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AFM **observation of force on a dielectric sphere in the evanescent field of totally reflected light**

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Abstract. – We present the first direct measurement of the radiation pressure force acting on a sphere in the evanescent field of a totally reflected light beam using the atomic force microscope (AFM). A dielectric sphere was attached to the AFM cantilever and placed into the evanescent light field of the Ar-laser beam illuminating a sapphire prism surface at an angle larger than the critical. A repulsive force due to the evanescent field was observed. The force decreases exponentially with the characteristic length of (45 ± 20) nm as the distance between the sphere and the total reflection surface increases. The measured magnitude of the force close to the surface is $(3 \pm 1.5) \cdot 10^{-10}$ N. Both the magnitude and the decay length are in good agreement with the calculated values.

Ever since the invention of the Scanning Tunnelling Microscope (STM) by Binning *et al.* in 1982 [1], improved forms and new applications of scanning tunnelling microscopes have emerged. The Atomic Force Microscope (AFM) was invented in 1986 [2] and the Photon Scanning Tunnelling Microscope (PSTM) three years later [3, 4]. PSTM operates in a similar way as STM, the only difference being that instead of electrons, the photons tunnel between the substrate and the tip. They tunnel through the evanescent field generated by the total internal reflection of light and are detected by an optically transparent probe tip. Recently, the development of Near-Field Scanning Optical Microscopes (NSOM) has been reported (for an overview see, *e.g.*, [5]). P. Bauer *et al.* combined near-field optical measurements with conventional AFM and detected the exponential decay of the evanescent field by measuring the intensity of the evanescent light with a photoconducting cantilever [6]. Whereas the developments of NSOM and PSTM have opened new possibilities of microscopy of soft dielectric surfaces, little is known about the force between a dielectric surface and a microscopic particle, mediated by a strong optical field. Let us remember that A. Ashkin reported the first observations of a radiation force of a strong laser light on a microscopic dielectric sphere [7, 8]. He was also the first who could trap, levitate and manipulate microparticles with an intense laser beam, which

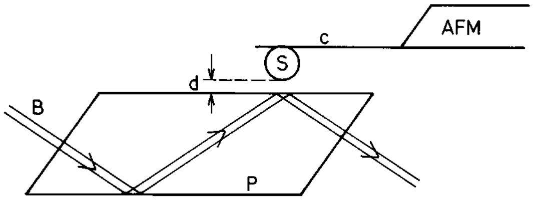

Fig. 1. – Experimental set-up. B: argon laser beam, P: sapphire prism, S: dielectric sphere, C: AFM cantilever, *d*: distance between the sphere and the prism surface. The figure is not in scale.

led to the development of optical tweezers. Interesting dynamic behaviour of micrometre-sized dielectric spheres in the evanescent field has been observed by S. Kawata *et al.* They have observed the repulsive force of the evanescent field on the dielectric sphere, but have not measured its magnitude or spatial dependence [9]. Recently, M. Abe *et al.* have measured the gradient of this force, acting on a conventional tip in high vacuum, but not the force itself [10]. Here, we report the first AFM measurements of the radiation pressure force acting on the tip in an evanescent light field at total internal reflection. In our experiment we used a quartz sphere attached to the AFM cantilever [11]. The sphere was put in the evanescent field and we measured the deflection of the cantilever, which is directly proportional to the force on the sphere. As we periodically increased and decreased the distance between the sphere and the totally reflecting surface (TRS), we recorded the spatial dependence of the force on the sphere.

