

**Direct Measurement of Molecular Attraction of Solid Bodies.
II. Method for Measuring the Gap. Results of Experiments.***

I. I. ABRIKOSOVA AND B. V. DERIAGIN**

Institute of Physical Chemistry, Academy of Sciences, USSR

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Results are presented of measurements of molecular attraction for fused quartz for distances from 0.08 to 1 μ . The data are in good agreement with calculations using the formula of the theory of E. M. Lifshitz, which deals with the case of separations which are much greater than the wavelengths of the fundamental ultraviolet absorption bands, and which contains no undetermined empirical constants. The agreement obtained substantiates both Lifshitz' theory and the electromagnetic nature of the molecular forces which was already suggested by P. N. Lebedev in 1894.

The results of measurements of Overbeek and Sparnaay exceed the theoretical values by almost a factor of 10^4 , apparently due to electrostatic effects.

1. METHOD OF MEASUREMENT OF SEPARATION.

THE size of the minimum gap H between the lens L and plate P was calculated from the diameter of Newton's rings measured with a microscope provided with an ocular scale, when the gap was illuminated by light from a 300 watt lamp through a constant deviation monochromator and the vertical illuminator of the microscope (see Fig. 1). It is easy to find the relation between the gap H , the diameter d_m of the m th dark ring, the wave length λ of the monochromatic light, and the radius R of the spherical surface. The condition for producing the m th dark ring is

$$2\delta_m + 2H + \lambda/2 = (2m + 1)\lambda/2. \quad (1)$$

From the geometry, it is clear that the part of the air gap which is denoted by δ_m in Fig. 2 is related to the diameter d_m of the m th ring by the relation

$$\delta_m = d_m^2 / 8R.$$

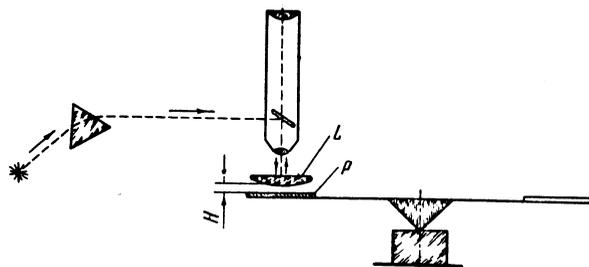


FIG. 1

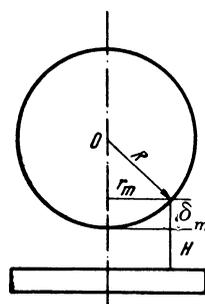


FIG. 2.

Substituting for δ_m in terms of d_m in Eq. (1), we obtain for the minimum distance H between the surfaces the expression

$$H = \frac{\lambda}{2} \left(m - \frac{d_m^2}{4R\lambda} \right), \quad (2)$$

from which it follows that to determine H we must know m , d_m , λ and R .

To determine the ring number m one can, while observing the rings, bring the surfaces into contact and thus compute the order number of the ring. Such a procedure is unsuitable when measuring molecular attraction, because of the possibility of contact electrification. We therefore used a different method based on the changes in the diameter of the interference ring when the number m and the wavelength λ of monochromatic light are varied for constant H .

We introduce the quantities $\Delta(d_m)^2$ and $\Delta(d_\lambda)^2$, defined by the following equations:

$$\Delta(d_m)^2 = d_{\lambda+\Delta\lambda, m}^2 - d_{\lambda, m}^2 \quad (3)$$

*Cf. the literature references in Reference 1.

**F. B. Leib participated in the development of the technique.

and

$$\Delta (d_{\lambda}^2) = d_{\lambda, m+\Delta m}^2 - d_{\lambda, m}^2. \quad (3')$$

Using the relation (2), we can write

$$\Delta (d_m^2) / \Delta \lambda = 4Rm \quad (4)$$

and

$$\Delta (d_{\lambda}^2) / \Delta m = 4R\lambda. \quad (4')$$

Dividing (4) by (4'), we get for m the expression

$$m = \lambda \Delta (d_m^2) \Delta m / \Delta (d_{\lambda}^2) \Delta \lambda. \quad (5)$$

Before starting the fundamental measurements, i. e., the measurement of the force of attraction F and the corresponding gap H , the number m of a particular ring was determined from (5), and from it the numbers of other rings. The radius R of the spherical surface was measured using the same optical system. According to (2), d_m^2 depends linearly on m for constant λ and H . If we plot d_m^2 as ordinate and m as abscissa, then if we divide the tangent of the angle between the line $d_m^2 = f(m)$ and the m axis by 4λ , we get the radius R .

