represent new and exciting physics. He set about quantifying with great precision the remarkable characteristics of this light emission, finding that the lifetime and the pulse-to-pulse synchronicity of each flash was on the order of 50 trillionths of a second. His group went on to thoroughly examine how SBSL was dependent on a wide range of experimental parameters[4]. Over 100 peer-reviewed papers have been published on SBSL since its discovery by Gaitan, but the mechanism of light emission remained elusive until now.

Is this new physics, as Putterman originally thought? The answer from Hilgenfeldt *et al.*[1] is no. But it took some pretty fancy detective work to resolve paradoxes and integrate physical principles — over enormously disparate ranges of energy and time — to come up with an illuminating explanation that quantitatively matched the data.

The broad understanding of the phenomenon is now as follows: the rarefied phase of the sound wave grows a bubble from about 5 μm in diameter to about 70 μm in diameter (around the thickness of a human hair). Then, as the sound field turns compressive, the virtually empty spherical bubble comes crashing in on itself, powered by the inertia of the surrounding water. The bubble maintains its spherical symmetry for almost the entire collapse phase, therefore optimizing the internal energy concentration. As the collapse accelerates, the residual gas caught inside the bubble is rapidly compressed, raising its temperature to 20,000–30,000 K. These temperatures are sufficient to create a plasma of ions, neutral atoms and electrons. By keeping track of the ways in which thermal energy in the collapsing bubble is distributed among these constituents, one can then understand the reverse process of light emission and extinction as the energy density of the expanding bubble is reduced and photons are emitted. About 20 μs later the processes of growth, collapse and light emission repeat themselves, resulting in a pulse of light every acoustic cycle.

The issue of new physics raised by Putterman is almost overshadowed by the fact that this ever-flashing bubble appears to be a wonderful laboratory for acoustics, fluid dynamics, thermodynamics, optics, plasma and quantum physics, all under highly dynamic conditions. And because of the high temperatures and pressures achieved inside the bubble, there is also some remarkable chemistry going on when diatomic gases are present. In what is now called the 'dissociation hypothesis'[5], diatomic gases (such as nitrogen) actually dissociate and dissolve into the surrounding fluid during the bubble collapse, leaving only noble gases (such as argon). Further experiments[6–8] have provided conclusive evidence for the validity of this hypothesis. Hilgenfeldt *et al.* have now been able to tie this chemistry and physics together to quantitatively explain many of the observations made for SBSL.

What is both remarkable and limiting in the sonoluminescence phenomenon is that the stability required to produce the clock-like synchronicity of SBSL depends largely on the behaviour of the bubble while it is relatively large, whereas the light emission occurs when the bubble is close to its smallest size. This coupling of bubble stability and light emission has discouraged researchers from going 'outside the box' to optimize the bubble growth, so as to maximize the internal temperature upon collapse.

Why increase the internal bubble temperature? If one were to grow the bubble by a factor of ten or more — to 1 mm in diameter — what might the temperature inside the bubble reach at its collapse? Could it reach the conditions that would allow for nuclear (hot) fusion inside the bubble if deuterium gas or a combination of deuterium and tritium gases were inside the bubble? No one can say for sure whether this is possible, and a small community of sonoluminescence researchers is quietly going on with this work, trying to avoid the hype that accompanied the 'cold' fusion claims of ten years ago. If it were possible, this would be table-top micro-thermonuclear fusion as suggested by Willy Moss of Lawrence Livermore Laboratory, whose computations helped to clarify the optical emission mechanism of SBSL[9]. Moss continues to provide guidance to experimentalists searching for what he calls a 'star in a jar'.

And there is another reason for the sustained interest in SBSL. Put simply, this bubble burning bright is 'cool' and accessible science. Here is a most amazing reactor for studying basic physics. Imagine if one could actually predict the onset conditions for the emission of neutrons from a collapsing bubble, in a jar of degassed heavy water through which an audible sound wave was propagating — it would be a resounding affirmation of the unity of physics, and we may not have to wait another ten years. □

Robert Apfel is in the Department of Mechanical Engineering, Yale University, 9 Hillhouse Avenue, New Haven, Connecticut 06520-8286, USA.
e-mail: robert.apfel@yale.edu

1. Hilgenfeldt, S., Grossmann, S. & Lohse, D. *Nature* **398,** 402–405 (1999).
2. Gaitan, D. F. thesis, Univ. Mississippi (1990).
3. Gaitan, D. F., Crum, L. A., Church, C. C. & Roy, R. A. *J. Acoust. Soc. Am.* **91,** 3166–3183 (1992).
4. Barber, B. P., Hiller, R. A., Löfstedt, R., Putterman, S. J. & Weninger, K. R. *Phys. Lett.* **281,** 66–143 (1997).
5. Lohse, D. & Hilgenfeldt, S. *J. Chem. Phys.* **107,** 6986–6997 (1997).
6. Holt, R. G. & Gaitan, D. F. *Phys. Rev. Lett.* **77,** 3791–3794 (1996).
7. Matula, T. J. & Crum, L. A. *Phys. Rev. Lett.* **80,** 865–868 (1998).
8. Ketterling, J. A. & Apfel, R. E. *Phys. Rev. Lett.* **81,** 4991–4994 (1998).
9. Moss, W. C. *et al. Phys. Rev. E* **59,** 2986–2992 (1999).

Daedalus

Oscillating enzymes

Last week Daedalus proposed piezoelectric catalysts, whose surfaces or cavities could be set into intense controlled vibration. Reagent molecules were adsorbed during the expansion phase; contraction brought them together to induce reaction; on the subsequent re-expansion the product molecule was set free.

He now muses that nature may have got there first. Enzymes, those amazingly specific biological catalysts, have extremely subtle surfaces. Only one molecule, or pair of molecules, can fit on a given surface; and their resulting reaction is extremely well defined. Daedalus reckons that the vibrational modes of the enzyme molecule must play a crucial part in its action.

All molecules, of course, can be excited into vibration by radiation of the right frequency. But only quite low-frequency modes, corresponding to wavelengths longer than about 0.05 mm in the far infrared, can be significantly excited merely by ambient temperature. And this, says Daedalus, explains why so many enzymes are such needlessly complicated molecules, very large compared with their active catalytic sites. An enzyme molecule has to be big and heavy, so as to have vibrational modes low enough to be usefully excited at body heat.

This train of thought has sparked two new DREADCO projects. The first and simpler is to irradiate yeast fermentations, penicillin production, sugar inversion and other well-known enzyme reactions, with intense beams of tuned far-infrared and millimetre-wave radiation, looking for sudden rises in output or changes of product. The active frequency will reveal the key vibrational mode of the enzyme. If enzyme reactions can indeed be accelerated or directed by well-judged irradiation, biotechnology will be transformed.

The second project is the creation of 'stripped down' enzyme molecules, equipped with active catalytic sites but without the surrounding heavy protein chains. Their vibrational modes will be much higher, in the mid- and near-infrared. When irradiated at these higher frequencies, they will churn out the product a lot faster; and they can be switched off simply by turning off the radiation. Again, the biotechnology industry should snap up the technique. Daedalus is also devising special diathermy machines and infrared health lamps, cunningly tuned to boost key biochemical reactions in their patients.

David Jones