18 Disordered and Biological Soft Matter

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In the group of disordered and biological soft-matter, we work on problems where disorder or non-equilibrium are important factors of the systems' physical properties. One aspect of this is biological matter, which is inherently out-of-equilibrium and typically has dynamic and soft elastic properties. In this context we study in particular the influence of mechanical forces on developmental biology, showing that environmental factors can lead to plasticity in development and thus have to be taken into account in the developmental control of an organism. In disordered media, we are investigating the effects of the wave nature of light on its transport in multiple scattering media, ranging from fundamental questions, such as the transition to Anderson localization in three dimensions, to the application in imaging techniques useful to study developmental processes in turbid tissues. Finally in non-equilibrium systems, we are studying the dynamics of granular gases and foams, in particular in the presence of levitation, such that effects due to gravity can be eliminated and the generic process can be studied. In the last year, we have made considerable progress in several of these areas, which are discussed in detail below. These subjects concern microscopy in turbid media, growth control via mechanical feedback, Anderson localization and the coarsening dynamics of levitated foams.

18.1 Microscopy in turbid media

Many biological tissues are turbid and thus not suitable for imaging techniques. While confocal imaging has lead to some improvements, several aspects of biological processes are not amenable to investigation via live imaging. We are in the process of developing a method based on the exploitation of multiple scattering for imaging

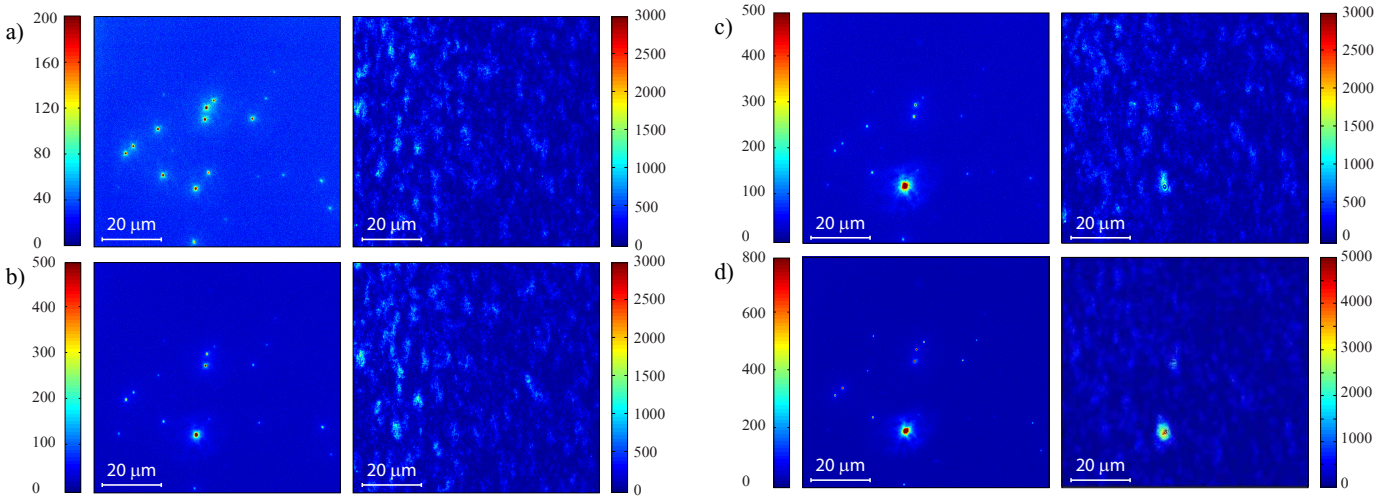

FIG. 18.1 – Illustration of the iterative scheme for finding a focus without optical access in the presence of several sources. The panels on the left show a direct view of the fluorescent sources (without turbid layer), whereas the panels on the right show the transmitted speckle pattern. Here a) is the situation before optimization and b) through d) after iterations with 7x7 (b), 14x14 (c) and 28x28 (d) segments, respectively. As can be seen, there is only a focus on a single fluorescent particle at the end, which can subsequently be scanned using the optical memory effect.