Since λ , m and R were always determined before the fundamental measurement, the latter reduced to measurement of a current i and the diameter of one (sometimes 2 – 3) interference ring. This last fact made possible the successful performance of the experiment, since it enabled us to concentrate our attention on the simultaneous measurement of only two quantities.

The precision of measurement of the gap H was almost entirely determined by the uncertainty in measurement of the diameter of the m th (usually the second) ring d_m , which amounted (for d_2) to $\sim \pm 1\%$, which guaranteed an accuracy in the measurement of the gap H of approximately $\pm 0.002 \mu$.

2. CLEANING OF SURFACES

The method of cleaning the glass and quartz surfaces with which the interaction was studied was an essential point. For a successful experiment, the surfaces must be carefully cleaned of

all films and dust particles.

The usual methods of chemical cleaning such as washing with chromic acid cleaner were not used, since they sometimes damage polished glass surfaces. We successfully used the following method for thorough cleaning of glass and quartz surfaces. We washed the plate and lens with distilled alcohol and ether, using cotton from which the grease had been removed in a Soxhlet extractor, and then processed them in a glow discharge under glass wool. The purity of the surface could be judged from the fact that after cleaning we always observed complete wetting of the glass surface by water.

It proved to be far more difficult to rid the surfaces of dust. Of all the methods tried by us (removal of dust particles with a grease-free brush, cotton, fabric, chamois, etc.), the best results were gotten when the surfaces (after cleaning in a glow discharge) were rubbed with grease-free cotton slightly moistened with pure ether. (This last step was, of course, for removal of dust and not for improving the cleanliness of the surface). The surfaces remained free of film after such treatment since, as was the case immediately after cleaning in the glow discharge, they were completely wet by water.

Before placing them on the balances, the surfaces were examined under a binocular microscope at 100-fold magnification.

3. FUNDAMENTAL EXPERIMENTAL DIFFICULTIES AND THEIR ELIMINATION

The main experimental difficulties were associated with 1) sensitivity of the apparatus to vibrations of the support, 2) dust particles falling on the surfaces under investigation, 3) electrification of the surfaces during cleaning.

1) The true sensitivity of the apparatus for determining the interaction force depends essentially on the vibration of the support on which the apparatus is placed; we therefore carried out special experiments to study the vibration of the apparatus and the effect of various damping mechanisms.

Vibrations of the support result in fluctuations of the current in the feedback circuit. By eliminating in turn all the sources of current fluctuations, we established that their main cause is the presence of industrial and vehicular noises which are transmitted through the ground and which vary in time in both amplitude and frequency. To measure the damping properties of various supports,

we removed the beam balance from our circuit, and put a mirror on the platform in its place (cf. Fig. 5, Ref. 1); we thus obtained a sensitive photoelectric indicator of vibrations of the support. Because of the fact that we had to come into direct contact with the equipment during preparation for measurement and during the measurement itself, damping mechanisms such as are used in setting up sensitive galvanometers were not suitable. We succeeded in obtaining the best results by placing the apparatus on a table with shock absorbers, which in turn was placed on a cement pedestal which was isolated from the foundation and embedded in the ground. (See Fig. 5, Ref. 1.)

To decrease the effect of vibration further, the optical relay system was improved: light reflected from mirror S_1 (Fig. 3) fixed on the beam balance was reflected once more from mirror S_2 which was coupled to the platform (cf. Fig. 5 of Ref. 1), which made the photocurrent independent of vibrations common to both the beam balance and the platform, and dependent only on the gap H .

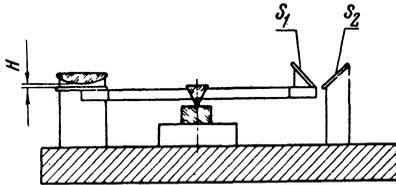


FIG. 3.

The angle between mirrors S_1 and S_2 was approximately 90° . By means of a screw brought out under the platform we could regulate the position of mirror S_2 for adjustment of the apparatus.

