We thank W. F. Koch for his assistance in anion analysis, D. Meisel and P. B. Macedo for valuable discussions, W. E. Keene, H. G. Sutter, P. Szoke, V. L. Rogers, M. A. Boroomand and J. J. Shirron for assistance in the experimental work and C. J. Jefferson for assistance in preparing the manuscript. This study was supported in part by the Electric Power Research Institute under contract no. RP1579-6.

Received 29 March; accepted 4 October 1982.

1. Dran, J. C., Maurette, M., Petit, J. C. & Vassent, B. in *Scientific Basis for Nuclear Waste Management* Vol. 3 (ed. Moore, J. G.) 449–456 (Plenum, New York, 1981).
2. Barkatt, A., Simmons, J. H. & Macedo, P. B. *Phys. Chem. Glasses* **22**, 73–85 (1981).
3. McVay, G. L. & Pederson, L. R. *J. Am. ceram. Soc.* **64**, 154–158 (1981).
4. Walker, D. D., Dukes, M. D., Plodinec, M. J. & Bibler, N. E. *Symp. on Chemical Consideration for Important Radioactive Waste Species*, Atlanta (1981).
5. Newkirk, H. W. *et al. J. Am. ceram. Soc.* (in the press).
6. Alexander, G. B., Heston, W. M. & Iler, R. K. *J. phys. Chem.* **58**, 453–455 (1954).
7. Adams, P. B. in *Ultrapurity* (eds Zief, M. & Speights, R. M.) Ch. 14 (Dekker, New York, 1972).
8. Dezelic, N., Bilinski, H. & Wolf, R. H. H. *J. inorg. nucl. Chem.* **33**, 791–798 (1971).
9. Ohta, H. & Suzuki, Y. *Bull. Am. ceram. Soc.* **57**, 602–604 (1978).
10. Tole, M. P. thesis, Pennsylvania State Univ. (1982).
11. Ghani, M. O. & Aleem, S. A. *Ind. J. agr. Sci.* **13**, 142–147 (1943).
12. Garrison, W. M., Morrison, D. C., Hamilton, J. G., Benson, A. A. & Calvin, M. *Science* **114**, 416–418 (1951).
13. Getoff, N. *Int. J. Appl. Rad. Isotopes* **13**, 205–213 (1962).
14. Gordon, S., Hart, E. J., Matheson, M. S., Rabani, J. & Thomas, J. K. *Disc. Faraday Soc.* **36**, 193–205 (1963).
15. Shaede, E. A., Edwards, B. F. P. & Walker, D. D. *J. phys. Chem.* **74**, 3217–3220 (1970).
16. White, D. E., Hem, J. D. & Waring, G. A. in *Data of Geochemistry* (ed. Fleischer, M.) (U.S. Government Printing Office, Washington DC, 1963).
17. Ernsberger, F. M. *J. Am. ceram. Soc.* **42**, 373–375 (1959).

The hydrophobic interaction is long range, decaying exponentially with distance

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The attractive interaction between organic nonpolar molecules, such as hydrocarbons, in water is unusually strong. This 'hydrophobic interaction'[1] is responsible for the very low solubility of hydrophobic molecules in water, and has a central role in micelle formation, biological membrane structure, and in determining the conformations of proteins[2,3]. It was once believed that because the interaction is so strong there is a 'hydrophobic bond' associated with it[2,4]; but it is now recognized that the interaction involves the configurational rearrangement of water molecules as two hydrophobic species come together[5–9] and is therefore of longer range than a typical covalent bond. However, there has been no experimental information available concerning the distance dependence and effective range of this interaction. From measurements of the total force as a function of distance between two hydrophobic surfaces immersed in aqueous electrolyte solutions we have determined accurately the attractive component due to the hydrophobic interaction and found that the hydrophobic interaction has the same range as, but is about an order of magnitude stronger than, the van der Waals-dispersion force; and that in the range 0–10 nm it decays exponentially with distance with a decay length of ~1 nm. The results can be roughly extrapolated to molecular interactions and show that the interaction free energy of two hydrophobic solute molecules of radius R (nm) in water at 21 °C is approximately given by $\Delta G_H = -40R$ kJ mol^{-1}, which is in agreement with previous estimates. However, the hydrophobic interaction is not due to a 'hydrophobic bond', and its long-range nature has obvious implications for the mechanism and rates of folding as well as the equilibrium conformations of proteins and other macromolecules.