Figure 1 schematically shows our experimental set-up. The evanescent field was obtained by illuminating a small millimetre-sized sapphire prism (refractive index $n_1 = 1.89$) with an argon-laser beam ($\lambda = 514.5$ nm). The beam was first expanded and then focused with a lens with a focal length of 5 cm. The focus of the beam was positioned on the upper surface of the prism with a micrometre translator. The incident angle of the beam to the TRS was $\vartheta = 55.5°$. The sphere (radius $r = 5$ μm, refractive index $n_3 = 1.56$) was approached to the surface exactly at the point of the laser beam focus. The spot on the prism surface was of elliptical shape with the axes of around 6 and 3 μm, as measured by observation of light scattered on the impurities on the prism surface under an optical microscope. This spot size was somewhat larger than calculated for a Gaussian beam due to the aberrations in the optical path. The cantilever, to which the sphere was attached, was made of SiN_3 and covered with gold for better reflection of the detection laser beam. The spring constant (the coefficient between the force, bending the cantilever, and the deflection in the direction perpendicular to the TRS) was $k = 0.38$ N/m. The total vertical range of measurement was 100 nm, the frequency of modulation of the distance between the TRS and the sphere was 0.5 Hz. All preparations for the measurement and the experiment observations were made under an optical microscope.

One of the difficulties of AFM measurements performed in the air is the capillary force. Layers of water are present on many surfaces, which cause a very strong attractive force due to surface tension. The order of magnitude of this force is up to 10^{-7} N [12], which is some orders of magnitude larger than the force we intended to measure. As a result, the sphere would be strongly bound to the surface and the measurement of the evanescent field force would be practically impossible. This effect can be considerably reduced by immersing the sphere and the surface in a liquid. In this case, we must be careful about the refractive indices (so that the total internal refraction still occurs), surface tension (because of the capillary forces), viscosity (if it is too high, the viscous retarding force influences the deflection), surface polarity (which causes additional electrostatic forces) and last, but not least, the rate of evaporation. When

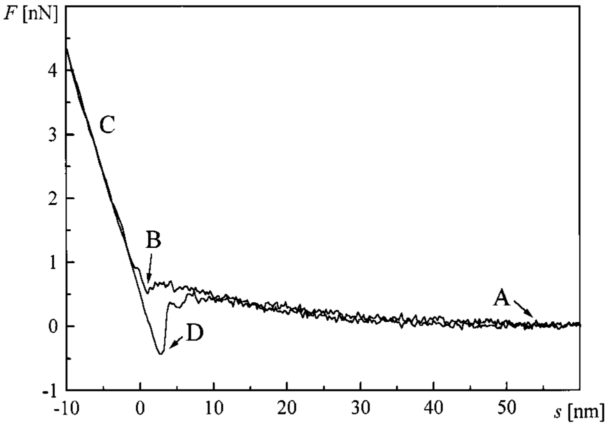

Fig. 2. – The force F acting on the sphere as a function of the prism position s in the absence of the evanescent electric field. A: the zero position, B: attraction due to Van-der-Waals forces, C: region of contact, D: snap-back point.

the prism is illuminated by a strong laser beam, droplets of some liquids evaporate in order of seconds —long before the measurement is completed. After testing several liquids we found that isobutyl-alcohol with $n_2 = 1.395$ has the most convenient properties for this experiment. The heating caused by the laser beam, however, still had to be taken into account. A small change in the temperature of the bimetallic lever causes a noticeable change in its deflection. The measured value is approximately $5 \cdot 10^{-3}$ rad/K [13], which gives for the cantilever length of 85 μm the vertical change of 400 nm/K. To avoid the effect caused by the heating of the lever, the zero-point of the force curve had to be determined for each measurement separately. Also the measurement itself had to be made in a relatively short period of time, before the effect of heating became noticeable. The average time for a single measurement was thus about 2 s.

The distance between the TRS and the sphere was changed by moving the prism up and down in order to measure the spatial dependence of the evanescent field force. Measurements were made alternatively in the absence and in the presence of the evanescent electric field. Altogether over 200 different force diagrams were recorded. In fig. 2 the measured force acting on the sphere is presented as a function of the prism surface position in the absence of the evanescent field. At the beginning of the measurement the sphere and the surface are wide apart and the lever is in the zero position (A). As the prism approaches the sphere, we observe a repulsive force, which increases with decreasing distance. Finally the attracting Van-der-Waals force drags the sphere to the surface (B). The sphere touches the surface and stays in contact (C). This part is used for calibrating the force curve, because here the movement of the prism is the same as the deflection of the lever. As the sphere is moved away from the surface, it stays in contact with the prism as long as the pulling force of the bent lever is smaller than the adhesive forces that act on the sphere. Then the sphere abruptly detaches (snap-back point, D) and returns to the equilibrium position. A force is again observed and we can assume that the origin of this force is electrostatic. It should also be mentioned that the prism position is not the same as the distance between the sphere and the surface, since the lever bends. The difference, however, is negligible in the whole range of measurement, except in the vicinity (within a few nanometers) of the surface.