2) The preparation of samples for measurement is a very important part of the experiment, since during cleaning the surfaces of dust the samples become electrified, as a result of which they interact with a force which far exceeds the molecular attraction and masks it. To eliminate charges from the surfaces of the plate and lens, we had to separate them and, by some means, ionize the air around the apparatus. When this was done, dust particles from the air frequently fell on the surfaces, and we had once again to clean them and remove the charge, until we succeeded in removing both the dust particles and the electrostatic interaction. As the tests showed, dust does not enter the gap if the distance

between plate and lens is very small, so that it is important to achieve simultaneous absence of dust and charge once, and then not separate the surfaces by more than $5 - 10 \mu$.

3) Electrical charges develop on clean dry surfaces very easily, from even the slightest contact with a clean brush or rubber gloves. Each time, before we succeeded in measuring the molecular attraction, we had to get rid of the surface charges by ionizing the air. We used the radioactive isotope S^{35} to remove the charges from the quartz surfaces. Removal of the charge turned out to be impossible when the surfaces were very close. Only for very large separations of the surfaces (1 mm and greater) was the action of the ionizer effective, which showed that the attractive forces observed previously were of electrical origin. The slow discharge when the gap between the surfaces is narrow is probably explained by the fact that very few ions enter such a gap.

As already mentioned, the sensitivity of the apparatus for measuring the attractive force is almost entirely determined by the current fluctuations in the feedback loop caused by vibrations of the support. For this reason, at the beginning, when we did not use all the methods described in this Section for preventing the vibration, the sensitivity proved to be insufficient for detecting and measuring the molecular attraction. After getting rid of the charges, no attraction between the surfaces was detected up to gaps of $H = 0.05 \mu$, while the accuracy of the force measurement was $\pm 10^{-2}$ dyne.

4. RESULTS OF MEASUREMENT

The basic result of the work is the detection and quantitative measurement of the molecular attraction between samples of fused quartz separated by a gap of $10^{-5} - 10^{-4}$ cm.

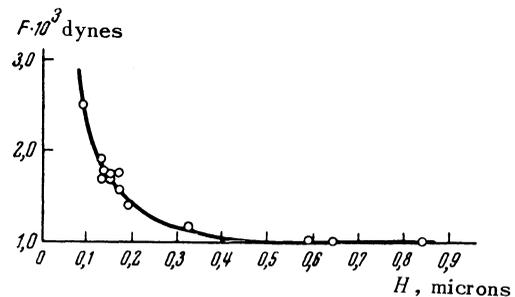


FIG. 4.

TABLE I.

$R = 10 \text{ cm}$ (measurements in air)		$R = 10 \text{ cm}$ (measurements in air)	
H in μ	$F \cdot 10^3$ in dynes	H in μ	$F \cdot 10^3$ in dynes
0.09	1.5 ₀	0.17	0.5 ₈
0.13	0.9 ₀	0.19	0.3 ₇
0.13	0.8 ₀	0.32	0.1 ₃
0.13	0.7 ₀	0.59	0.0
0.14	0.7 ₀	0.64	0.0
0.16	0.7 ₅	0.82	0.0

In Fig. 4 and Table I we give the dependence of the force of attraction F on the separation H , as measured in air (the radius of the sphere was $R = 10 \text{ cm}$).

This dependence $F(H)$ corresponds to the minimum of all the attraction effects observed by us with quartz glass samples. This last point, together with the satisfactory reproducibility of the effect in different experiments, made it possible for us to assume that the effect was of molecular origin. However, to convince ourselves completely of the validity of this assumption, we had to assure ourselves of the absence of spurious attraction effects in our experiments. The most important disturbing influence in measuring the molecular attraction was the electrostatic interaction of the samples. One might therefore suppose that the dependence shown in Fig. 4 includes an electrostatic contribution, and that the molecular attraction which we are trying to measure is only a part of what is measured in the experiment.

If the electrostatic charges are removed completely and the observed attraction between the objects is actually the molecular attraction, then it should be 1) insensitive to repeated ionization of the air around the samples; 2) proportional to the radius of the spherical surface (cf. Eq. 9 of Ref. 1); 3) reproducible from experiment to experiment both with respect to magnitude and with respect to the manner in which the force falls off with distance; 4) reproducible in experiments where the surfaces are brought close to one another at various points; 5) unaffected by removal of air from the gap between the objects.