We have measured the forces between two hydrophobic surfaces in aqueous solutions in the distance range $D = 0$ (contact) to $D > 50$ nm.The experimental techniques used were similar to those used previously for measuring the forces between mica surfaces in liquids[10–14], which allow for the force F between two crossed cylinders of mica of radius R to be measured with a distance resolution of about 0.2 nm. In the present experiments the mica surfaces were rendered hydrophobic by the adsorption of a monolayer of the cationic surfactant hexadecyltrimethylammonium bromide, CH_3–$(CH_2)_{15}$–$N(CH_3)_3^{\oplus}Br^{\ominus}$ or CTAB, from solution. At concentrations just below the CMC (10^{-3} M) the positive $CTA^{\oplus}$ group adsorbs onto the negatively charged mica surface as a compact monolayer exposing a hydrophobic surface composed of CH_3 and CH_2 groups[12]. In this range of concentrations the net surface charge on the mica$^{\ominus}$–$CTA^{\oplus}$ surface goes from being negative to positive, passing through its point of zero charge (PZC). Thus in addition to any attractive force between two such monolayer-covered surfaces there is a repulsive electric 'double-layer' force arising from the incomplete charge neutralization at the mica$^{\ominus}$–$CTA^{\oplus}$ interface. We have measured how these forces vary with distance for a range of CTAB concentrations in both distilled water and in NaCl and KBr solutions up to 0.1 M and at various pH values in the range 5.4–10.4.

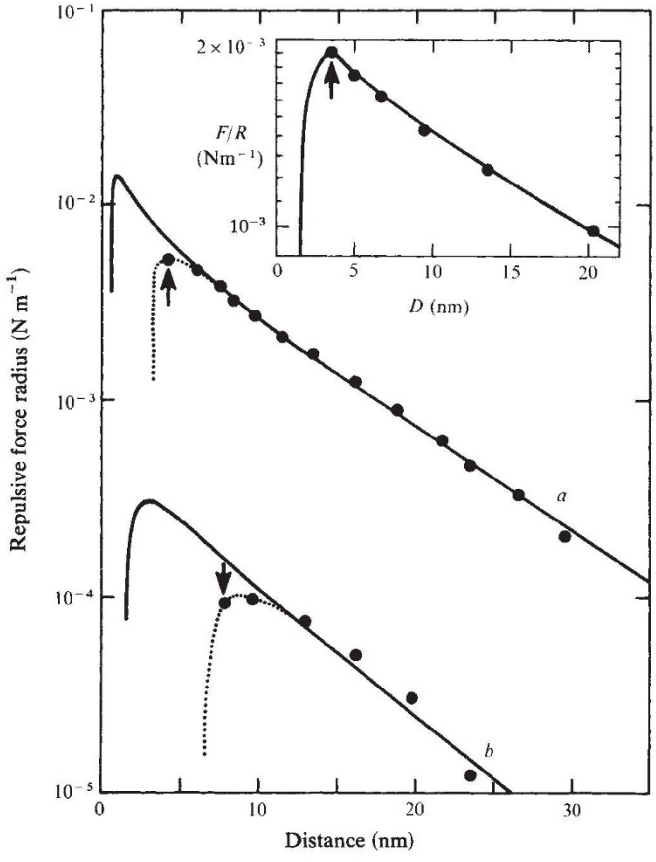

Fig. 1 Measured repulsive force F between two cylindrically curved hydrophobic surfaces (of radii R) as a function of distance D in ~10^{-3} M NaCl and KBr solutions at 21 °C (plotted as normalized force F/R). The effective surface charge density corresponding to the observed double-layer forces are 1e per 5 nm^2 (a), and 1e per 95 nm^2 (b). The solid lines are the theoretical force laws expected from the classical DLVO theory[15,16]. Dotted lines, experiment force laws. Inset: measured force law between uncoated mica surfaces where excellent agreement with the DLVO theory is obtained. Errors in distance measurements are negligible (±0.2 nm); errors in the force are roughly equal to the size of the experimental points, except at smaller distances where the errors are smaller.

