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# *In situ* search for 3D Anderson localization of ultrasound in resonant emulsions

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**Abstract**—“After more than a half century of Anderson localization, the subject is more alive than ever” [1]. In acoustics, the first observation of sound localization in three dimensions has been reported in a random elastic network of aluminum beads, a so-called “mesoglass” [2]. Here, we propose to investigate this complex wave phenomenon by studying ultrasonic wave transport through *in situ* experiments performed within an all-fluid system of disordered resonant scatterers, so-called “resonant emulsions”.

## I. INTRODUCTION

In scattering media, the coherent part of waves loses its energy after one scattering mean free path, but, in the absence of dissipation, this energy remains in the system and is scattered in all directions. The energy associated with the resulting incoherent field normally follows, on average, a diffusion process (like heat). For strongly scattering media, the mean free path can be smaller than the wavelength and the wave energy may remain confined in the vicinity of the source, leading to Anderson localization [3]. The search for the experimental observation of this complex wave phenomenon is still challenging in three-dimensional (3D) disordered samples, especially for light [4]. On the other hand, Anderson localization has been unambiguously demonstrated for ultrasound in 3D elastic networks [2]. Here, we propose to investigate Anderson localization within systems composed of resonant liquid droplets randomly dispersed into a fluid-like matrix. These “resonant emulsions” present some advantages since they have extremely low absorption for ultrasound, which can be a crucial point for an unambiguous interpretation of Anderson localization experiments [4], [5]. In addition, their all-fluid structure allows for an *in situ* investigation of the acoustic field at any position inside the sample.

In this paper, we first briefly describe the fabrication of our resonant emulsions and the acoustical setup that we have used to study ultrasonic wave transport in these strongly scattering media. Then, we report experimental and theoretical results on both diffusive and sub-diffusive regimes depending on the droplet volume fraction.

## II. EXPERIMENTAL SECTION

### A. Emulsion fabrication

The two constitutive fluid phases of our model system of disordered resonant scatterers, namely resonant emulsions,

were chosen for their acoustic properties. Indeed, the fluorinated oil which is the constituent of the liquid droplets has a low sound speed ( $c_1 = 0.64$  mm/ $\mu$ s) compared to the suspending water-based gel-matrix ( $c_0 = 1.49$  mm/ $\mu$ s). Such a large sound-speed contrast between the scatterers and the surrounding medium induces very sharp acoustic Mie resonances [6] associated with large values of the amplitude attenuation coefficient  $\alpha$ . As a result, the scattering mean free path  $l$  ( $=1/2\alpha$ ) may become smaller than the incident wavelength, suggesting that this system may be suitable for the observation of Anderson localization. In addition, the intrinsic absorption in both fluorinated oil and water-based gel is quite negligible in the MHz range. The injection of the fluorinated-oil droplets within the water-based gel-matrix was achieved thanks to robotics, allowing a precise control of the resonant emulsion properties such as the volume fraction  $\Phi$  and the mean radius  $a$  of the droplets, as well as the particle size polydispersity [7].

### B. Acoustical setup

The synthesized resonant emulsion was then confined in a cylindrical PVC cell, closed at the bottom by a very thin plastic sheet (20  $\mu$ m thick), in order to obtain a slab with a thickness  $L$  of 12 mm and a radius  $R$  of 45 mm. A point source was incident at the bottom of the slab by using a 2.25 MHz focused ultrasound transducer that generated a 15-cycle Gaussian pulse centered at 2.25 MHz ( $ka \sim 0.6$  with  $k$  the wavevector). Then, we introduced a tiny needle hydrophone (diameter  $\varnothing \sim \lambda$ ) from the top of the sample to measure the acoustic field within the resonant emulsion. This hydrophone was small enough to ensure adequate spatial resolution of the acoustic phase of the multiply scattered acoustic waves (which is essential to measure the scattered field accurately). The hydrophone was mounted on motorized linear stages to record the acoustic field at any desired location within the sample in a transverse plane (at depth  $z$ ), enabling the intensity profile  $I(\rho, t)$  to be measured as a function of time  $t$  and polar coordinate  $\rho$ .

### C. Transverse confinement measurements

As in previous work on localization of ultrasound [2], we performed transverse confinement measurements within

our resonant emulsions. The key idea consists in measuring the transmitted intensity  $I(\rho, t)$  to probe the transverse growth of the intensity profile. In the diffusive regime, the ratio off-axis/on-axis of the intensity can be described by a Gaussian function with a time-dependent mean square width  $\sigma^2(t)$  ( $= -\rho^2 / \ln[I(\rho, t)/I(0, t)]$ ). Such measurements of the transverse width provide a unique method for measuring the diffusion coefficient  $D$  independent of boundary conditions and absorption [8].

### III. PRELIMINARY RESULTS

#### A. Diffusive regime

First, we consider a *dilute* resonant emulsion ( $\Phi = 3\%$ ). From intensity profile measurements, the extracted mean square width  $\sigma^2(t)$  exhibits a *linear* time dependence (figure 1) as expected for the diffusive regime. The diffusion coefficient  $D$  ( $= \sigma^2(t)/4t$ ) can be deduced from these experimental measurements and was found to be equal to  $1.05 \text{ mm}^2/\mu\text{s}$ .

