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SYNCHRONOUS PICOSECOND SONOLUMINESCENCE:
DEVELOPING AND CHARACTERIZING A NEW LIGHT
SOURCE

FINAL REPORT SUBMITTED TO:

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DIVISION OF ADVANCED ENERGY PROJECTS
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U.S. DEPARTMENT OF ENERGY

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Original
I certify that this is an
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submitted to the DOE June 1995,
Seth J. Putterman

MASTER

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SYNCHRONOUS PICOSECOND SONOLUMINESCENCE

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ATTACHMENTS {Abbreviated Version}

Publications: {Title Page and Abstract}

Observation of Synchronous Picosecond Sonoluminescence* by B.P. Barber and S.J. Putterman, *Nature* 352 ,318,(1991)

Resolving the Picosecond Characteristics of Synchronous Sonoluminescence* by B.P. Barber, R. Hiller, K. Arisaka, H. Fetterman, S.Putterman, *Jl Acoust Soc Am*, 91, 3061, (1992).

Spectrum of Synchronous Picosecond Sonoluminescence by R. Hiller, S. Putterman and B.P. Barber, *Phys Rev Lett*, 69, 1182, (1992).

Light Scattering Measurements of the Repetitive Supersonic Implosion of a Sonoluminescing Bubble, *Phys Rev Lett*, 69, 3839 (1992).

Toward a Hydrodynamic Theory of Sonoluminescence, by R. Löfstedt, B.P. Barber and S. Putterman, *Phys Fluids A5* , 2911, (1993).

Sensitivity of Sonoluminescence to Experimental Parameters, by B.P. Barber, C.C. Wu, R. Löfstedt, P.H. Roberts, S. Putterman, *Phys Rev Lett* ,72, 1380, (1994).

Effect of Noble Gas Doping in Single Bubble Sonoluminescence, by R. Hiller, K. Weninger, S. Putterman, and B.P. Barber, *Science* 266 , 248, (1994).

Observation of a New Phase of Sonoluminescence at Low Partial Pressures by B.P. Barber, K. Weninger, R. Löfstedt, S. Putterman; Submitted to *Phys Rev Lett* .

On Sonoluminescing Bubbles and Mass Diffusion, by R. Löfstedt, K. Weninger, S. Putterman and B. P. Barber, to appear *Phys Rev E*

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preprints

Publicity and Articles for the General Public:

Sonoluminescence in From the Dark, by J. Maddox *Nature* 361, 397 (1993).

New Shot at Cold (sic) Fusion By Pumping Sound Waves into Tiny Bubbles by
M. Browne , *New York Times* December 20, 1994 p. C1: CORRECTION,
December 23, 1994 p.2

Sonoluminescence: Sound into Light, by S. Putterman , *Scientific American*,
February 1995 p.32.

Producing Light from a Bubble of Air by R. Hiller and B.P. Barber, *Scientific
American* February 1995, p.78.

Un Son et Lumiere avec une Bulle [A sound and light show with a bubble] by S.
Putterman, *La Recherche*, 255, 750, (1993)

Patent Disclosure:

Converting Acoustic Energy into Other Useful Forms: a Patent Application filed
Feb 1994 by S.J. Putterman B.P. Barber, R. Hiller and R. Löfstedt;
[included herein are the summary and claims and abstract].

An asterisk * indicates research papers that were primarily supported by the
Division of Engineering and Geophysics (U.S. DOE). These early papers are
included for completeness.

SYNCHRONOUS PICOSECOND SONOLUMINESCENCE

1) *Preamble :*

The Division of Advanced Energy Projects of the Office of Basic Energy Science of the U.S. Department of Energy has funded research on Sonoluminescence from December 1991 until December 1994 (with a no cost extension to April 1995) . This final report describes the advances achieved during the above period and copies of our publications are attached. This report also outlines suggested directions for future research in this area of endeavor.

2) *Introduction: :*

Sonoluminescence is the remarkable physical process whereby sound energy is transduced into light by the motion of a trapped bubble of gas in a liquid. Interest in sonoluminescence (or SL as we like to call it) is based upon our insight that sound energy must focus by over twelve orders of magnitude to make light. Thus SL is Nature's most nonlinear oscillator.

3) *Key Discoveries:*

An extremely readable account of our work is provided by the attached article from Scientific American. Details of our work are provided by the attached publications , which have all appeared in major journals. Here we summarize our major findings.