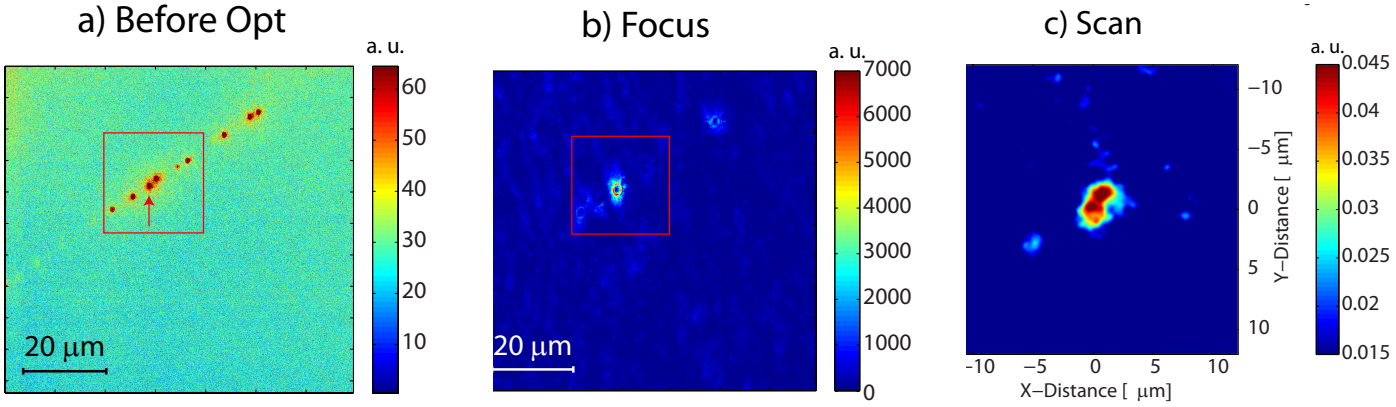

FIG. 18.2 – Scanning microscope images of a collection of fluorescent beads hidden behind a turbid layer:
a) direct view of the fluorescent particles in the absence of a turbid layer,
b) image created after iteratively adjusting the wave-front to the fluorescent signal and
c) the reconstructed image corresponding to the field of view of a) after scanning b) using the optical memory effect.
This result shows that it is possible to obtain diffraction limited resolution behind turbid layers of several mean free paths.

using the technique of wave-front shaping to create a focus behind [1] or inside [2] turbid media. We have previously been able to show that such a focus can be scanned for imaging purposes due to the optical memory effect [3], in both two [4] and three [5] dimensions. Because the focus is created by interference of multiple scattering paths in the turbid medium and the engineered phase shifts between these paths by a spatial light modulator, the resolution of the technique is not limited by the turbidity, but only by the wave-length of light used. Hence diffraction limited imaging is possible behind turbid layers many mean free paths thick.

Now we have been able to create the initial focus without optical access using the integrated fluorescence signal as a feedback for the optimization of the spatial light modulator phase field [6]. Moreover, this has shown that an iterative use of this optimization leads to a specific focusing on a single fluorescent structure (see Fig. 18.1). Thus even in the presence of several sources, iterative wave-front shaping leads to a single scannable focus that can subsequently be used to image the surroundings of the initial focus. This is shown in Fig. 18.2, where the direct fluorescence image of a set of particles is compared with a scattered light fluorescent image obtained with direct focusing on one bead. As an extension of the technique, the field of view for such images can be enlarged by successively bleaching the initially chosen beads and thus scanning several areas in sequence.

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18.2 Mechanical regulation of growth in the Drosophila wing disc

How an organ regulates its final size remains a big unsolved question in developmental biology. In recent years, the hypothesis that mechanical forces play a key role in this regulation has gained much attention [1, 2], since several conundrums in growth regulation have a natural explanation in this framework. The main object of study for this problem is the wing imaginal disc in Drosophila, which is a precursor organ that will form the final wing during metamorphosis. This is because of the relative simplicity of the tissue, being a single layer quasi-two dimensional sheet of cells and the powerful genetic tools available for studying pathways. While indirect evidence for such a regulation has been accumulating, from the fact that mechanical stresses are present in the wing disc [3–5] to the distribution of packing of the cells reproduced only in models including mechanical feedback [6, 7], there is still no direct evidence for such a regulation.

