Heat flux at the nanoscale: beyond the Stefan Boltzmann law

Does the classical Stefan-Boltzmann law for blackbody radiation apply to nanometre-size objects? To answer this question, the heat flux in vacuum between two surfaces at different temperature and separated by distances between one micron and 100 nm has been measured accurately and compared to theory. The research involved two CNRS laboratories, the Néel Institute and the Charles Fabry Laboratory of the Institut d'Optique (Paris). At the nanometre scale, the measurements show large discrepancies with the Stefan-Boltzmann law.

Proposed in the 19th century, the Stefan-Boltzmann formula can be derived from Planck's quantum theory and correctly describes the total radiative exchange at large distances. In particular, it is well known that, in the "far field" regime, the heat flux exchanged between two flat parallel surfaces is independent of the distance between the two surfaces. But, in the "near field" regime, we measure a strong distance dependence: the heat flux increases dramatically when the distance between the two surfaces becomes smaller than about one micron.

In fact, this effect was discovered in the framework of the Apollo program, where efficient protection against thermal radiation was needed. A very large increase of the heat flux between two closely spaced metallic films was observed. In 1971, Polder and van Hove gave the first theoretical description of the phenomenon. Stimulated by recent advances in NEMS (Nano Electrical-Mechanical Systems), for which the increased heat flux at short distances can be of importance, we have designed an experimental setup specifically to study such effects.

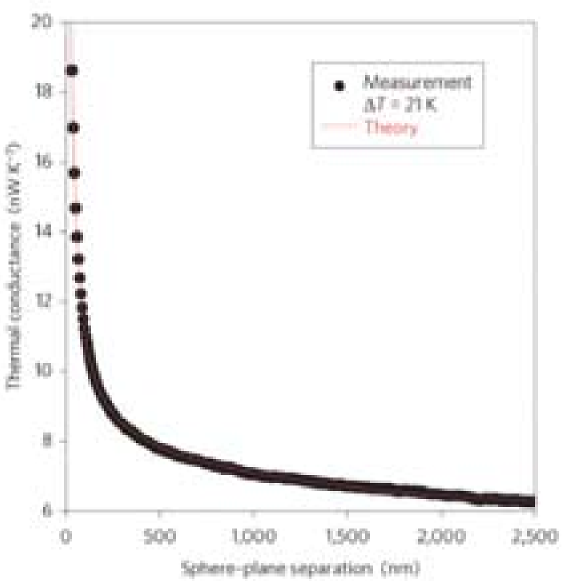
Developments in the measurement of the Casimir force under vacuum guided the design of our experiments: improvements in measuring techniques provided by Scanning Probe Microscopy as well as new techniques for fabricating micro-objects allow experimental study of the sub-micron regime of the radiative heat flux. In 2006 already, a French team (De Wilde et al) demonstrated that one can detect the thermal radiation in the near field regime using scanning probe methods. The theory group at the Institut d'Optique then produced quantitative calculations of heat transfer between polar dielectric surfaces like the glass substrates used in our work. The calculations predicted fluxes larger by a factor of 10 compared to metallic surfaces. This is essentially due to the resonant excitation of the surface phonon polaritons that are present in glasses.

Fig. 1 shows our results and the comparison with theory. The underlying physics governing the large increase of the heat flux that we observe at the nanometre scale is closely related to the Casimir effect. This mechanical effect, an attractive force between two mirrors, is due to the quantum fluctuations in the electrodynamic coupling between the mirrors.

But, instead of quantum fluctuations, the thermal coupling between the two surfaces through overlapping of evanescent waves is due to thermally induced, surface excitations. The surface excitations are thermally excited phonon-polariton waves. The effects can be accounted for by the dipolar coupling between two nanoparticles separated by nanometre distances, which determines the attractive van der Waals interaction between the particles, and their energy exchange. The dipolar coupling is not taken into account in the Planck far field theory. It becomes the dominant contribution at short distances.

The precision obtained in this measurement opens the possibility of doing experimental studies of roughness effects or of non-local effects at distances much smaller than a micron. For a better comparison between theory and experiment, an experimental vacuum force machine adapted to a parallel plane geometry is being constructed.

Room temperature thermal conductance between a 40 micron diameter sphere and a plate as a function of gap distance. The black dots represent experimental data and the red line the theoretical model. The temperature difference between the plate and the sphere is 21 K.



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FURTHER READING

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