In the past years we have discovered that:

a) each cycle of sound creates one flash of light and that the jitter in the time between successive flashes is measured in picoseconds,

b) the individual flashes of light have widths that are also measured in picoseconds [note that the acoustic periods are about 30.microseconds, so that there are over 30,000. flashes per second],

c) the spectrum of the emitted light is broadband and extends far into the ultraviolet; in fact the spectrum is increasing at the highest measurable energies [7.eV or 190.nm] where the transmission edge of the water cuts off the signal. The spectrum has no peaks or lines and is featureless on a log -log plot ,

so that when compared to, say, the tail of a Bremsstrahlung spectrum the corresponding SL temperature is well over 100,000K!

d) the trapped gas bubble is collapsing at supersonic velocities as it reaches the light emitting moment and the net volume collapse of the bubble is over a factor of 2 million. The net collapse can be higher if as we suggested the supersonic collapse launches a strong imploding shock wave [note that we have here a process which generates over 30,000 implosions per second!],

e) SL is extremely sensitive to the gas make-up of the bubble: for instance doping with a noble gas is can be essential,

f) SL is extremely sensitive to the concentration of gas in the water: for instance certain gases give SL only when their partial pressures in solution are extremely low. For example Deuterium gas gives light only when it is dissolved into the water at parts per billion which is a partial pressure of 3 Torr,

g) at low water temperatures the intensity of SL can be increased by about a factor of 30 over room temperature. A trapped Xenon bubble can be coaxed to yield peak powers of light emission approaching 100.mW,

h) the transition to SL is accompanied by a bifurcation in the bubble dynamics: at the transition to SL the bubble suddenly decreases in size,

i) the light-emitting region is smaller than the wavelength of light that we measure,

j) SL can be reached with sound field amplitudes as low as .4 Atm when the static [or ambient] pressure is lowered to around 1/3 Atm ; this implies that the energy focusing characteristic of SL here approaches 13 orders of magnitude.

4) Key Engineering Advances and New Facilities Developed:

In order to make the above discoveries we achieved a number of important engineering advances and developed new facilities for carrying out the indicated measurements. These include:

a) a sealed acoustic resonator into which a bubble could be seeded. When working with gases such as deuterium it is essential that the air be excluded, i.e. there must not be a free surface through which air could diffuse into the system. The system for seeding the bubble is shown in the photos in the Scientific American article, a patent application for this technique as well as many other issues described herein has been filed,

b) gas manifolds for controlling the gas content of the water in the acoustic resonator,

c) a Mie scattering facility that can resolve on nanosecond time scales the supersonic motion of bubbles smaller than a micron,

d) a fully calibrated spectrometer that can measure the spectrum of SL from 200nm to 800nm [note that alignment of the bubble is critical],

e) a femtosecond light scattering facility that can resolve the final moment of collapse,

f) an apparatus for measuring the outgoing shock wave that is emitted by the collapsing bubble; this apparatus makes use of a pinpoint microphone,

g) a 20GHz timing and counting facility for measuring the flash width and flash-to-flash jitter,

h) a means whereby the light emission can be mode-locked to the sound field, thus providing for very long runs even when resonances shift due to various systematic effects such as temperature.

5) *Publicity:*

This project has generated an enormous amount of favorable publicity. To our relief the publicity has focused almost entirely on the new science. *Nature*, *Physics Today*, *Science* and the *New York Times* among others have written complimentary stories that are in large part accurate. Please note the extremely detailed figures in the *New York Times* as well as an actual photo of SL. The title editor of the *New York Times* is separate from the reporter and so it was unfortunately necessary for them to print a correction to the title.

The response from the academic community has been astounding. I have been invited to Caltech for three speeches. Also included are Harvard, Brown, Yale, Penn, Cornell, Duke, Chicago, Stanford, San Diego, Berkeley, Santa Cruz, Los Alamos, Livermore, Argonne, and many more.

6) *Recommendations Regarding Future Research:*

Our success with sonoluminescence suggests three compelling lines for future investigation. These are: a) probing and understanding the stability of the repetitive shock wave implosions and the implications for the efforts to achieve Inertial Confinement Fusion (ICF), b) probing the limits of energy concentration that can be achieved with SL and in particular the possibility that SL might be strong enough to generate fusion in a Deuterium bubble, and c) measuring correlations in the outgoing light. These are discussed in order below.

a) Why are the repetitive bubble implosions so spherical and so stable? Just prior to the light emission the bubble's volume collapses by a factor of one million. The efficiency and stability with which the repetitive flashes of light are

emitted suggests that this collapse is very spherical. Furthermore the collapsing bubble launches an imploding shock wave that further increases the compression. Our estimates indicate that the shock makes survives to radii smaller than $1,000\text{\AA}$.

