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SONOLUMINESCENCE AND ACOUSTIC INERTIAL CONFINEMENT FUSION

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ABSTRACT

Sonoluminescence (SL) is a remarkable consequence of acoustic cavitation: Generating light from sound has an intrinsic appeal that extends beyond that of science. Indeed, many of us are aware of the movie Chain Reaction, in which the forces of evil were attempting to take over the world with their newly-discovered knowledge of sonoluminescence. Equally intriguing, at least to the author, is that there was actually a pop music concert held in the United States, dedicated to sonoluminescence, which was attended by thousands of (presumably) scientific illiterates! It was titled "Sonoluminol". Much of this interest has been associated with the phenomenon of Single-Bubble-Sonoluminescence (SBSL), which has captured the attention of thousands of pre-college science students, who have demonstrated this phenomenon in science fairs and similar events all over the world. The attraction of SBSL was that it might be possible, with a simple table-top apparatus, to achieve bubble internal temperatures of hundreds of thousands, if not millions of degrees. Although SBSL attracted the attention of many scientists, detailed research in this subject was restricted to a handful of individuals who rapidly gained enough insight into the topic to have it declared "understood", and that maximum temperatures were restricted to a few tens of thousands, if even that high. Thus, it was with considerable skepticism from some, and great delight to others, that a group headed by Rusi Taleyarkhan from Oak Ridge National Laboratory (ORNL) presented evidence for thermonuclear fusion during collapse of a cavitation bubble. At the 145th meeting of the Acoustical Society of America, a special session was organized to discuss in detail and in a scientific context these exciting developments in cavitation research. The author wrote a review of this session, which was published in ECHOES ["Reducing Confusion about Fusion", Volume 13, No. 3, pp 8-9, Summer 2003], a non-technical newsletter of the Acoustical Society of America. This review is reprinted below.

INTRODUCTION

A special session was held at the ASA Spring meeting in Nashville on the topic of "acoustic inertial confinement fusion"; this session was appropriately called "sono(con)fusion" for its remarkable claims and the controversies surrounding these claims. By the way, the terms "sonofusion" and "bubble fusion" are not favored by proponents of "Acoustic ICF" because these terms have been used before by conventional "cold fusion" believers who use ultrasound to enhance conventional cold fusion.

The central premise for acoustic ICF involves the ability for a bubble to concentrate energy during its collapse. The simplest form of this remarkable energy concentration is found in single bubble sonoluminescence (SBSL), in which a single bubble is acoustically levitated in a liquid due to the radiation pressure forces exerted on the bubble. Under the appropriate conditions, these acoustic radiation pressure forces exactly balance the buoyancy forces exerted by gravity and the bubble remains at a fixed position with respect to the container that contains the standing wave sound field. Consequently, this levitated bubble is driven into radial oscillations by the sound field. Again, under certain relatively restricted conditions of acoustic pressure amplitude and frequency, and with a considerable amount of gas removed from the liquid, the bubble gives off a steady glow of light—hence the term "sonoluminescence". Because this phenomenon is quite unique, it has been a subject of considerable interest for more than a decade. [See S. J. Putterman, Scientific American, Vol. 272, 46 (February, 1995) and L. A. Crum, Physics Today , Vol. 47, 22 (September, 1994)].

SBSL attracted considerable attention because it was discovered that the light output was not steady, but actually consisted of an intense light flash EVERY acoustic cycle; furthermore, the duration of this flash was determined to be on the order of a few tens of picoseconds, about one millionth the period of the acoustic field that was oscillating the bubble. This short flash, and the associated anomalous optical spectrum, suggested that the interior of the bubble was very hot, and a number of papers were soon published concerning the origin of the intense flash. Some of these papers even proposed that the interior of the bubble could reach a temperature sufficient for the thermonuclear fusion, provided, of course, that the compressed interior contents of the bubble contained the appropriate molecular species (deuterium nuclei). These highly speculative claims of potential fusion from SBSL were largely ignored because the temperature required for significant D-D fusion is on the order of 100 million degrees. Furthermore, as researchers learned more and more about the phenomenon, it appears as if the temperature within a sonoluminescing bubble, although hot, didn't exceed a few tens of thousands of degrees [Brenner, et al., Rev. Mod. Phys, Vol. 74, 425 (2002) and Y. T. Didenko and K. S.

Suslick, Nature, Vol. 418, 394 (2002)]. However, as Putterman, et al. pointed out [Optics Letters, Vol. 26,575 (2001)], it's possible that these researchers were only observing the exterior of a very hot (in the interior) blackbody.

