Microimplosions: Cavitation Collapse and Shock Wave Emission on a Nanosecond Time Scale

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A streak camera with high spatial and temporal resolution was used for imaging the dynamics of the violent collapse in single-bubble sonoluminescence. The high pressure in the last phase of the bubble collapse leads to the emission of a shock wave, which is launched with a shock velocity of almost 4000 m/s. The shock amplitude decays much faster than $\sim 1/r$. From the strongly nonlinear propagation the pressure in the vicinity of the bubble can be calculated to be in the range of 40–60 kbar.

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In 1990 Gaitan [1] demonstrated that a single oscillating gas bubble can be trapped in water in the pressure antinode of a resonant sound field. In a small parameter range of the acoustic driving pressure Pa and the gas concentration of the water [1–5] the bubble oscillations can be extremely nonlinear leading to a very violent bubble collapse and the emission of short light pulses (single-bubble sonoluminescence, SBSL). In the past many investigations were concentrated on the light emission process itself, a problem which in principle now is solved [6]. Additionally to the light a pressure wave is emitted in the end phase of the collapse. In all applications of intensive ultrasound, as in cleaning, in degassing, or in ultrasonic medical imaging with microbubbles as contrast agent, and in all areas of cavitation damage this pressure wave is much more important than the emitted light.

The pressure wave was characterized far away from the bubble by several groups with polyvinylidene fluoride (PVDF) needle hydrophones [7–9], a fiber optic hydrophone [10], and a schlieren-optics method [11]. In their investigations Holzfuss *et al.* [11] also found strong evidence for a nonlinear propagation of the shock wave at the beginning of the emission. But because of their limited time resolution of about 10 ns they were not able to characterize the shock wave in the vicinity of the bubble. As the light emission, the amplitude of the pressure wave is strongly related to the bubble dynamics [11,12], which in principle can be determined by Mie scattering. In previous investigations fast photomultiplier tubes were used for the detection of the scattered light, leading to radius-time curves which can be directly compared with hydrodynamic simulations [13,14]. The bandwidth of the photomultiplier tubes limited the achievable time resolution in this kind of experiments to about 5 ns. To overcome this restriction Wenninger *et al.* [7] used a pulsed laser technique with a time resolution of about 500 ps. For comparison, the duration of the emitted light pulse is in the range of 100 ps [15–17].

In this work we present an image of the last stage of the bubble collapse using a fast streak camera for detection. Besides the high time resolution a streak camera has the advantage that it also allows a high spatial resolution in one direction. The experimental setup is shown in Fig. 1. A single SL bubble was trapped in a 250 ml spherical quartz glass flask filled with filtered, degassed water, which was driven at its first radial oscillation mode at about 20 kHz by two piezoelectric disks. The resonator had two flat windows of high optical quality on opposite sides to enable undisturbed imaging of the bubble. The whole resonator is integrated in a small cooling box (not shown in Fig. 1). All measurements were carried out at 6 °C to improve the space stability of the bubble. The O_2 concentration was controlled with an oximeter. The amplitude of the driving pressure was measured by a PVDF needle hydrophone, which was calibrated with a fiber optic probe hydrophone [18,19]. Light from a 20 mW HeNe laser was scattered at the bubble and then focused through one of the quartz windows onto the entrance slit of the streak camera (Hamamatsu C5680). The slit width was adjusted to 25 μm, leading to a time resolution of 400 ps in the 50 ns time window of the streak camera. The spatial resolution was 13 μm, limited mainly by the aberrations of the optical system and by space instabilities of the bubble itself. The aperture of the system was about $f/2.8$ defined by the quartz windows of the resonator. The angle between the optical axis of the streak camera and the laser was 25°. A red filter in front of the streak camera reduced

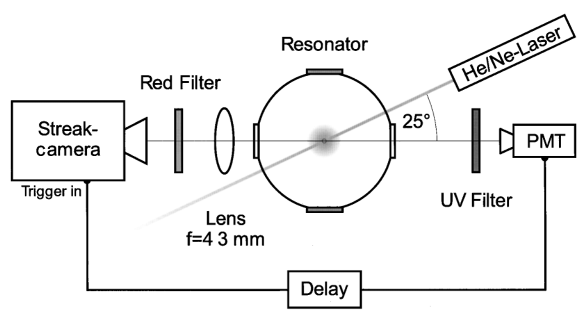

FIG. 1. Experimental setup. The SBSL bubble is trapped in the pressure antinode of the sound field in a water filled spherical quartz glass resonator. The laser light scattered at the bubble is detected with high spatial and temporal resolution by a streak camera. The streak camera is triggered by the previous SL pulse using a fast photomultiplier tube (PMT) and a time delay.