We have now tackled this problem experimentally and mechanically stressed live wing discs, while determining their proliferation rate. For this purpose, we use a stretch-

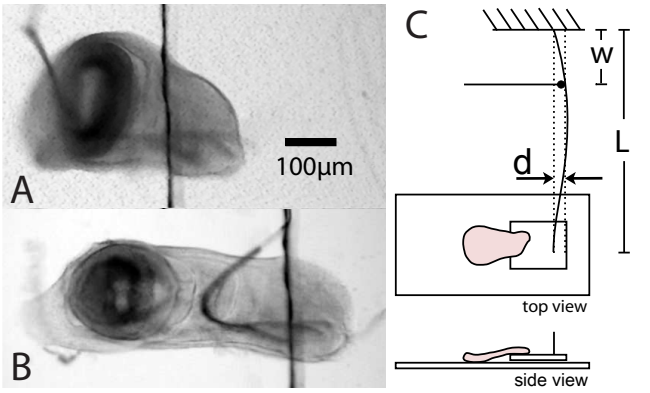

FIG. 18.3 – Illustration of the setup used to mechanically stimulate the wing imaginal disc. A wing disc is attached to two glass coverslips separately, one of which is movable using a spring sheet in order to apply a calibrated force. Panel A shows a wing disc before stretching, and B the same disc after application of 350 μN. The schematic of the setup is shown in C, where the spring sheet of length L is pushed a distance d at position w giving rise to a force on the wing disc of $F = \frac{6EI}{w^2(L-w)}d$. Here, I is the area moment of inertia of the spring sheet and E its elastic modulus.

ing apparatus described in Fig. 18.3 [8], which is capable of applying calibrated forces of the order of 20 to 500 μN to the tissue. With this, strains between a few percent to unity are possible. Mechanically stretching the tissue at different forces allows us to determine the systematics of the growth response in the tissue, which is shown in Fig. 18.4 [9]. As can be seen, after an hour of stretching, the proliferation rate has increased by a factor two. In fact, when applying a compressive force, the tissue is stretched as well due to the appearance of a buckling instability. This can be used to test whether stress or strain is more likely to be the controlling factor. As can be seen in Fig. 18.4B, in case of buckling, where the stresses are highly different to the case of uniaxial tension, the change in growth rates are the same within errors, as is the total strain. This points to the fact that the total strain is the controlling factor, as is also the case in a theoretical model [10]. This model also predicts a molecular mechanism for the regulation of growth, for which there is evidence from other tissues [11].

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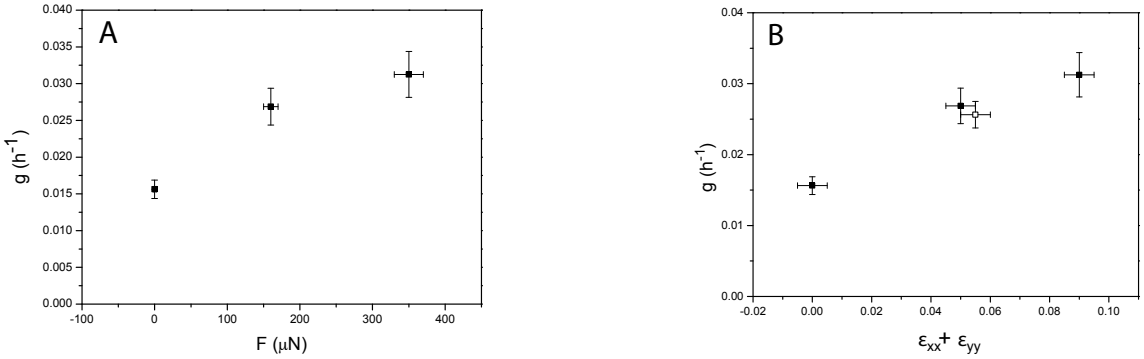

FIG. 18.4 – The proliferation rate of the wing disc tissue has been determined after one hour of stretching for different applied forces. The results are shown here as a function of the applied force (A) as well as of the ensuing total strain in the tissue (B). As can be seen, the proliferation rate strongly increases on the application of mechanical tension. On compressing the tissue, it buckles, leading to a positive strain comparable to a stretching experiment, shown by the open symbol in (B). This implies that the strain rather than the stress of the tissue leads to the increase in growth rate.