The force measurements in the presence of the evanescent electric field give similar behaviour

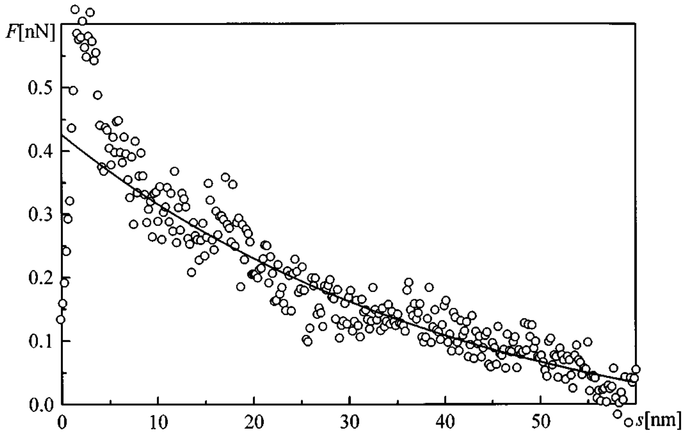

Fig. 3. – The difference between the force on the sphere in the presence of the evanescent field and in its absence. The solid curve represents the exponential decay fit to the experimental data. The characteristic length is 42 nm.

as those without the field. There is, however, a systematically observed small but noticeable difference, indicating an additional repulsive force on the sphere when the evanescent field is turned on. In order to analyse this additional repulsive force, we have subtracted a large number of force curves measured with and without the evanescent light field. A representative curve, showing this difference, is presented in fig. 3 as a function of the prism position. The difference clearly shows the additional repulsive force in the case of evanescent electric field. The magnitude of the repulsive force within some nanometers of the prism surface is estimated to be $(3 \pm 1.5) \cdot 10^{-10}$ N. The force decreases as the distance between the sphere and the prism is increased. The decay is found to be approximately exponential with the characteristic length of (45 ± 20) nm. A deviation from the exponential decay of this repulsive force is observed for distances smaller than 5 nm. Depending on the experimental run, the calculated force either increases or decreases slightly in this region. The range of this deviation coincides with the range of strong attractive force, which is always observed for very small separations (fig. 2). Because the measured spatial dependence of the force in this region differs slightly from run to run, one obtains, after subtracting data from two different experimental runs (with and without light), a deviation from the exponential decay for separations smaller than 5 nm. This scattering of data is, however, not significant and can be attributed to surface imperfections.

The magnitude and the decay length of the repulsive force can also be estimated theoretically. Total internal reflection occurs if the light propagates in the medium with refractive index n_1 (in our case the prism) and falls upon the interface with another medium (refractive index $n_2 < n_1$) at an angle ϑ, which is larger than the critical angle. The intensity of the evanescent field in the second medium decays exponentially with the decay constant [4]

