[3] Evans, W. D., Belian, R. D., Conner, J. P., Strong, I. B., Hiltner, W. A., and Kunkel, W. E., *Astrophys. J.*, **162**, L115 (1970).
[4] Lewin, W. G., McClintock, J. E., Ryckman, S. G., Glass, I. S., and Smith, W. B., *Astrophys. J.*, **162**, L109 (1970).
[5] Riegler, G. R., Boldt, E., and Serlemitsos, P., *Nature*, **226**, 1041 (1970).
[6] Friedman, H., Fritz, G., Henry, R. C., Hollinger, J. P., Meekins, J. F., and Sadeh, D., *Nature*, **221**, 345 (1969).
[7] Boldt, E. A., Holt, S. S., and Serlemitsos, P. J., *Astrophys. J.*, **164**, L9 (1971).
[8] Angel, J. R. P., Kestenbaum, H., and Novick, R., *Astrophys. J.*, **169**, L57 (1971).
[9] Griffiths, R. E., Cooke, B. A., and Pounds, K. A., *Nature Physical Science*, **229**, 175 (1971); corrigendum, *Nature Physical Science*, **231**, 136 (1971).
[10] Hiltner, W. A., and Mook, D. E., *Ann. Rev. Astron. Astrophys.*, **8**, 139 (1970).
[11] Westphal, J. A., Sandage, A., and Kristian, J., *Astrophys. J.*, **154**, 139 (1968).
[12] Gribbin, J. R., Feldman, P. A., and Plagemann, S. H., *Nature*, **225**, 1123 (1970).
[13] Feldman, P. A., Gribbin, J. R., and Plagemann, S. H., *Nature*, **226**, 432 (1970).
[14] Gribbin, J., *Astrophys. Lett.*, **8**, 175 (1971).

Measurement of van der Waals Dispersion Forces in the Range 1.4 to 130 nm

THIS communication describes an experimental study of the van der Waals dispersion forces between curved mica surfaces. The mica specimens were glued to cylindrical glass mountings and supported with their axes at right angles; the contact resembles that between a sphere and a flat. For separations in the range 1.4 to 20 nm the forces were measured by the "jump" method described by Tabor and Winterton[1]. In this method one of the surfaces (the upper surface) is mounted at the end of a double cantilever spring, and the lower surface, facing the upper, is supported on a stiff piezoelectric transducer. If the lower surface is moved towards the upper, at some point—depending on the stiffness of the spring—the two will jump into contact. The measurement of this jump distance as a function of the spring stiffness is the basis of the jump method. In the present apparatus the spring stiffness was varied by adjusting the clamping position along its length, and the distance between the surfaces was measured to about 0.2 nm using multiple beam interferometry[1]. In the earlier work the smallest separation was 5 nm, but we have extended the separation down to 1.4 nm and improved the accuracy of measurement. Experiments were carried out in air at atmospheric pressure.

For separations in the range 10 to 130 nm the forces were measured by a new dynamic method. By feeding the piezoelectric transducer with an a.c. voltage from a high stability oscillator the lower surface could be set vibrating at very small amplitudes over a convenient range of frequencies. The upper surface was supported on a stiff spring also made of piezoelectric (bimorph) material: its natural frequency depended both on the spring stiffness and on the van der Waals force exerted upon it by the lower surface. The principle of the dynamic method is to determine the natural frequency as a function of separation from which the law of force may be deduced. The natural or resonant frequency was determined to 1 part in 10^6 by a null method: the oscillator frequency was set at a fixed value and the voltage outputs of both oscillator and bimorph fed into a lock-in amplifier system (Brookdeal Electronics Ltd, type 40) which measured the relative phases of the vibrating surfaces and was set so as to give a zero meter reading when the vibrations of the two surfaces were exactly 90° out of phase, this being the resonance condition. The oscillator frequency was fixed at some convenient value and the distance between the surfaces gradually varied: the separation at which the meter pointer passed through the zero was then determined to an accuracy of about 0.2 nm. The forcing frequency was then changed and the new position of resonance found; in this way the whole range between 10 to 130 nm could be covered in about 30 min. The accuracy of the null method is high in that there are no systematic errors in the measurements: the damping of the system only determines the sharpness of the sweep through the null reading on the meter, and it is possible for readings to be made using amplitudes no greater than 0.1 nm. Experiments were carried out in a vacuum of about 5×10^{-5} mm Hg. Typical frequencies around 100 c.p.s. were used.

In the region where the measurements of the two methods overlapped (that is between 10 and 20 nm) the results, both as regards the magnitude of the force and the power law, were in complete agreement.

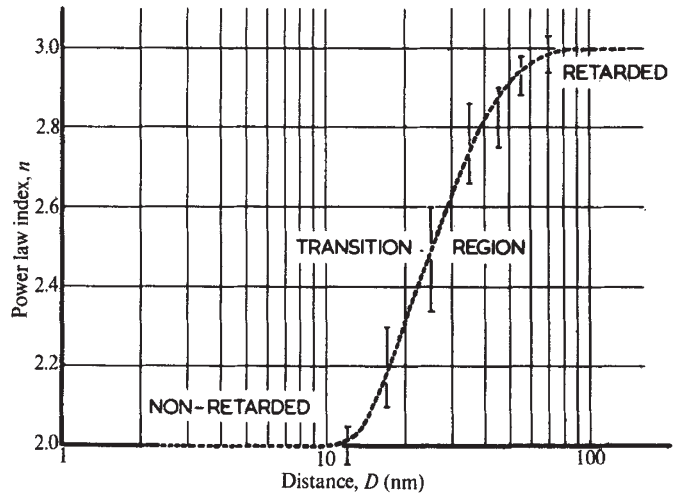

Fig. 1 Variation of power law index, n, of the van der Waals law of force between crossed mica cylinders with distance of separation D. Below 12 nm the forces are non-retarded and the law of force is $F=AR/6D^n$, with $A=(1.35\pm0.15)\times10^{-19}$ J, $n=2$, and where R is the radius of the cylinders. Above 50 nm the forces are retarded and the law of force is $F=2\pi BR/3D^n$, with $B=(0.97\pm0.06)\times10^{-28}$ J m, $n=3$.

The results may be summarized as follows. In the range 2 to 12 nm the forces are completely non-retarded with a Hamaker constant of $A=(1.35\pm0.15)\times10^{-19}$ J. For separations greater than 12 nm the power law of the interaction increases above 2.0 and by 50 nm has reached 2.9. Thus the transition between non-retarded and retarded forces (shown in Fig. 1) may be said to occur between 12 nm and 50 nm. Above 50 nm the forces are retarded with a Hamaker constant of $B=(0.97\pm0.06)\times10^{-28}$ J m. Agreement with theory, to be discussed elsewhere, is very good.

Jump experiments were also carried out down to separations of 1.4 nm with a monomolecular layer of stearic acid on each mica surface deposited from a Langmuir trough (layer thickness 2.5 nm). The results suggest that for separations greater than about 5 nm the forces are as for bulk mica, but that for separations less than 3 nm the forces are slightly less and appear to be dominated by the properties of the monolayers themselves.

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[1] Tabor, D., and Winterton, R. H. S., *Proc. Roy. Soc.*, A, **312**, 435 (1969).