at this low pressure, perhaps because of the shrinking of some silica particles present.

RESULTS

The measurements are presented in logarithmic form in fig. 2. Several series of measurement are reported; each series includes all the treatments described above, although after some series the plates were not dismounted and cleaned again. With the system containing the 413.5 cm radius lens, a minimum distance of 45 nm was reached before repulsion due to contacting obstacles occurred. With the lens of 83.75 cm radius, separations as small as 10 nm were achieved. However, no measurements were executed below 25 nm, for at this distance the inaccuracy inherent in the reflectometer caused an uncertainty of 2 nm in the distance. This error increases



fused silica, $\bar{B} = 1.05 \times 10^{-19}$ erg cm, $R_{\mathrm{I}} = 413.5$ cm, $R_{\mathrm{II}} = 83.75$ cm.

FIG. 2.—Attraction between a flat plate and a plano-convex lens of fused silica. The upper line represents the system with the 413.5 cm radius lens, 6 series of measurements are reported. The lower line represents the system with the 83.75 cm radius lens, here 5 series are reported. Crosses indicate forces measured with a standard deviation in the force of 0.5×10^{-3} dyn; for dots the standard deviation is 12×10^{-3} dyn. The lines are drawn with a slope of -3.00 corresponding to eqn (2) and (3); the standard deviation in $\bar{B}$ amounts 0.04×10^{-19} erg cm.

rapidly as the distance decreases below 25 nm. Adapting the reflectometer for more accurate measurements at distances below 25 nm would have involved major changes in the apparatus. Within the limits of error both graphs in fig. 2 show a d^{-3} dependence of the dispersion forces for separations greater than 50 nm as expected for retarded dispersion forces. Both lines obey the equation:

$$F = 2\pi RB/3d^3, \tag{2}$$

where F is the dispersion force and R the radius of curvature. In both systems the value of the retarded Hamaker constant B is equal to 1.05×10^{-19} erg cm, in agreement with results found for fused silica by other authors who deduce values ranging from 0.81 to 2.0×10^{-19} erg cm.[1,3,8,4*] The range of the truly non-retarded dispersion forces was not reached. But as can be seen in fig. 2 the d^{-3} dependence of the force changes towards a d^{-2} dependence for distances below 50 nm.

DISCUSSION

When the separation between the plates is large compared to $\lambda_0/2\pi$ the general formula found by Lifshitz [7] can be simplified considerably. Here λ_0 is a wavelength associated with the absorption band which contributes most to the dispersion forces. For a sphere separated from a flat plate of the same material in vacuum the retarded dispersion forces can be expressed as

$$F = \frac{\pi^2 hc\, R}{720\, d^3}\frac{(\varepsilon_0-1)^2}{(\varepsilon_0+1)^2}\phi(\varepsilon_0), \tag{3}$$

where h is Planck's constant, c is the velocity of light, ε_0 the static dielectric constant and $\phi(\varepsilon_0)$ a monotonic function of ε_0 rising from 0.35 for $\varepsilon_0 = 1$ to 1 for $\varepsilon_0 = \infty$. Eqn (3) is equivalent to eqn (2), so B can be computed once a value of ε_0 is chosen. Lifshitz recommends the use of n^2 for ε_0 (n is the index of refraction). Based on this assumption, B for fused silica is 0.57×10^{-19} erg cm. Hunklinger [5] proved that such a value for ε_0 is correct on the basis of a simplified model for ε as a function of the wavelength. Only a small correction term accounting for the influence of the infra-red absorption band on the dispersion forces then has to be added to eqn (3). However, the contribution of this term is too small to be detected in the measurements reported here. At separations small compared to $\lambda_0/2\pi$, a d^{-2} dependence occurs according to Lifshitz. Since λ_0 equals about 120 nm for fused silica the truly non-retarded dispersion forces can be expected to occur well below 20 nm. Because of the present inaccuracy in our measurement of the distance the measurement of non-retarded forces could not be presented here. Around 20 nm a transition region between retarded and non-retarded forces is expected. This region is found to begin at separations of about 50 nm (fig. 2); the d^{-3} dependence of the force changing towards a d^{-2} dependence for smaller distances.

We thank Dr. P. H. Wiersema for his encouragement and stimulating discussions. This work is a part of the research programme of the Foundation for Fundamental Research (F.O.M.) and was made possible by financial support from the Netherlands Organization for Pure Research (Z.W.O.).

* Recently it came to our attention that in the work reported in ref. (4) an error of about 20 % was made in the calculation of the distance between the fused silica plates. This implies that the value of B reported in that publication for fused silica (0.66×10^{-19} erg cm) should be corrected, increasing it by a factor of about 2.

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