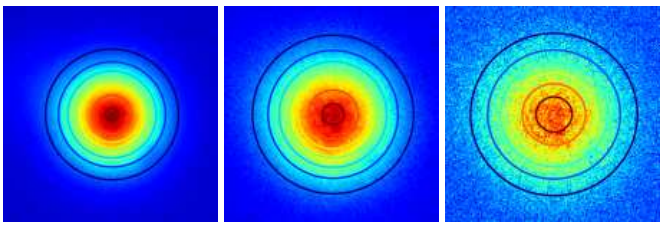

FIG. 18.5 – Spatially resolved intensity distributions behind a sample showing Anderson localization as a function of time after 2 ns, 4 ns, and 6 ns. The diffusive spread of the photons corresponding to the width can be seen to slow down, associated with a transition to localization.

18.3 Localization of light

The fact that multiply scattered waves can show a breakdown of diffusion is known as Anderson localization and has been theoretically predicted a long time ago [1]. Due to the fractal dimension of Brownian motion being two, this localization always appears in low dimensional systems. However in three dimensions, there is a transition to localization only with increasing disorder, when the mean free paths becomes comparable to the wavelength [2]. Due to the extreme nature of the necessary disorder, this transition has been very difficult to observe and many claims have been shown to be due to other effects, such as absorption [3, 4].

Using time resolved transmission experiments, we have been able to clarify the effects of absorption and find evidence for Anderson localization in three dimensional samples [5, 6]. However, the most direct determination of localization, which is completely independent of absorption is in the determination of transmission with both temporal and spatial resolution, such that the spread of the diffusive photon cloud and the stop of this spread can be observed directly, which has been predicted theoretically [7]. We have carried out such experiments (see Fig. 18.5 [8]) in sample previously found to show long time tails in time of flight measurements [5], where we have found an unambiguous saturation of the width, see Fig. 18.6. In order to quantify the properties of the localized modes more accurately, the intensity distribution of these modes needs to be determined, which is predicted to be highly skewed [9]. To do this, we use the non-linear optical properties of TiO_2 [10] to obtain a readout for the intensity distribution inside the sample. Thus we measure the amount of frequency shift in the transmitted light using band pass filters behind the sample, centered at different wave-lengths [11]. This is shown in Fig. 18.6 for a localizing sample. As can be seen, there are non-linear effects, which are important at long times, where there are localized modes, however the non-linearities are sufficiently weak to be treated perturbatively. This also means that these investigations open up a way to experimentally

