Avalanches of Popping Bubbles in Collapsing Foams

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We report acoustic measurements of popping bubbles during the collapsing of aqueous foams. The sound pattern is analyzed using classical methods of statistical physics. It is found that membrane rupture concerns a wide variety of situations: small and large membranes at the air/foam interface. Avalanches of popping bubbles are put into evidence. Time durations in between successive pops seem to be distributed on a universal power law.

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Cellular structures are very common in nature [1,2]. Each cell of the cellular structure can be a bubble in a beer, a biological cell in a tissue [3], a grain in a polycrystal [4], or a magnetic domain in a solid [5]. Foams have become paradigms of disordered cellular systems. Indeed, polygonal bubbles composing foams are characterized by a wide variety of side numbers and face areas. Among the physical properties of interest, one is the long-term behavior of a froth driven by topological rearrangements.

A fundamental process is the foam drainage due to competition between gravity forces and capillary pressure in channels and plateau borders. This drainage implies some fragility of the bubbles located in drying regions of the foam. It results in wall ruptures and bubble pops. Burnett *et al.* [6] reported cascades of wall ruptures in soap solutions. More recently, Müller and di Meglio [7] reported acoustic experiments on foams; they observed non-Poissonian distributions of popping events by counting the number of pops in various time intervals. A fundamental question concerns the type(s) of bubbles which is (are) exploding at the air/foam interface. Another fundamental question is the nature of correlations in the cascades of wall ruptures. In order to answer those questions, we report new acoustic experiments on aqueous foam systems allowing for simultaneous measurements of both correlations and energy dissipation. The sound patterns are analyzed using classical methods of statistical physics, and empirical laws are proposed. Fundamental processes at the surface of collapsing foams are then discussed.

Foams have been created by continuously injecting air at the base of a water/soap mixture in a cylindric vessel. With this method, the bubbles are roughly monodisperse and spherical at the bottom of the foam layer (typically a diameter ≈2.5 mm). However, bubbles grow and shrink inside the layer due to classical coarsening. At the top of the foam, large polyhedral bubbles can be observed (typically the diameter ≈8–10 mm). Different commercial soaps have been tested. They are composed of anionic tensioactives such as dodecylsulfate. Various concentrations below the critical micellar concentration (CMC) have been used. After injecting air, the foam is left to coarsen and collapse freely. We have measured the width W of the foam layer as a function of time t. Three successive regimes have been observed: (i) a stable regime $W = W_0$ controlled by both coarsening of bubbles and the drainage of liquid in plateau borders, (ii) an exponential decay $W = (W_0 - W_r)\exp(-t/T) + W_r$ due to popping events, and finally (iii) a stable regime for a residual thin foam layer $W = W_r$ due to the capillary of liquid in plateau borders.

In the present work, we are mainly interested in the macroscopic collapse of the foam, i.e., the second regime. Bubble explosions occur mainly at the air/foam interface. Indeed, each bubble at the surface presents a very thin and curved face which is more fragile than the planar faces located inside the foam. The characteristic time T of the exponential decay depends on numerous parameters such as air flow during the foam creation, the concentration of tensioactives, the viscosity of the mixture, etc. We have selected soap/water mixtures with characteristic times T larger than 50 min. Typically, we recorded the first 10 min of collapsing such that the popping rate is quasilinear in time. In order to capture bubble pops, a high-quality microphone was placed above the top of the foam. The sound emitted by the popping bubbles was recorded at a sampling rate of 32 kHz (a much larger resolution than in [7]). In order to minimize the external noise and to prevent any secondary reflection of the acoustic waves, the experimental setup was placed in a special "anechoic chamber." A typical recording of the (dimensionless) acoustic activity $A(t)$ is presented in Fig. 1. Four successive pops are seen. Each pop looks like a "wave packet" made of $\nu \approx 8$ kHz oscillations modulated by a Gaussian-like envelope. Oscillations correspond thus to a sound wavelength $\lambda \approx 40$ mm, i.e., four times the typical size of surface bubbles such as those in organ tubes [8]. The characteristic duration of a pop is typically $\tau_0 = 1$ ms. In order to extract the exact position and intensity of each peak, we have numerically treated the time series. First, a low frequency filter is applied in order to remove low frequency noise which is still present in the anechoic chamber. Then, the residual noise is