The scientific community was thus quite shocked to find that Science published an article by a group at Oak Ridge National Laboratory [Taleyarkhan, et al., Science, Vol. 295 1868 (2002)] in which evidence was presented for thermonuclear fusion from a cloud of collapsing vapor bubbles. This paper was greeted with enormous skepticism, even ridicule, but there were also believers—indeed, we all WANTED to believe that acoustics was involved in the "discovery of the century", as one wag put it. Efforts to gather both the proponents and critics of this purported discovery for a grand debate had previously been unsuccessful. Indeed, the American Physical Society unsuccessfully tried to devote an entire evening to it at one of their national meetings. Thus, this session, organized by Felipe Gaitan, Glynn Holt, and Tom Matula was thus a unique event, and attracted a full audience for the full-day affair.

The session opened with a broad review of the theory behind the Acoustic ICF claims by Academician Robert Nigmatulin, President of the Academy of Science of Bashkortostan and a member of the Russian Duma. In an animated and spirited defense of Acoustic ICF, he described in some detail the modeling and analyses related to the physical and chemical kinetics that were used in their hydrodynamic shock code evaluations that predicted plasma compression and temperature states suitable for nuclear fusion under conditions of their experiments. That is, these simulations predicted conditions required to obtain the extreme conditions required by the Oak Ridge group to justify their claim of over 100,000 neutrons per second emitted by their apparatus. Indeed, if Acoustic ICF is ever confirmed, then Prof. Nigmatulin argued that the gas densities in the core of the bubble must reach levels of about 100 gm/cm^3, pressures on the order of 10^{11} atmospheres, and temperatures as high as 100 million degrees—and all of this must occur within a tenth of a picosecond (10^{-13} s). It is easy to understand skepticism when all of this is supposed to occur in acoustically driven oscillating vapor bubble clouds in a laboratory benchtop apparatus!

Prof. Nigmatulin's dramatic defense of the Acoustic ICF was followed by a skeptical Seth Putterman, from UCLA, who pointed out a number of weaknesses in the Oak Ridge experiments. Nevertheless, Prof. Putterman, a proponent of searching for Acoustic ICF, described his own attempts to measure neutrons emitted by cavitating bubbles, and in particular, the construction of one of the world's most sensitive neutron detectors. So far, Putterman reports, he has been unsuccessful in detecting any neutrons that were coincident with sonoluminescence during cavitation collapse. Putterman argued that his own extensive spectroscopic data suggested that reports of temperatures of only 6,000 degrees inside a sonoluminescing hydrogen bubble were misleading, in the same way that measurements of our sun give similar values—because they only measure the temperature at the surface of the sun, while internal temperatures can reach several million degrees. His own molecular dynamics simulations predict SBSL temperatures closer to 10^6 K.

Felipe Gaitan, the discoverer of SBSL, reported the attempts of his company, Impulse Devices, Inc.—a company founded to explore Acoustic ICF—to construct sophisticated experimental systems to routinely produce neutrons from cavitating bubbles. The key feature of such systems is the employment of high ambient pressure to increase densities and energies in the collapse zone. These systems, although still in development, are expected to reach extreme acoustic conditions and, if the Oak Ridge experiments are confirmed, much higher levels of neutron emissions.

Ken Suslick, a Chemistry Professor from the University of Illinois, another skeptic of Acoustic ICF, described in some detail the chemistry within a highly compressed and heated gas. He noted that atomic and molecular dissociation and ionization were difficult barriers to breach, because they required lots of energy, and described his own detailed experiments to measure the temperature within a sonoluminescing gas bubble. These facts indicate that there are several liquids that would not be suitable for generating Acoustic ICF, and that the role of vapor in preventing the heating of a fusion plasma must be carefully considered. His experiments suggested that counter to the claims of others that temperatures could reach millions of degrees, his own data, using a variety of molecular liquids, suggested that a paltry 7,000-10,000 degrees was much more likely. (Countering Suslick's claims was simulations from Putterman's group which showed that even when cooling due to ionization is allowed, the interior of a xenon bubble reaches a million kelvins.) Suslick also described the results of a joint experiment with Prof. Putterman in which they attempted to duplicate some, but not all aspects, of the Oak Ridge Group's measurements using an acoustic horn to induce cavitation and observed no cavitation-correlated neutrons.

Tom Matula, a physicist at the University of Washington, described his attempts to utilize powerful stone-crushing acoustic sources, such as lithotripters, to generate extremely high acoustic pressures and thus to maximize the intensity of the cavitation bubble collapse. The key features of these devices are that the acoustic pressures (positive and negative) are much greater than has been achieved by the Oak Ridge group. He showed a successful experiment in which a small neutron source was used to nucleate bubbles that resulted in sonoluminescence emissions.