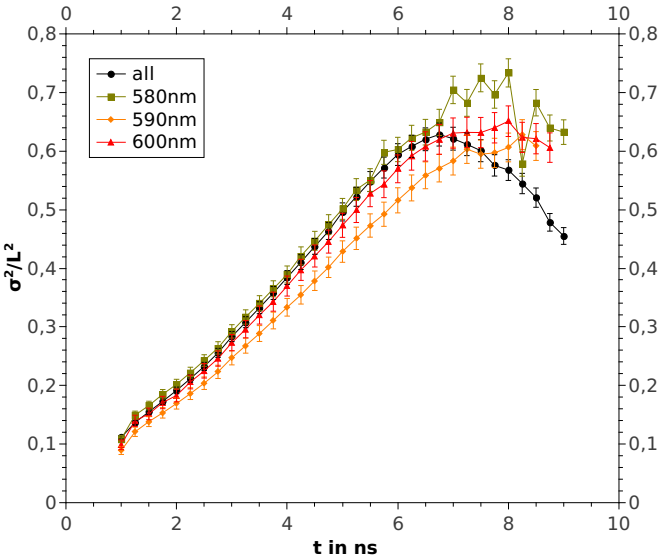

FIG. 18.6 – Time dependence of the width of the photon distribution spectrally resolved for the same sample. Due to the non-linear optical properties of TiO_2, part of the transmitted light exhibits shifts in frequency. This light can be used to study the interplay of non-linear effects with Anderson localization. The fact that both the frequency shifted light as well as the elastically scattered part show a saturation of the profile width demonstrated that the non-linear effects are sufficiently weak to be treated perturbatively.

study the interplay between non-linear effects and Anderson localization, which has so far been possible only in theoretical investigations [12].

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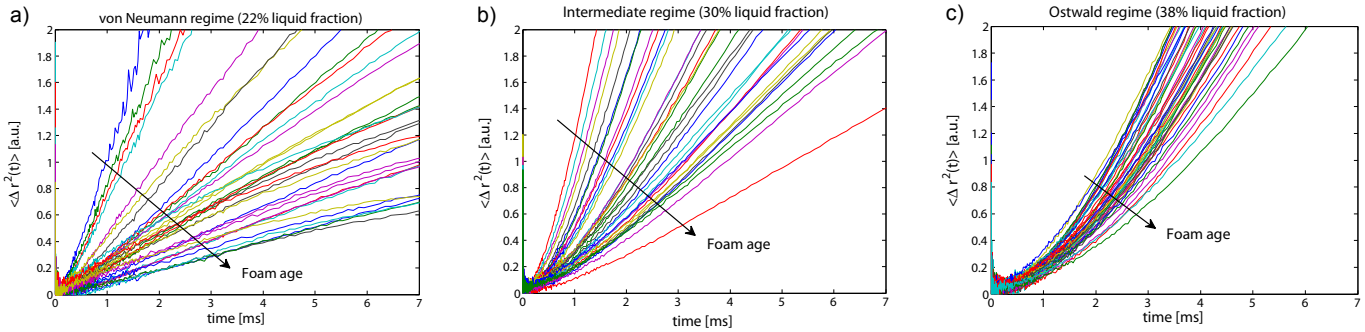

FIG. 18.7 – The mean square displacement of scatterers in the foam is shown as a function of correlation time for three different liquid fractions (a: 22 %, b: 30 % and c: 38%). This shows the local dynamics of bubbles, which can be seen to be diffusive ($\langle \Delta r^2 \rangle \propto t$) in the von Neumann regime and ballistic ($\langle \Delta r^2 \rangle \propto t^2$) in the Ostwald regime.

18.4 Dynamics of levitated foams

Using diamagnetic levitation [1–3], we have studied the coarsening behavior of foams of different liquid fractions [4]. While this has been studied theoretically for a long time yielding different predictions for dry foams by von Neumann [5] and wet foams by Ostwald [6], an experimental investigation has proven difficult due to the drainage of liquid due to gravity. Finding different coarsening dynamics at different liquid fractions according to the predictions [4], we have now studied the microscopic dynamics in the different regimes. Using diffusing wave spectroscopy [7, 8], i.e. the correlation of speckles in multiply scattered light transmitted through the foam, we determine the mean square fluctuations of the foam bubbles for varying liquid fraction. As can be seen in Fig. 18.7 [4], at low liquid fraction, where the bubbles overlap strongly and are deformed, the dynamics is diffusive and the corresponding size increases with foam age, as is expected from the coarsening of the foam. At high liquid fractions, where bubbles are separated and spherical, the dynamics is ballistic and influenced by residual flows in the liquid of the foam. This dynamics also does not change with the age of the foam and thus is not influenced by the coarsening process. At intermediate liquid fractions, the dynamics is more complicated and shows a crossover between diffusive and ballistic dynamics. Similarly, the coarsening process is not homogeneous in time, but is described by van Neumanns law at long times, when the larger bubbles start to overlap and by Ostwald ripening at short times.

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