Further investigations were devoted to checking whether these points were fulfilled by the attraction which we claimed to be molecular. The measurements in vacuum proved to be the most exact and reproducible. The results of experiments in vacuum are given in Fig. 5 and Table 2. Curve I

refers to a radius $R = 10 \text{ cm}$, curve II to $R = 26 \text{ cm}$. Within the limits of error of the measurements, these data satisfy all the requirements enumerated above.

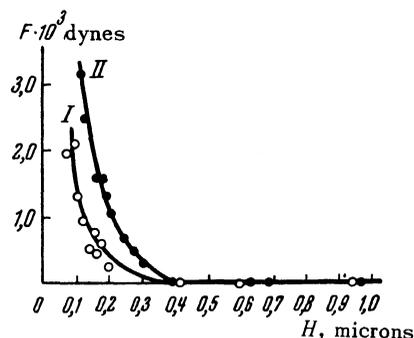


FIG. 5.

TABLE II.

$R = 10 \text{ cm}$		$R = 26 \text{ cm}$	
H in μ	$F \cdot 10^3$ in dynes	H in μ	$F \cdot 10^3$ in dynes
0.08	1.9 ₅	0.13	3.1 ₄
0.10	2.0 ₈	0.14	2.4 ₉
0.11	1.3 ₀	0.17	1.5 ₇
0.13	0.9 ₁	0.18	1.5 ₇
0.15	0.5 ₂	0.20	1.3 ₁
0.16	0.7 ₂	0.22	1.0 ₅
0.17	0.4 ₆	0.25	0.6 ₆
0.18	0.5 ₉	0.28	0.4 ₆
0.20	0.2 ₆	0.31	0.2 ₆
0.42	0	0.42	0
0.64	0	0.62	0
0.96	0	0.71	0
		0.96	0

In Fig. 6, we show on a log-log scale the results of a large number of experiments which were separated by large time intervals and were carried out with various quartz samples. The lens radius was $R = 11.1$ cm. The open circles show points which were gotten from measurements in air. Just before each of these measurements, the air around the samples was subjected to repeated ionization by strong sources. (The straight line shown in the figure was calculated from Lifshitz' theory, which we shall discuss later.)

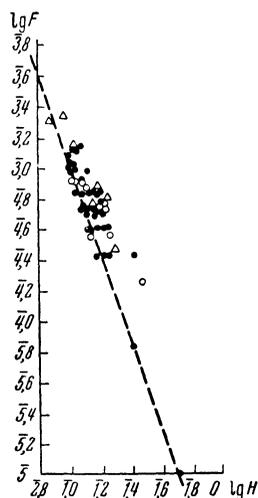


FIG. 6

According to Eq. (9) of Ref. 1, the quotient of $F(H)$ by $2\pi R$, where R is the radius of the spherical surface, is the energy of attraction, $U(H)$, of two infinite plates, per square cm of area. Figure 7 shows the dependence of the energy U on the separation H , where the dark circles refer to experiments with lens radius $R = 11.1$ cm, the triangles — $R = 10$ cm, and the open circles — $R = 25.4$ cm. This graph illustrates the linear dependence of the attractive forces on the sphere radius, and thus shows that the attractive energy $U(H)$ for the plane case does not depend on which lens was used for measuring the force of attraction.*

Thus all the points enumerated above are satisfied.

*We have not been able to increase the number of different radii R , since for $R < 10$ cm the attractive forces are small, while for $R > 26$ cm it is very hard to avoid the effects of dust particles.

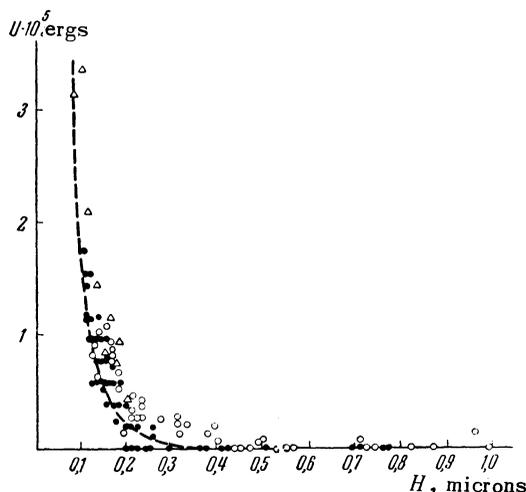


FIG. 7.