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the SL intensity to the level of the scattered light intensity. The streak camera was triggered by a fast photomultiplier tube (PMT) and a time delay on the previous SL pulse. Therefore the red laser light was blocked by an uv filter in front of this PMT. To increase the signal to noise ratio about 10^5 streak images were on-line integrated. The achieved time resolution was about 500 ps limited mainly by the time jitter between subsequent SL pulses than by the slit width of the streak camera.

In Fig. 2(a) a streak image of the end phase of the collapse is shown. The time and space axis are marked by arrows, and dark parts of the image correspond to high light intensity. Therefore the SL pulse, which is also marked, appears as a dark spot. Before the SL pulse is emitted, the radius and thereby the scattered light of the collapsing bubble decrease rapidly, leading to a single line in the streak image with fast intensity decay. After the SL pulse one can distinguish three lines. The center line represents the reexpansion of the bubble. This part and the influence of the outgoing shock wave on the interpretation of Mie-scattering data are discussed by the authors in more detail in [20].

In this paper we will concentrate our discussion on the two outer lines caused by the outgoing shock wave which is emitted simultaneously with the SL pulse from the bubble. Most of the light seen in Fig. 2(a) is scattered at the strong gradient of the refractive index at the shock front (schlieren optics). Remarkable is the curvature of the outer lines, demonstrating the strongly nonlinear propagation at the beginning of the emission.

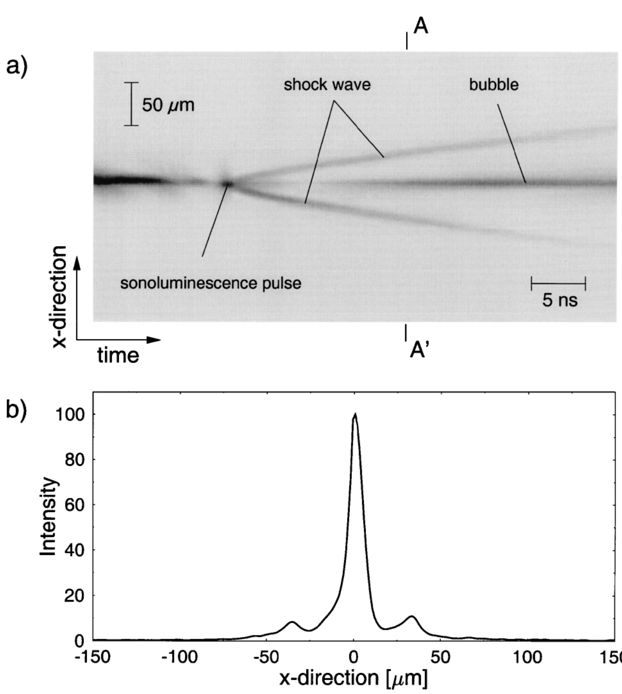

FIG. 2. (a) Streak image of the SBSL bubble collapse. Laser light is scattered at the bubble as well as at the emitted shock wave. (b) Line scan A-A' of the streak image.

In the next step the distance of the shock front from the collapse center was determined from the streak image at different times. Using line scans as shown in Fig. 2(b) the distance could be obtained with an accuracy of $\pm 2\ \mu$m. The result together with a fit is shown in Fig. 3.

The velocity $v(t)$, also shown in Fig. 3, is the derivative of the fit. At the beginning the shock wave propagates with a velocity of almost 4000 m/s and ends up with 1430 m/s, the speed of sound in water at 6 °C. The increased shock front velocity is caused by the nonlinear equation of state of water and can be used to estimate the shock wave amplitude. The relationship between the amplitude p of a shock wave and its velocity v is given by Cole [21]:

$$p = B\left[2\frac{n-1}{n+1}\left(\frac{v}{c}-1\right)+1\right]^{2n/(n-1)} - B \qquad (1)$$

(parameters of the Tait equation of state: $B = 2750$ bars; $n = 7.44$; speed of sound: $c = 1430$ m/s at a water temperature of 6 °C).