Dr. Larry Forsley brought some perspective to the search for an acoustic means to induce nuclear fusion. Forsley, a researcher in the multi-billion dollar laser induced fusion effort for the past two decades, expressed excitement at the relatively rapid (and inexpensive) success of acoustic efforts at inertial confinement implosions. However, he cautioned that, even if fusion reactions were confirmed, that this was only half the battle – the other half would be to trap the resulting fusion products in order to achieve "yield" from the reactions. He noted that the figure of merit for achieving yield would be the product of the density times the radius for the material immediately surrounding the reaction site to be greater than or equal to 0.3 gm/cm^2, a rather daunting figure. For example, this would require compressed and heated deuterium located 1 mm from the bubble center to have a density of 3 times that of normal water!

The highlight of the meeting, however, was a presentation by Dr. Rusi Taleyarkhanof Oak Ridge National Laboratory. Dr. Taleyarkhan presented a detailed description of the controversial experiment that claimed evidence for thermonuclear fusion from cavitating bubbles. In this experiment, Taleyarkhan's group introduced two significant changes to the typical SBSL scenario described above. First of all, they increased the acoustic intensity inside their cavitation chamber by more than an order of magnitude over that normally used for SBSL studies. Secondly, they removed all traces of dissolved gases from the liquid undergoing cavitation, and initiated the cavitation nucleation process by using a pulsed neutron source. In this way, they could generate a cavitation nucleus—necessary for the production of a cavitation bubble—by the "bubble chamber effect", in which an incoming high energy neutron would interact with a deuterated (hydrocarbon) liquid which was under significant tension and produce VERY SMALL (nanometer scale) vapor bubbles. These very small vapor bubbles were produced exactly at that precise time during the acoustic cycle when the liquid was under maximum tensile stress. The creation of a very small vapor (rather than gas) bubble, in the presence of an intense acoustic pressure field, resulted in a bubble growing to a large size (building up a huge reservoir of work potential), and then subsequently imploding without significant retardation or repulsion by the interior components of the bubble—that is, much of the vapor would condense as the liquid interface advanced toward the center of the bubble. Of course, not all the vapor would condense and a very small amount (~5%) of it would be compressed enormously by this implosion, heating and compressing the remaining vapor in the interior to those ultrahigh values described earlier by Prof. Nigmatulin. The Oak Ridge group chose a liquid that could be "deuterated"; i.e., the normal hydrogen atoms being replaced by deuterium (D) atoms, a material that can undergo thermonuclear fusion. Evidence for Acoustic ICF was of two kinds: (1) the presence of 2.45 MeV neutrons coincident and time correlated with the emission of sonoluminescence flashes, and (2) a radioactive material that is the biproduct of D_D fusion, viz., tritium.

Taleyarkhan's presentation was followed by one from a second group at Oak Ridge, D. Shapira and M. Saltmarsh, that was asked to obtain data using a different neutron-gamma detection system. Shapira described in great detail his group's analysis of their neutron-gamma data supposedly created by Acoustic ICF and found that the excess neutrons they detected with cavitation on (versus cavitation off) were lower than what one would expect from the reported tritium data. This apparent "failure-to-reproduce" the results of the Taleyarkhan group was a major argument, said the critics, that the entire experiment, including the unexplained tritium data, was suspect. Shapiro pointed out that the neutrons from the PNG were probably the source of the "excess" neutrons that Taleyarkhan attributed to Acoustic ICF.

Perhaps the best part of the entire session was a panel discussion at the end of the afternoon session in which the various supporters and critics of the Oak Ridge Acoustic ICF experiment offered arguments and rebuttals for or against their stated positions. Nigmatulin explained that while chemical reactions can be important limitations in SBSL experiments, they are overcome in Acoustic ICF experiments due to the significant additional energy available for compression. Taleyarkhan challenged Shapira's analysis of his neutron data by stating that Shapira's detection system was set up to discard most of the 2.45 MeV neutrons, and therefore, the calibrated measured efficiency was several orders of magnitude lower than what one would compute for an ideal detector. He pointed to the fact that the independent detection system set up by Shapira also measured statistically significant (~10 standard deviations) "increases" in nuclear emissions which were time-correlated with SL flash emission and as such should be considered an instance of limited confirmation of the reported results in Science. No tritium data were taken by Shapira during the experiment, and as such, meaningful comparisons can not be made with the tritium data obtained under different operation conditions reported in Science.

Colin West, a member of the Oak Ridge group proposed an experiment that could be done rather easily by other groups with acoustic systems expertise to confirm the presence or absence of tritium during acoustic cavitation of a deuterated liquid. Finally, Taleyarkhan promised to show additional new data, once it was approved for release by the upper management of Oak Ridge, and that these data would provide additional strong evidence in support of their earlier experiments.

All in all, this session was a most exciting one, and as is typical of such debates in science, ended without any resolution of the major issues. The traditional call for further experiments is a valid one and hopefully it will be heard by the funding agencies; however, if the history of science repeats itself, the truth is out there, and perhaps it will be revealed at some future ASA meeting.