5. DISCUSSION OF RESULTS

Considering that the present work has as its purpose the detection and measurement of an effect whose existence could not be demonstrated previously by direct experiments, we feel that it is necessary to consider in more detail the analysis of the results of the measurements and the basis for their interpretation. Such an analysis requires us to look at two questions: the demonstration that the effect discovered in this work is not the consequence of some deficiency in the method of measurement, and the demonstration that the attraction measured in the present work is not associated with some other non-molecular attraction.

The agreement between measurements done in air and in vacuum indicates that they are independent of convection currents, radiometer effects, the presence of a viscous air layer between the bodies, and of the presence of water vapor in the air.

To avoid errors in the measurements due to various mechanical effects of parts of the apparatus, for example elastic forces in the wires carrying current to the coil, friction between the knife edge and its bearing, dust particles remaining on the surfaces of the bodies, etc., we took the following precautions. The elastic effect of the conductors was reduced to a minimum by using very thin wollaston wire annealed over a gas flame. The agate prism and its agate bearing satisfied all the requirements which are imposed on such components in the best types of microanalytic balances. In good microanalytic balances having a balance arm and pans weighing several tens of grams, friction

does not hinder weighing to $10^{-5} - 10^{-6}$ gm. Since friction is proportional to load, it is understandable why with our balance, where the beam weighed 0.1 gm, we could completely neglect the friction between the prism and its support in measurements with an accuracy of $1 - 2 \times 10^{-7}$ gm.

The presence of dust on the surfaces, which could influence the measurements, was always detected by observing the appearance, as the gap was decreased, of repulsive forces which could be recorded by our equipment with the same sensitivity as were the attractive forces, and which never varied smoothly with varying distance. The measurements were taken only if, when the gap was decreased to $0.05 - 0.1 \mu$, no forces other than the attractive forces were observed.

We also believe that the observed attraction cannot be explained by the presence of films remaining on the surfaces after cleaning. The presence on the quartz surfaces of adsorbed water layers, which is unavoidable when measurements are made in air or in poor vacuum, did not affect the results of the measurement since, first of all, the separation between the objects was much greater than the possible thickness of such layers, and, secondly, the dielectric constant, which is closely related to the magnitude of the molecular attraction, is approximately the same for adsorbed layers of water as it is for quartz.

If the dielectric constants of the layer and the quartz are almost the same, then the presence of an adsorbed layer of thickness, say, 10 \AA , is equivalent to a change of the gap by an amount of the same order, i. e., by 10 \AA , which for an accuracy in measurement of H of $\sim 100 \text{ \AA}$ has no effect whatsoever on the results. The assumption that an adsorbed water layer has about the same dielectric constant as quartz is supported by experiments of Kurbatov² who finds that even for a thickness of 4 - 5 monolayers the dielectric constant of an adsorbed water layer is lower by an order of magnitude than that of the volume phase.

Different cleaning methods were used in various experiments. For example, the curve of Fig. 4 refers to experiments where the dust particles were removed with a grease-free brush, whereas the graphs of Figs. 5 and 6 are for cases where ether and grease-free cotton were used for cleansing. If we should claim that the attraction is associated with the surface films, then the agreement of the results of so many experiments would make it necessary to assume that the same surface film was present in all cases, which is altogether improbable.

The absence of a possible effect of contact

electrification of the quartz surfaces on the results of the measurements was verified in the experiment.

Even without making the appropriate computations, we can say that the attractive forces shown, for example, in Fig. 5 are not gravitational forces, since the latter cannot show such a marked change when the gap is changed by an amount small compared to the separation of the centers of mass of the bodies.

There is no need to discuss magnetic forces for the case where quartz samples are used. As for attractive forces between the bodies due to their electrification, these were discussed in detail earlier.

6. COMPARISON WITH THEORY

1) Comparison with the results of computations based on summation of interactions of all pairs of molecules.

If we follow the method of summation of interactions of all pairs of molecules, which is the one used until recently,¹ then for the case of a sphere and a plane we must use the formula

$$F = AR/6H^2.$$

Substituting the results of our experiments in this formula, we get for the constant A the value 5×10^{-14} ergs. But the constant A for quartz is approximately 10^{-12} ergs, i. e., 20 times greater than the value given by the experiment.