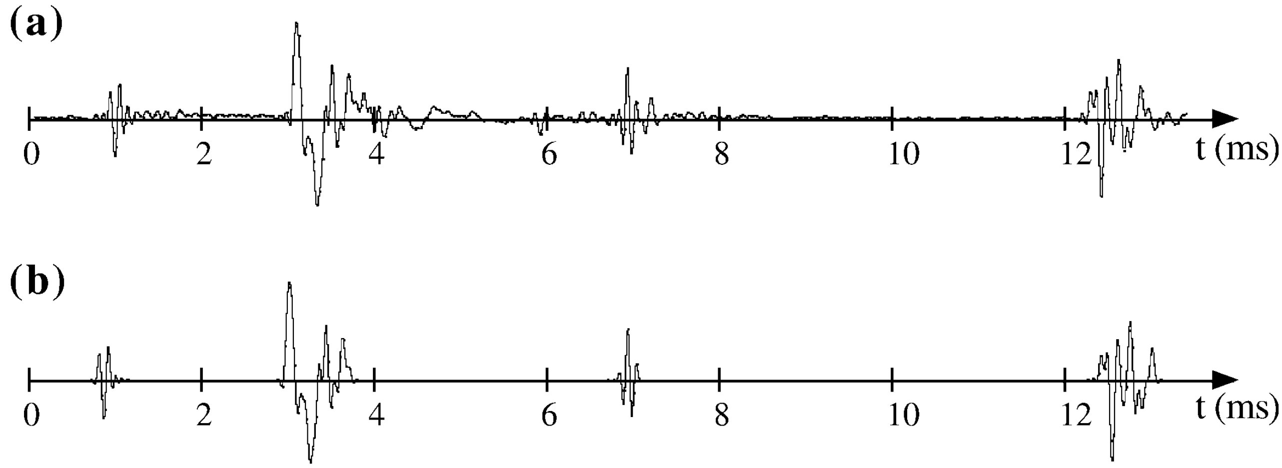

FIG. 1. Acoustic recording of crackling bubbles in a collapsing dry foam: (a) typical recording which is 12 ms long, and (b) filtered recording for which a white noise component has been removed.

removed by selecting a lower cutoff for the peak amplitudes (noise thresholding). The resulting filtered signal is also shown in Figure 1. Pops are not erased with our filtering method. We checked whether or not simultaneous pops occur: about 0.5% of the popping events are found to overlap in time, and thus do not influence the following statistics. Figure 2 presents a typical time series which is 10 min long. Thousands of events are typically observed. One should note that exploding events are not homogeneously distributed along the time axis. Bursts of acoustic activity separated by periods of stasis are observed. This heterogeneous acoustic activity will be characterized below.

The acoustic energy E dissipated within each pop (occurring at t_0) is then calculated, i.e.,

$$E = \int_{t_0-\tau_0/2}^{t_0+\tau_0/2} A^2(t)\,dt\,, \tag{1}$$

where t_0 and τ_0 are, respectively, the pop position and duration. The dissipated energy E is given in arbitrary units and is attributed to the rupture of the bubble membrane, i.e., to be proportional to the surface area of the disappearing bubble (and not especially the volume of the bubble). Figure 3 presents a typical histogram $h(E)$ of the frequency of peak occurrence as a function of the peak intensity E. Two different soap/water mixtures are illustrated. In a log-log plot, the first part of $h(E)$ looks like a parabola, i.e., a log-normal distribution. Such a distribution is fitted on the data of Fig. 3 and is represented by the continuous curves. However, a log-normal distribution is not sufficient to describe completely the histograms since a long tail is observed for high values of E, i.e., for large events. In fact, one observes a power law

$$h(E) \sim E^{-\nu} \tag{2}$$

for high E values. This power law behavior of the tail has held for over two decades for the best cases. The tail