Figure 4 shows the calculated shock wave amplitudes vs the distance from the bubble for three different driving pressures of the resonator. The horizontal axis in Fig. 4 starts at 2.5 μm. At smaller distances the shock wave is not fully developed and Eq. (1) is not valid anymore. The pressure amplitude at minimum bubble radius increases with increasing driving pressure and can reach values up to 60 kbar. The accuracy of the shown pressure values can be estimated to be better than $\pm 20\%$.

Because of the strong absorption of the short pressure pulse the wave attenuates much faster than proportional to $1/r$. This explains the difference to earlier far field measurements with hydrophones [10]. There the maximum pressure at minimum bubble radius was extrapolated from pressure values found at a distance of some millimeters to be in the range 5–15 kbar.

With the values of Fig. 4 it can be estimated that the shock wave loses more than 50% of its initial energy by absorption on the first 25 μm of its propagation.

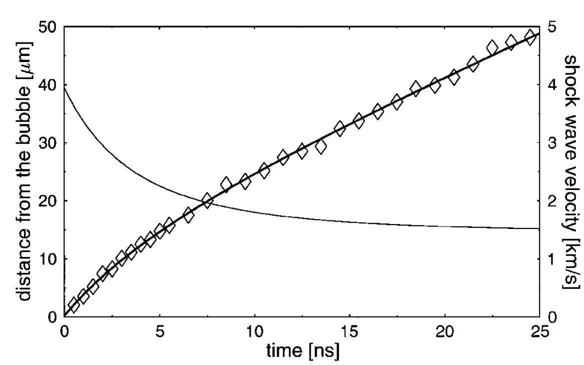

FIG. 3. Distance of the shock wave from the bubble $r(t)$ determined from the streak image (open symbols) and corresponding fit (solid line). The shock wave velocity $v(t)$ is the derivative of the fit.

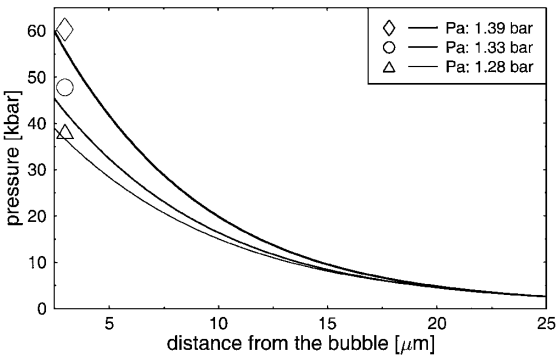

FIG. 4. Shock wave amplitudes vs distance from the bubble and calculated maximum pressures inside the bubble (open symbols) for three different driving pressures of the resonator. Pressure values up to 60 kbar can be reached.

The energy loss is converted into heat. But the temperature rise in the water due to that energy loss is too small to contribute to sonochemical effects in the vicinity of the bubble. On the other hand, the large shock front velocity could be the reason for high velocity interparticle collisions in liquids containing solid powders [22]. All cavitation bubbles emit pressure waves, which, for example, in the case of an ultrasonic bath sum up to the so-called "cavitation noise." Note that our experiments give no evidence that there is an ingoing shock wave in the case of light emitting bubbles [23,24]. Using simple hydrodynamic models for bubble dynamics (Rayleigh-Plesset equation) assuming adiabatic compression of the gas content and a uniform pressure inside the bubble at minimum bubble radius leads to internal pressure values of about 35–60 kbar (open symbols in Fig. 4) in good agreement with our experimental results. Our results also agree well with calculations given by Holzfuss *et al.* for the shock front velocity [11]. Using the Gilmore model for the bubble dynamics and the Kirkwood-Bethe hypothesis for the dynamics of the pressure pulse they found shock velocities of about 4000 m/s.

In conclusion, our results show that the dynamics of the cavitation bubble can be studied with high spatial and temporal resolution with direct imaging using a streak camera as detector. Because of the high pressure at minimum bubble radius a shock wave is emitted with a velocity of almost 4000 m/s. From the strongly nonlinear propagation pressure amplitudes of up to 60 kbar in the vicinity of the bubble can be calculated. Our results also show that SBSL is a model system for cavitation in general. The high reproducibility of the cavitation collapse in SBSL enables experiments to study the collapse phase on a time scale where the physics behind ultrasonic applications take place.

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