Such a comparison shows the unsuitability of the computational methods used up to now (at least, for the case of distances of order 10^{-5} cm). We may therefore assert that the results of the experiments have quite general significance, despite the fact that only one material was measured.

If we use the same summation method, but include the correction of Casimir and Polder (cf. Ref. 1), then we should use the formula

$$U = A_1/30\pi H^3.$$

for the energy $U(H)$.

Substituting our experimental results, we obtain for the constant A_1 a value of approximately 3×10^{-18} erg-cm. Using the formula $A_1 = \pi^2 q^2 c_1$ we get $A_1 = 1 \times 10^{-18}$ erg-cm (the value of the polarizability α being taken from the work of Margenau³).

Thus here too there is disagreement between theory and experiment, but the discrepancy is

much less than for the case where the London forces are summed.¹

2) Comparison with the theory of E. M. Lifshitz.

Precise comparison with the theory of Lifshitz⁴ requires adequate knowledge of the optical properties of the material within its absorption regions. However the character of the absorption of quartz (its transparency for wavelengths equal to the gaps H used in the experiments) enables us to make an approximate theoretical estimate.

The theoretical value of the force per cm^2 for two plates is given for quartz by the formula

$$f(H) = \frac{\hbar c}{H^4} \frac{\pi^2}{240} \left(\frac{\epsilon_0 - 1}{\epsilon_0 + 1} \right)^2 \varphi(\epsilon_0),$$

where ϵ_0 is taken equal to the square of the refractive index in the optical region, and $\varphi(\epsilon_0)$ is given by the table presented in Reference 1.

In order to compare the theoretical values with directly measured experimental quantities, we carry out a series of transformations. By integrating the expression for $f(H)$, we get a formula for the energy of attraction, per cm^2 , for two plates, in the form

$$U(H) = \frac{\hbar c}{3H^2} \frac{\pi^2}{240} \left(\frac{\epsilon_0 - 1}{\epsilon_0 + 1} \right)^2 \varphi(\epsilon_0).$$

The dotted curve in Fig. 7 shows $U(H)$ as computed from this formula, where ϵ_0 was taken equal to the square of the index of refraction in the optical region.

To go over from the energy $U(H)$ to the force $F(H)$ between a sphere of radius R and a plane, we make use of the relation given earlier:

$$F(H) = 2\pi R U(H).$$

The dependence of $F(H)$ calculated in this fashion is given in log-log plot in Fig. 6 (for $R = 11.1 \text{ cm}$).

Considering the roughness of the estimate as well as the uncertainties in the measurements, such agreement can be regarded as altogether satisfactory.

The agreement of experiment and theory shown in the graphs (cf. Figs. 6 and 7) should be regarded on the one hand as support of the validity of the theory of E. M. Lifshitz, and on the other hand as one of the essential proofs of the molecular nature of the attractive effect measured in the experiment.

The agreement of the results of experiment with a theory which explains the molecular interaction

as the effect of electromagnetic fields, which exist within every absorbing medium and extend beyond its boundaries, enables us to answer a question which was posed by P. N. Lebedev in 1894 (cf. Ref. 1). Molecular attraction actually does "reduce to electromagnetic forces" and "no other forces of presently unknown origin" enter into its description.

We note that in the experiments of Overbeek and Sparnaay,⁵ results differing from ours were obtained. Overbeek and Sparnaay measured the attractive forces between plates of fused quartz by means of a special dynamometer in which the shift of the spring was measured by an electric capacitor method; the separation of the plates was determined from the interference fringes produced by the narrow slit; in the discussion of the Faraday Society in 1954, this work was presented at the same time as ours.⁶ The results of the Dutch workers were given in the form of a graph, on a logarithmic scale, of the dependence of the attractive force on distance, and a computation of the experimental value of the constant A which was found to be $3.8 \times 10^{-11} \text{ erg}$.

If we make the computation according to Lifshitz' theory, then we obtain, for a separation of 1200 \AA between quartz plates, an attractive force of approximately $2 \times 10^{-4} \text{ dynes/cm}^2$, whereas this distance corresponded to a force of 1 dyne in the experiments of Overbeek and Sparnaay. Thus the experimental data are higher than theory by about a factor of 10.⁴

The poor reproducibility of the data of Overbeek and Sparnaay as well as the too high value of the attractive effect found in their experiments are probably associated with surface electrification.