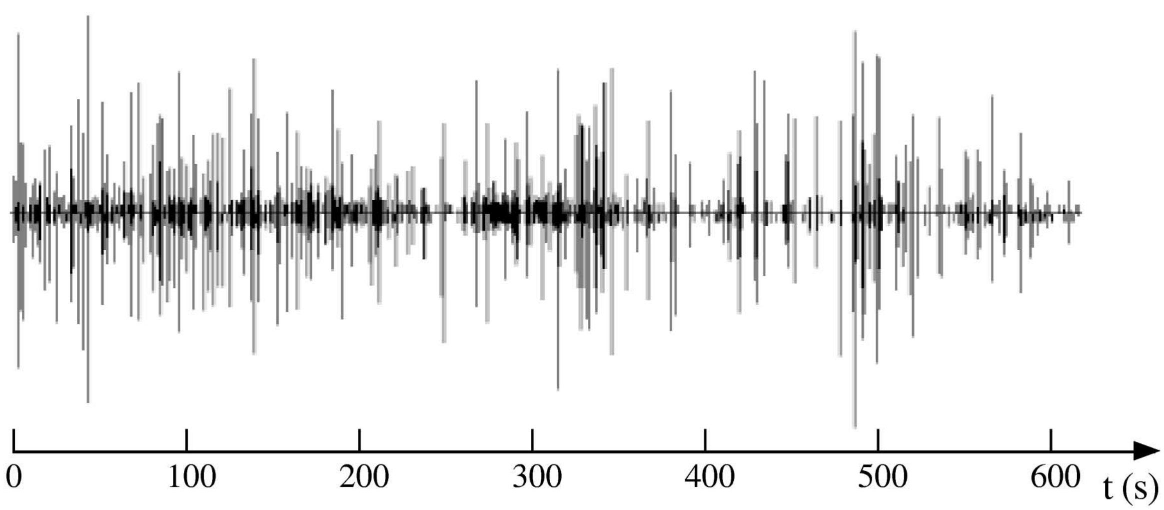

FIG. 2. Typical filtered acoustic recording 10 min long. It is the case of sample 1 (detergent/water mixture with a concentration around 50% of the CMC).

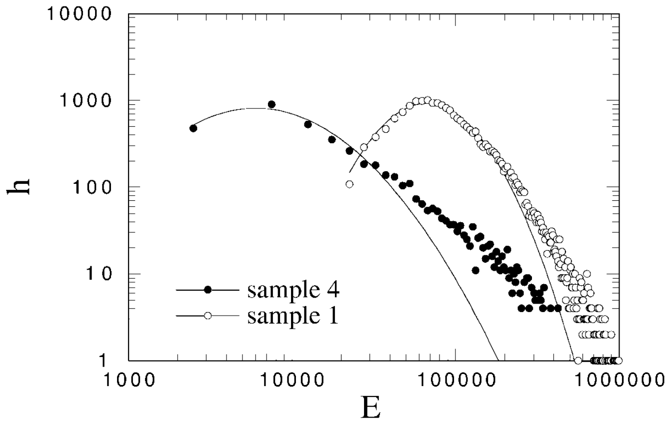

FIG. 3. The histogram h of the energy E dissipated during each bubble explosion. Two different cases are represented: sample 4 (bubble bath with a concentration around the CMC) and sample 1 (see Fig. 2). The continuous curves represent fits with log-normal distributions which miss, nevertheless, the tail of h for large events.

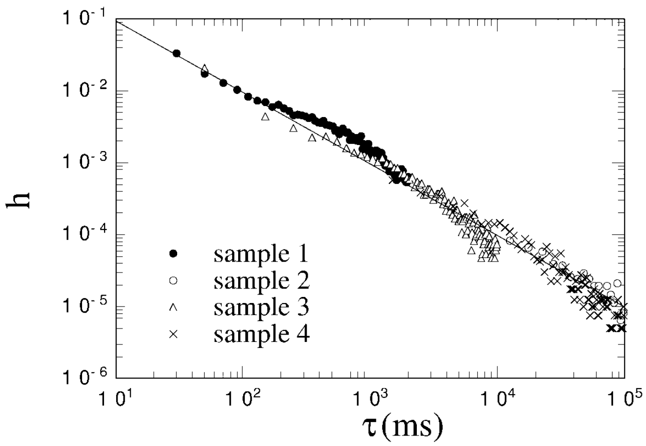

FIG 4. Log-log plot of the histogram h for the interpeaks durations τ. Four different cases are illustrated: sample 1 (see Fig. 2), sample 2 (detergent/water mixture with a concentration around the CMC), sample 3 (washing up liquid with a concentration around 50).

