A Fresh Start for Foam Physics

Denis Weaire

Numerical simulation is making ever greater inroads into the toughest problems of materials science, involving coupled effects on different scales. In the case of foam physics, Saye and Sethian on page 720 of this issue, have set out to meet this challenge with detailed simulations of the gas and liquid dynamics that dictate events in the life of bubbles (1).

The static equilibrium structure of a liquid foam is almost entirely determined by the minimization of its surface energy. The idealized model that neglects everything else might be called the Plateau foam, in honor of the 19th-century physicist who first described conditions for stable foams (2). This model poses intriguing puzzles for geometers, so physicists and mathematicians have found common cause, and even attended common conferences, to debate its deep questions.

In 1887, the model was deftly applied by Lord Kelvin to calculate the shape of bubbles packed in a particular crystalline arrangement, in the course of his personal, and rather quixotic, quest for the nature of the ether of space (3). However, analytic tricks cannot in general capture the subtle shapes of foam cells, even in equilibrium. It was Brakke’s Surface Evolver software (4) that opened up the field in modern times. It would be hard to overestimate his remarkable contribution to the study of foams in equilibrium and related research areas.

After more than a century of admiring Plateau foam, and several decades of analyzing its equilibrium structures, it appears to be time to move on to a more general and practical model more capable of describing local dynamics, such as is implicated in the bursting of a bubble and its aftermath. The task is inviting but not easy. To do so, Saye and Sethian have developed a formalism to accurately describe local fluid motion within bubbles, soap films, and their junctions (the so-called Plateau borders).

Three phases of evolution of a small foam sample, such as shown in the figure, are identified and separated for the purposes of simulation. They are the approach to equilibrium, involving rearrange-
ments of bubbles, followed by liquid drainage through the films and Plateau borders, and finally film rupture caused by thinning. This last event throws the system far out of equilibrium, so that we may return to the first phase, and so on.

More approximate or empirical descriptions of this motion in foams near equilibrium have been successful in analyzing many important practical scenarios such as arise in chemical engineering (5). For example, consider the case of local fluid flow when bubbles are rearranged by an imposed shear. In the Plateau foam, these events are considered to be instantaneous and punctuate any slow (i.e., quasistatic) evolution of a structure. In reality, these events occur on a finite time scale that is determined by dissipation associated with fluid viscosity. Time scales lie at the heart of the mysteries of foam rheology (the description of its movement): Foam belongs in the category of a complex fluid.

The new methodology should soon offer fresh insights. Still, there are many real-world cases that cannot be described by the present model. It is formulated for “dry” foams containing little liquid, as is the case of large bubbles in equilibrium under gravity. Far from equilibrium, for example, in the churning foam of a washing machine, we encounter wet foams that do not get a chance to drain.

Also, a foam out of equilibrium is subject to subtle dynamic effects associated with its surfactant-covered surfaces. Surface energy depends on surfactant surface concentration, which may vary spatially or temporally, and is coupled to bulk concentration. The term “Marangoni effect” is often applied to the phenomena that arise from this dependence, of which the most important is the very existence of the foam in a reasonably stable state (but it may be more familiar as the “tears of wine” effect for a mixed water-alcohol solvent). Surfactant-covered surfaces have a complex rheology of their own, contributing obscurely to that of the foam as a whole and also influencing the internal hydrodynamics of drainage.

Despite the eminent precedents and the help (as well as the criticism) of physical chemists, physicists have so far failed to grapple effectively with this complex of complications at the film surface. It has proved very difficult to formulate surface effects in a reliable and general way, but this impasse has somehow to be confronted if the new dynamic methodologies are to be fully realistic. However, this new class of numerical modelers has laid foundations for a fresh start. These efforts arrive just in time to help confront the mass of new data soon to be provided by x-ray tomography. It can let us look inside foams and can even be time-resolved so that the dynamics of local structural changes can be revealed.

References

10.1126/science.1238247

Controlling Atomic Line Shapes

C. D. Lin and Wei-Chun Chu

The spectroscopy of light absorption is an essential tool for uncovering the microscopic structure of a material. The observed spectral line positions reveal the energy levels of the excited quantum states, whereas the line shapes are determined by how the material relaxes after light is absorbed. In the optical frequency regime, the absorption profile has a symmetric shape. By coupling the material to an intense optical laser, however, the absorption can be controlled, leading to many interesting phenomena such as electromagnetically induced transparency (EIT) (1), slow and stopped light (2), and others. Extending such manipulations to extreme ultraviolet (XUV) and soft x-ray frequencies has presented a challenge. With the advent of intense ultrafast few-femtosecond infrared lasers in recent years, as reported on page 716 of this issue, Ott et al. (3) demonstrate that such manipulations are now possible.

In the XUV region, the absorption line shape is described by the asymmetric Fano profile (4). The asymmetry results from the quantum interference of two ionization pathways—one by direct ionization, the other via autoionization to an unstable bound state followed by autoionization. In their experiment, Ott et al. show that they can change the shape parameter \( q \) of a Fano resonance by adjusting the intensity of a coupling laser. This achievement owes much to their high-resolution spectrometers, which can trace accurate line profiles of Fano resonances. Because attosecond XUV pulses are used to excite the atom, the same setup will be able to control the dynamics of a many-electron wave packet, or specifically the reaction dynamics, on attosecond time scales.

Ott et al. co-propagated a broadband XUV attosecond pulse train and a few-cycle near-infrared (NIR) laser with a fixed time delay in a helium target. At a laser intensity of about 2 TW/cm\(^2\), they found that the asymmetric Fano profiles of the doubly excited states turn into symmetric Lorentzian ones, and the symmetric profiles of the singly excited states, at much lower energies, turn into asymmetric ones. They attribute the change in line shapes to the additional phase acquired by the Fano resonances in the presence of the NIR laser. Thus, by tuning the laser intensity, the Fano profiles could be manipulated. Unfortunately, only the data at a fixed time delay were reported; thus, the dynamics of autoionization was left unexplored. The analysis also assumes that the laser field could only change the shape parameter \( q \) and that the line shape stays in the general form. This picture also omits the effect of ionization and coupling with other states by the intense laser field. Follow-up experiments will be designed to examine resonance profiles at different time delays and to analyze the data with possible deviations from the Fano line shape.

The same type of experiments using broadband XUV and intense IR pulses with additional control tailored to specific systems should be within reach in the coming years. Nonlinear optics developed with infrared and visible lasers can be readily extended to experiments that use both XUV and IR frequencies (5). In a typical EIT system involving the ground state and two Fano resonances, 2s2p and 2s\(^2\)p, in the case of helium atom (see the figure, panel A), a 200-attosecond pulse is used to populate 2s2p in the presence of a

Intense infrared lasers can be used to control the spectral line shapes of atoms, with implications for spectroscopy and quantum dynamical processes.