3) Application to the theory of Coagulation.

According to the theory of Fuchs⁷ the rate of coagulation of a disperse system whose particles of radius r attract one another with an energy $U(x)$ as a function of the distance x between their centers, is increased relative to the case where $U(x) = 0$ which was treated by M. Smoluchowski by a factor of

$$1 : 2r \int_{2r}^{\infty} \frac{\exp\{-U(x)/kT\} dx}{x^2} \quad (6)$$

$$= 1 : \int_0^{\infty} \frac{\exp\{-U/kT\} d\tau}{(1+\tau)^2},$$

where

$$\tau = (x - 2r) / 2r.$$

If τ is sufficiently small (compared to the wavelengths of the fundamental bands in the absorption spectrum of the particles) then, for values satisfying the condition $x - 2r \ll 2r$, U can be expressed as

$$U = \frac{A 2r}{24(x-2r)} = \frac{1}{24} \frac{A}{\tau}.$$

Considering that $A/24$ and kT are quantities of the same order of magnitude, we see that the coefficient of acceleration of coagulation will be considerably greater than unity*, since U/kT will have sizable values over quite a wide range of values of τ starting from zero, so the acceleration coefficient will be independent of r . However if r is made sufficiently large, this result is changed. In fact, for sufficiently large r , the main part of the integral in (6) comes from values of x for which we must introduce corrections for electromagnetic retardation, which reduces U and consequently also decreases the acceleration of the coagulation. So, for example, for aerosols with particles having $r > 0.3 \mu$, the acceleration of the coagulation due to the effects of molecular forces will be extremely small.

The situation is different in the case of lyophobic sols, where in addition to the attractive energy there is an energy of repulsion caused by the overlap of the ion clouds of the two particles. In this case, for sufficiently coarse particles both terms in the interaction energy will (at those distances for which they are sizable) be proportional to the radius; therefore the presence or absence of an energy barrier for the resultant interaction, which essentially determines the stability of the system, will not depend on the radius of the particles but only on the law of fall-off with gap width of the two terms in the interaction energy. It is therefore obvious that for small thicknesses of the ion atmospheres (i. e. for medium and high concentrations of electrolyte) less than 10^{-6} cm, the behavior of the molecular forces is important for distances where corrections for electromagnetic retardation are not necessary, so that the previously developed theory of the stability of sols, and in particular the sixth power law⁹ for the coagulating effect of ions of opposite sign, (the Hardy-Schulze law), remains valid. The limit of applicability of this law is therefore not determined by the particle radius** but by the concentration: for very low

concentrations, because of the more rapid dropoff of the attractive force at large distances (because of the extra power of the gap width), it is easy to show that the 6th power law should go over into an 8th power law. Since very small coagulant concentrations can be observed only for highly charged (tri- or quadrivalent) ions, such an effect is to be expected only for these cases.

CONCLUSIONS

1. A method is developed which enables one to measure the interaction between very smooth, solid, transparent bodies as a function of their separation. The force is measured by means of a special beam microbalance with photocell-magnet negative feedback. The separation of the bodies is computed from the diameters of Newton's rings. The range of forces measured is $1 - 2 \times 10^{-4}$ - 20 dynes, and the separations 10^{-5} - 10^{-3} cm.

2.) The molecular attraction of samples of quartz glass was detected and measured. The energy of attraction per cm^2 , $U(H)$, between two plates varies with separation H approximately as H^{-3} , and is approximately 1×10^{-5} ergs for $H = 1.5 \times 10^{-5}$ cm.

3.) It is shown experimentally that the attractive force between a spherical and a plane surface is proportional to the radius of the sphere, which is in accord with the molecular nature of these forces.

4.) The work described is the first direct experimental test of the theory of molecular attractive forces between condensed bodies.

5.) An analysis is made of the present state of the problem of molecular attraction. It is indicated that the usually accepted notion of additivity of molecular attractive forces in condensed media has no basis either theoretically or experimentally.

6.) We demonstrate experimentally that computations of the molecular attraction of macroscopic bodies by summing the interaction computed from London's formula over all pairs of molecules are inapplicable when the separation of surfaces is 1×10^{-5} cm or greater. Better results are gotten if the electromagnetic retardation is included.