$$2\kappa = 2k_0\sqrt{n_1^2 \sin^2 \vartheta - n_2^2}, \tag{1}$$

where k_0 is the wave number in vacuum. The decay length is defined as $1/(2\kappa)$. If another optical element is brought into the vicinity of the TRS, a frustrated total internal reflection occurs. In this case the transmission coefficient is finite and light tunnels through the intermediate layer into the third medium. The amount of the transmitted light strongly depends on the length of the optical path in the second medium. In order to estimate the force acting on the sphere, *i.e.* on the third medium, we use the Maxwell stress tensor (see, *e.g.*, [14]) and integrate it over the surface of the sphere. We assume that all the light coupled into the sphere is trapped and absorbed in the sphere, partly because of additional total reflections within the sphere, and partly due to the absorbing contact region between the sphere and the cantilever. Due to these losses we do not expect the force to be influenced by the Mie resonances that would appear in the free sphere [8]. The electric field and the stress tensor are therefore non-zero only on the part of the sphere where light enters. To a good approximation this part of the sphere can be considered as a flat surface because of the rapidly decaying electric field —its characteristic length is much smaller than the radius of the sphere. The effective area of the flat surface is roughly πr^2, where r denotes the radius of the sphere cross-section in the depth of about one and a half characteristic lengths. The contribution to the total force at this distance amounts to only about 10% of the total value. The estimated value of the plane surface is thus $S_{\text{eff}} = (2.5 \pm 1)\ \mu\text{m}^2$ for the sphere of radius 5 μm. With these assumptions, we can calculate the electric field in the gap between the prism and the sphere and deduce the corresponding Maxwell stress tensor. This is done simply by using the plane-wave ansatz and taking into account the boundary conditions for the electric and magnetic field. The procedure is therefore similar to the derivation of Fresnel equations for light incident on an interface between two optical media [14,15]. By integration of the Maxwell tensor components over the effective flat surface, the force of the evanescent field is

$$F = \frac{\varepsilon\varepsilon_0 S_{\text{eff}} E_0^2}{2} \frac{4k_1(\kappa^2 - k_3^2)}{(k_1^2+\kappa^2)(\kappa^2+k_3^2)\cosh(2\kappa d) + (k_1^2-\kappa^2)(\kappa^2+k_3^2) + 4k_1\kappa^2 k_3}, \tag{2}$$

where ε is the dielectric constant of the intermediate medium (alcohol), $k_1 = k_0 n_1 \cos\vartheta$ is the component of the wave vector in the prism, perpendicular to the surface, $k_3 = k_0\sqrt{n_3^2 - n_1^2\sin^2\vartheta}$ is the perpendicular component of the wave vector in the sphere and d is the width of the gap. ϑ is the incident angle at the interface between the first (prism) and the second medium (alcohol). E_0 is the amplitude of the incident electric field. At constant laser power $P_0 = 0.5$ W and with $\sim 50\%$ losses in the optical path, it is estimated to be $E_0 \sim (4 \pm 2)\cdot 10^6$ V/m. Evaluating expression (2), the estimated total evanescent field force close to the surface is $F = (3.5 \pm 2)\cdot 10^{-10}$ N, which is in good agreement with the measured value. As expected, the magnitude of this force is comparable to the radiation pressure force measured by Ashkin. The main difference is that in the unperturbed evanescent light field there is no momentum flow and the force on the sphere emerges due to momentum transfer when the light tunnels between a TRS and a sphere. Also, in our case the component of the force due to induced dipole moment of the sphere in the gradient of the field is negligible.

The characteristic length of the decaying electric field, $1/\kappa$, is calculated from eq. (1). For the force, proportional to the square of the electric field, the decay length in our experiment is estimated to be 60 nm ± 15 nm.

In conclusion, we report what we believe to be the first direct observation of the radiation pressure force, exerted by the evanescent light field above a totally reflecting surface on a dielectric sphere. The force is repulsive, which is consistent with other observations [9], and is in good agreement with calculations using the Maxwell stress tensor. The measured magnitude of this force is $(3 \pm 1.5)\cdot 10^{-10}$ N for a dielectric sphere of radius 5 μm in the evanescent field of a 500 mW laser focused to a diameter of 5 μm. The experimentally determined decay length of the repulsive force is 45 nm ± 20 nm and is also consistent, within experimental error, with the calculated value 60 nm ± 15 nm. We have thus shown that the AFM can be successfully used to measure directly the force of the evanescent field, which cannot be done by other techniques. We believe that the observed phenomena could be interesting for the application in surface-sensitive techniques that use optical fields. In particular, using modulation techniques, the size of the interacting objects could be reduced significantly. This could open new ways to observe dielectric surfaces on a submicron scale.

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