exponent ν has nonuniversal values, i.e., depends mainly on the nature of the soap/water mixture. Exponent ν values vary from 1.5 up to 3.0. The asymptotic power law behavior indicates that the distribution of peak amplitudes is quite broad. In other words, no sharp cutoff is observed in $h(E)$ for high E values. This implies that a wide variety of membrane areas is exploding. This experimental result is in contrast with the widely accepted and intuitive argument that only large membranes are more curved and more fragile, exploding at the air/foam interface (argument used in some simulations [9]). The latter intuitive argument would, however, lead to a sharp exponential cutoff in $h(E)$. On the contrary, our experiment demonstrates that no critical membrane area seems to exist. The stabilization of some bubbles with respect to apparently weak bubbles should find some explanation by considering the neighboring environment of each bubble [10]. Those correlations have been confirmed by the direct observation of a collapsing foam in vertical Hele Shaw cells which is outside the scope of the present work and will be published elsewhere [11].

Let us investigate whether temporal correlations exist or not. Figure 4 presents in a log-log plot the histogram $h(\tau)$ of the interpeak durations τ, i.e., the time intervals τ separating successive bubble explosions. Four different series obtained with four different soap/water mixtures are illustrated. For each analyzed series, the data points have been rescaled by a certain factor in order to emphasize that all series seem to behave like a power law

$$h(\tau) \sim \tau^{-\alpha} \quad (2)$$

with an exponent $\alpha = 1.0 \pm 0.1$. A power law with $\alpha = 1$ is illustrated by the continuous line in Fig. 4. The power law holds over two decades for each histogram. The value of the exponent α does not change when other types of soap/water mixtures are used. Only the total number of explosions as well as the total dissipated energy may change. For a homogeneous (random) occurrence of bubble explosions, one expects an exponential decay for $h(\tau)$. The power law behavior (3) indicates that bubble explosions are correlated events. Moreover, a unique value for α implies that the temporal correlations in the collapsing foam are universal. Containers of various diameters (respectively 5, 10, and 20 cm) have been also used. The statistical results do not dramatically change by varying the container diameter. In order to obtain better power law behaviors holding over three decades or more, one needs many pop events, and thus larger characteristic times T. This corresponds to difficult experimental situations.

In former experiments, only the popping rate has been studied [7]. Our acoustic experiments at higher frequencies allow us to study the energy release as well as heterogeneity of acoustic activity. The power law behavior of $h(\tau)$ and the long tail of $h(E)$ suggest that energy release is discontinuous and quite similar to self-organized critical (SOC) systems [12]. Simulations [13] and experiments [14] have indeed shown that a slowly driven foam can be described by avalanches having a broad distribution of event rate versus energy release. In these studies, events are abrupt topological rearrangements (mainly the coarsening and vanishing of bubbles), while in the present study, events are popping bubbles at the surface of a collapsing foam. One understands that the explosion of a bubble implies a topological change for neighboring bubbles which may propagate in the bulk of the foam as well as along the air/foam interface [11]. These topological changes may destabilize other bubbles at the interface and thus create avalanches of popping bubbles.

In summary, our acoustic experiments have shown the intermittent and correlated character of popping bubbles in a collapsing dry foam. In other words, the dynamics of a collapsing foam is discontinuous and evolves by sudden bursts of activity separated by periods of stasis. The avalanching process seems to be characterized by a unique power law behavior. Moreover, we have discovered that a wide variety of bubble sizes participate in the phenomenon. In other words, there is *no rupture threshold* in the size of the bubble membrane.

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