It is essential to learn why researchers in SL are blessed with over 30,000 spherical implosions per second of running time [which in turn can be hours long]. As shown in the figure on the next page the imploding bubble also launches an outgoing shock into the surrounding fluid. The response of a one micron microphone to this shock is shown as a function of time. This measurement is limited by the bandwidth and the distance from the bubble. But working back it appears that at its source this shock is nearly a megabar. It is important to study the angular dependence of the emitted shock and the emitted light on a flash to flash basis so as to determine exactly how spherical the collapse really is. In this direction one will learn a lot from perturbing the sphericity of the bubble at its maximum radius just prior to the collapse. Does the imposed convolution straighten out or get worse during the ensuing collapse? And at what rate does this all occur? We propose that the answers to these questions for SL will have a strong bearing on attempts to improve the sphericity of the collapses in ICF.

b) What are the limits of energy concentration that can be achieved with SL? This question has not been answered either experimentally or theoretically. From the point of view of experiment the spectral density of the emitted light increases with photon energy until the cutoff of water is reached. Between this cutoff {at 7eV } and the next real window {at 5KeV! } we know of no clean diagnostic for the measurement of photon energies. Except of course the fact that at 500eV Deuterium and D-T can fuse to create outgoing neutrons. We think it's reasonable to claim that the bubble temperatures [at collapse] reach $100,000\text{K}$ but whether they get up to 500eV is not demonstrated but at this point in time such a marvelous effect cannot be ruled out. It is essential that the possibility of generating *sonofusion* be carefully investigated. It is a high risk high gain possibility that must not be overlooked.

From the perspective of theory the key question is the stability of the imploding shock as it focuses towards minute radii. If the shock makes it down to $1,000\text{\AA}$ then the core temperature reaches about $100,000\text{K}$ consistent with the lower bound determined by the SL spectra. If the shock makes it down to $100\text{\AA}$ then the temperatures exceed 500eV and fusion should occur. It would constitute an extraordinary discovery to find that acoustics could drive inertial confinement fusion.

Key to this particular endeavor is a capability to count low neutron fluxes. Our published estimates in Physical Review Letters (duplicated in this report) indicate that the yield should be about 10 neutrons per second in the simplest set-up. At such yields one must be careful to avoid the traps which served to magnify the cold fusion debacle. We recommend capturing each event using NE213D

scintillator fluid gated by the SL flashes .{Use of ordinary He3 neutron counters or neutron-gamma discriminators will lead to very serious problems at these counting levels.} The precise timing of the SL flashes enables one to dramatically reduce background levels. The search for "hot spot fusion" should take place in a laboratory that is capable of diagnosing the bubble motion. This includes: flash widths, spectra and especially light scattering measurements of radius vs time. At UCLA we have for instance found that the greatest compression take place in an ethane bubble (probably because it has a low heat capacity ratio). For ethane the collapse exceeds 3,000,000:1. This diagnostic obviously suggests searching for fusion in Deuterated ethane- C_2D_6 . The increase of SL intensity with cooling suggests another parameter which could be exploited. Clearly there are many angles to pursue in this venture.

c) Are there photon correlations in the outgoing light fronts? Our light scattering measurement indicate that the light is emitted from a region smaller than the wavelength of light. Does this imply a correlation? As a first shot at this issue we propose to measure the angular dependence of the intensity correlations . This is the Hanbury-Brown and Twiss effect. This measurement is a two pronged sword. First one should seek out unexpected correlations that would result from coherent light. We note that even broad band light can be coherent as occurs for instance when femtosecond pulses are "chirped" by their passage through water. But even if the light is completely incoherent there is still a correlation to be found. In astronomy this correlation yields the radii of stars. Here it will yield the radius of the hot spot from which the light is emitted. Knowledge of the size of the hot spot will in turn tell us how well the shock has focused which as we have mentioned is key to knowing how high an energy is achieved with the SL mechanism. In addition to intensity interferometry we can also try the usual Michelson interferometry. What's unique here is that we will be learning not only about the light but also about the dynamics of the spherical collapse.

Addendum to final report being the abstract of a speech presented on the funded research at the DOE

Thursday August 8, 1996

US DOE Germantown c/o Dr W Polansky

PROBING THE UNKNOWNNS OF SONOLUMINESCENCE

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The passage of sound through a fluid with a trapped bubble of gas results in the spontaneous concentration of energy by a factor in excess of one trillion, so as to generate the clock-like emission of picosecond flashes of ultra-violet light. The mechanism whereby this process occurs is unknown and the limits of energy amplification that can be achieved have yet to be realized.

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