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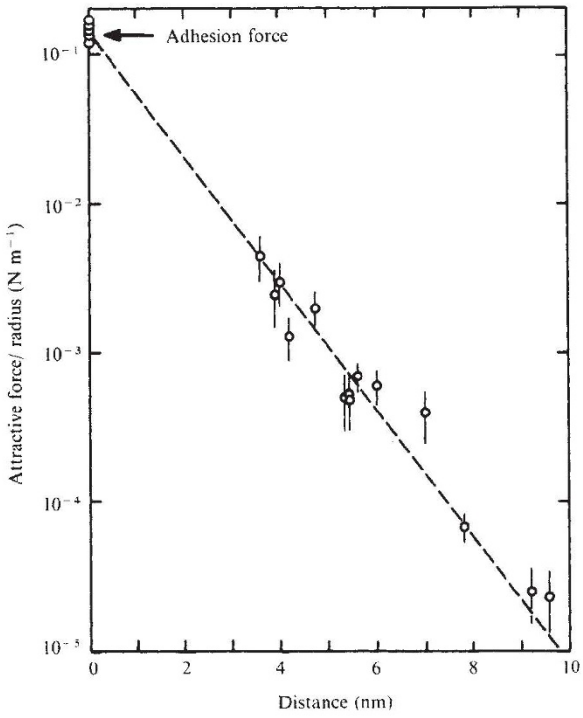

Fig. 2 Attractive force law F_H as a function of distance D as deduced from a wide range of force curves such as those shown in Fig. 1 (and for different values of R between 0.75 and 2.0 cm). Experimental points are obtained from the differences between the measured and theoretical forces in the regions of the observed maxima (arrows in Fig. 1). The hydrophobic interaction decays exponentially out to a separation of about 10 nm, and is given by $F_H/R = 0.14\,e^{-D/1.0}\,N\,m^{-1}$.

Figure 1 shows the measured forces in two instances: high surface charge, and very low surface charge (near the PZC). In each case (and in many others, not shown) the attractive component of the interaction greatly exceeds that expected from the normal van der Waals-dispersion contribution to the total van der Waals + double layer (DLVO) interaction[15,16], which is shown as the solid curves in Fig. 1. This is in marked contrast to similar measurements of forces between uncoated mica surfaces in dilute electrolyte solutions[11,14] where the agreement with the DLVO theory is excellent (Fig. 1 inset).

By subtracting the measured forces from the theoretical curves one can deduce the additional attractive force between the hydrophobic surfaces at different values of D down to the 'force barriers' (arrows in Fig. 1), below which the net force becomes rapidly attractive and the two surfaces jump into monolayer contact at $D = 0$.

The additional attractive (hydrophobic) force is plotted as F_H/R against D in Fig. 2, where we have also included the adhesion or 'pull-off' force at $D = 0$, given by the force needed to separate the two surfaces from adhesive contact. It is apparent that over the distance range 0–10 nm the hydrophobic force-law is well described by an exponential function given by

$$F_H/R = C\,e^{-D/D_0}$$

where $C = 0.14 \pm 0.02\,Nm^{-1}$, and decay length $D_0 = 1.0 \pm 0.1$ nm.

We found that the strength of this interaction is not sensitive to the type and concentration of the electrolyte present, nor to the *p*H. The adhesion force F_H/R at $D = 0$ did, however, increase slightly when the repulsive double-layer forces were weaker, as might be expected. Experiments were also performed with the surfactant concentration progressively diluted to 1/100 of the CMC with no resulting change in the attractive force-law, thus ruling out the possibility that the presence of surfactants is responsible for the extra attraction (through some bridging mechanism involving premicellar aggregates, for example).

The measured attractive force-law is about an order of magnitude larger than the maximum possible van der Waals-dispersion force; and since it decays exponentially with distance rather than as a power law it cannot be attributed to a 'modified' dispersion interaction. It is most likely that this force is the 'hydrophobic interaction'. Although we cannot discuss here all the implications arising from this work or correlate our results with previous experimental and theoretical studies the following three points are notable:

(1) The hydrophobic interaction acts over long-range and cannot be considered as arising from any bond-like association. For two surfaces 50% of the total interaction free energy occurs at distances beyond about two water molecule diameters. The exponential dependence of the interaction has been predicted in recent theories of solvation forces[7,8].