7.) The experimental data are found to be in accord with Lifshitz' theory. This agreement supports P. N. Lebedev's hypothesis of the electromagnetic nature of molecular forces.

8.) Since the London-Hamaker H^{-2} law for $U(H)$ appears as the particular limiting case of Lifshitz' theory for small distances, for which there is no electromagnetic retardation, the

*This conclusion was already drawn in Ref. 8.

** Thus we cannot agree with the assertion of Verwey and Overbeek¹⁰ that this law requires correction for retardation effects in the case of large particle size and only in that case.

confirmation of this theory gives a basis for using the H^{-2} law at small distances.

9.) The observed deviation from the H^{-2} law, toward lower values, for large distances (10^{-5} cm) indicates (as is easily seen) a small effect of molecular forces on the rate of coagulation of aerosols with particle diameters greater than 3×10^{-5} cm.

10.) The data obtained demonstrate the existence of molecular forces of long range surface interaction, which is one of the corner stones of the contemporary theory of the stability and coagulation of colloids.

11.) The data show that deviations from the 6th power law of the charge, which occurs in the Hardy-Schulze rule, are to be expected for very low concentrations of electrolyte and highly charged ions of opposite sign.

12.) It is pointed out that the measured values of molecular attractive forces in the experiments of Overbeek and Sparnaay exceed both the theoretical values as well as our results by 3-4 orders of magnitude, apparently because effects not related to molecular forces played a part in their measurements.

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¹B. V. Deriagin and I. I. Abrikosova, J. Exptl. Theoret. Phys. (U.S.S.R.) 30, 993 (1956).

²L. N. Kurbatov, Zh. Fiz. Khim 28, 287 (1954).

³H. Margenau, Rev. Mod. Phys., 11, 1 (1939).

⁴E. M. Lifshitz, J. Exptl. Theoret. Phys. (U.S.S.R.) 29, 94 (1955); Soviet Phys. JETP 2, 73 (1956).

⁵J. Th. Overbeek and M. J. Sparnaay, J. Colloid Sci., 7, 343 (1952).

⁶Discussion Faraday Society, 18, 12 (1954), Coagulation and Flocculation.

⁷N. Fuchs, Z. Physik 89, 736 (1934).

⁸I. V. Petrianov, N. N. Tunitskii, J. Phys. Chem. USSR 17 408 (1943); Acta Physicochim. USSR 18, 185 (1942).

⁹B. V. Deriagin and L. D. Landau, J. Exptl. Theoret. Phys. (U.S.S.R.) 11, 802 (1941); 15, 662 (1945); Acta Physicochim. USSR 14, 633 (1941).

¹⁰E. Verwey and J. Th. Overbeek, *Theory of the Stability of Lyophobic Colloids*. Elsevier, Amsterdam, 1948.

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Elastic Scattering of 310 Mev π^+ Mesons from Protons

E. L. GRIGORIEV AND N. A. MITIN

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The angular distribution of 310 mev π^+ mesons elastically scattered by protons in photoemulsions has been measured. The differential scattering cross section based on 427 observed cases has been obtained in the center-of-mass system.

The phase analysis, taking into account only the S and P states, and assuming the Fermi solution, gave the following values for the phase shifts: $\alpha_3 = -23^\circ$, $\alpha_{33} = 132^\circ$, $\alpha_{31} = -9^\circ$. The D state, apparently, contributes little to scattering in comparison with the S and P states.

EXPERIMENTS conducted in recent years for studying the scattering of π mesons have made possible the development of a series of essential laws of interaction of π mesons with nucleons. These experiments have shown that the scattering cross section attains a maximum value for energies of π mesons near 200 mev.^{1,2} Attempts have been made to associate this maximum with the existence of an excited state of the nucleon.³ Theoretical estimates for such an assumption lead to a satisfactory agreement with experiment over

a significant range of meson energies.

The combined available evidence for total and differential cross sections for meson nucleon scattering gives reason to think that the experimental results for meson scattering down to an energy of 230 mev could be satisfactorily explained on the supposition that only S and P states participate in the scattering. It might be expected that even at meson energies of 200-250 mev the D states likewise should take part in the scattering; however, the poor accuracy of the measurements does