(2) The measured force law given above corresponds to a pair interaction free energy of

$$\Delta G_H = -CRD_0\,e^{-D/D_0} \approx -84R\,e^{-D/D_0}\,kJ\,mol^{-1}\ (R\ in\ nm)$$

for two crossed cylinders or for a sphere of radius R near a flat surface, while more generally the value of R above should be replaced by $R_1R_2/(R_1+R_2)$ for two interacting spheres of radii R_1 and R_2. Although there are obvious objections to extrapolating this expression down to molecular radii, it does give surprisingly good values when used to estimate the hydrophobic interaction of small solute molecules in water. Thus for two dissolved methane molecules (hard sphere radius $R = 0.18$ nm)[17–19], two benzene molecules ($R = 0.25$ nm)[17,18], and two cyclohexane molecules ($R = 0.28$ nm)[17,18], the values obtained for the free energy of dimerization ($\Delta G_H \approx -42R$ kJ mol^{-1} at $D = 0$) in each case are $\Delta G_H \approx 7.6$, 10.5 and 11.8 kJ mol^{-1}, respectively, which compare surprisingly well with the various theoretical and experimentally determined values of 7.5–8.8 (refs 5, 6), 8.5–9.6 (refs 9, 20) and 11.3 (ref. 20) kJ mol^{-1}.

(3) The long-range attractive forces measured between surfactant[12] and lipid bilayers[21,22], where both hydrophilic and hydrophobic groups are present at these interfaces, appear to be well described by the van der Waals-dispersion force, suggesting that the hydrophobic interaction is neutralized when the local structure of water molecules is dominated by their interaction with nearby hydrophilic groups.

Received 2 August; accepted 20 September 1982.

1. Franks, F. *Water: A Comprehensive Treatise* Vol. 4 (ed. Franks, F.) Ch. 1 (Plenum, New York, 1973).
2. Kauzmann, W. *Adv. Protein Chem.* **14,** 1–63 (1959).
3. Tanford, C. *The Hydrophobic Effect* 2nd edn (Wiley, New York, 1980).
4. Nemethy, G. & Scheraga, H. A. *J. phys. Chem.* **66,** 1773–1789 (1962).
5. Ben-Naim, A., Wilf, J. & Yaacobi, M. *J. phys. Chem.* **77,** 95–102 (1973).
6. Dashevsky, V. G. & Sarkisov, G. N. *Molec. Phys.* **27,** 1271–1290 (1974).
7. Marcelja, S., Mitchell, D. J., Ninham, B. W. & Sculley, M. J. *JCS Faraday Trans. II* **73,** 630–648 (1977).
8. Chan, D. Y. C., Mitchell, D. J., Ninham, B. W. & Pailthorpe, B. A. *Molec. Phys.* **35,** 1669–1679 (1978).
9. Rossky, P. J. & Friedman, H. L. *J. phys. Chem.* **84,** 587–589 (1980).
10. Israelachvili, J. N. & Adams, G. E. *Nature* **262,** 774–776 (1976); *JCS Faraday Trans. I* **74,** 975–1001 (1978).
11. Pashley, R. M. *J. Colloid Interface Sci.* **80,** 153–162 (1981).
12. Pashley, R. M. & Israelachvili, J. N. *Colloids & Surfaces* **2,** 169–187 (1981).
13. Horn, R. G. & Israelachvili, J. N. *J. chem. Phys.* **75,** 1400–1411 (1981).
14. Israelachvili, J. N. *Phil. Mag.* A**43,** 753–770 (1981).
15. Verwey, E. J. W. & Overbeek, J. Th. G. *Theory of the Stability of Lyophobic Colloids* (Elsevier, New York, 1947).
16. Chan, D. Y. C., Pashley, R. M. & White, L. R. *J. Colloid Interface Sci.* **77,** 283–285 (1980).
17. Evans, D. F., Tominaga, T. & Davis, H. T. *J. chem. Phys.* **74,** 1298–1305 (1981).
18. Dymond, J. H. *J. phys. Chem.* **85,** 3291–3294 (1981).
19. Harris, K. R. & Trappeniers, N. J. *Physica* **104A,** 262–280 (1980).
20. Tucker, E. E., Lane, E. H. & Christian, S. D. *J. Solut. Chem.* **10,** 1–20 (1981).
21. Parsegian, V. A., Fuller, N. & Rand, R. P. *Proc. natn. Acad. Sci. U.S.A.* **76,** 2750–2754 (1979).
22. Ohshima, H., Inoko, Y. & Mitsui, T. *J. Colloid Interface Sci.* **86,** 57–72 (1982).