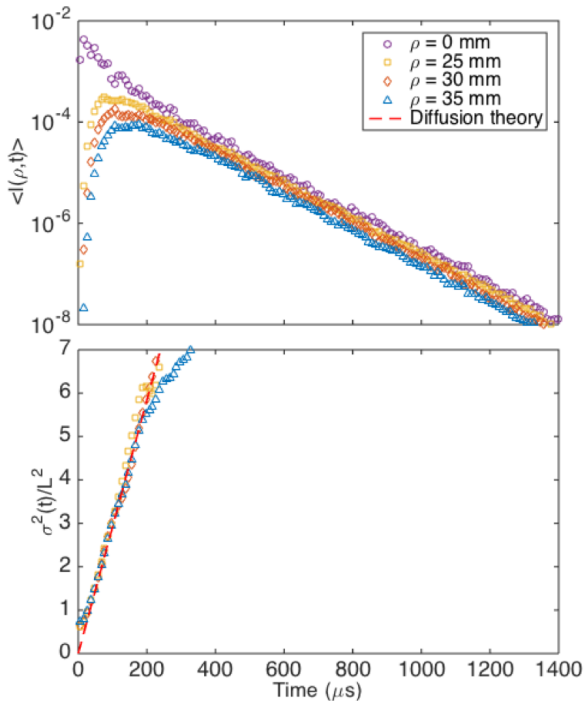


Fig. 1. Transverse confinement measurements in a dilute resonant emulsion ( $\Phi = 3\%$ ). On the top: experimental averaged time-dependent intensity for different radial distances  $\rho$  from the center of the sample  $\rho = 0$ . On the bottom: experimental  $\sigma^2(t)$ , normalized by the sample thickness  $L$ , for different  $\rho$ . The dashed red line represents a fit with diffusion theory providing  $D = 1.05 \text{ mm}^2/\mu\text{s}$ .

#### B. Sub-diffusive regime

For a *concentrated* resonant emulsion ( $\Phi = 30\%$ ), the mean square width  $\sigma^2(t)$  exhibits a *non-linear* time dependence (figure 2). Such a deviation from the diffusive regime indicates a slowdown of the diffusion process that can be viewed as a re-normalisation of the diffusion coefficient  $D$ . The diffusion process is not completely stopped at long times since no

saturation of the mean square width is observed (figure 2). This behavior suggests that the transport is sub-diffusive. Note that at the longest times that were experimentally accessible, the mean square width has become quite large compared with the thickness squared,  $\sigma^2/L^2 \sim 6$ , whereas at the mobility edge that separates extended from localized behavior, one would expect  $\sigma^2/L^2 \sim 1$  [9]. Thus, the observation that  $\sigma^2/L^2 \sim 6$  at long times is consistent with sub-diffusive behavior for which  $\sigma$  will continue to grow without leveling off at even longer times. This result appears to be different to the results reported for Anderson localized ultrasound in “3D mesoglasses” [2], where at all times it was found that  $\sigma^2 < L^2$ , with  $\sigma$  approaching a constant value at the longest times investigated experimentally.

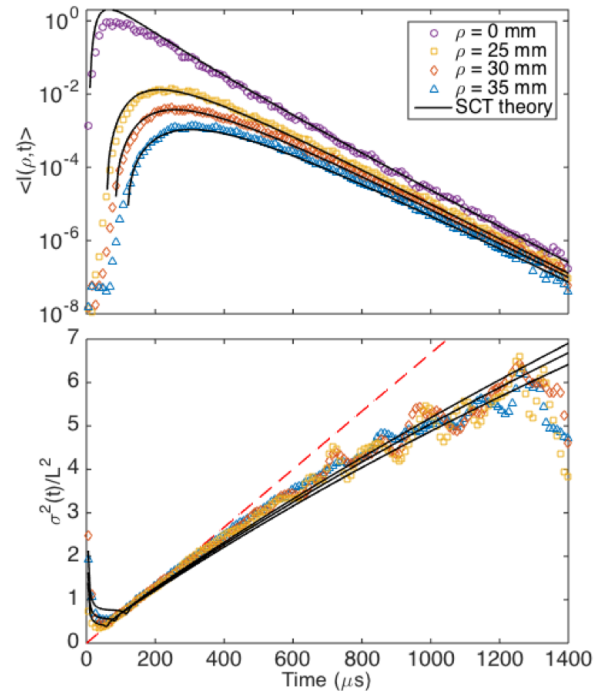


Fig. 2. Transverse confinement measurements in a concentrated resonant emulsion ( $\Phi = 30\%$ ). On the top: experimental averaged time-dependent intensity for different radial distances  $\rho$  from the center of the sample  $\rho = 0$ . On the bottom: experimental  $\sigma^2(t)$ , normalized by the sample thickness, for different  $\rho$ . The black solid lines correspond to self-consistent theory predictions. The red dashed line is an example of diffusive behavior obtained with  $D = 0.24 \text{ mm}^2/\mu\text{s}$ .

In order to assess more quantitatively the behavior seen in these preliminary experimental results, we performed some calculations in the framework of the self-consistent theory (SCT) of localization [9], [10]. Using this model, we tried to fit our experimental results, with the resulting fitted curves being shown by black solid lines in figure 2. This provided convincing results for the averaged temporal intensities  $\langle I(\rho, t) \rangle$ , but slight deviations are observed for the time-dependence of the mean square widths  $\sigma^2(t)$ . For these fitted curves, the correlation length  $\xi = L/25$ , which corresponds to a value of  $kl$  equal to 1.13 times the critical value that would be reached at the Anderson transition. Here  $k$  is the wavevector.

Thus, SCT predicts sub-diffusive behavior for our sample, with parameters indicating that the behaviour is fairly close to the Anderson transition. Note that the slowing down of the diffusive process exhibited by the experimental mean square widths seems to be somewhat more pronounced than the theoretical predictions, suggesting that the data may in fact be closer to the transition than indicated by these parameters. Additional calculations with other input parameters for the model should provide better agreement with the experimental data and allow the proximity to the Anderson localization transition to be determined more precisely.

Since the scattering mean free path  $l$  ( $\sim 0.23$  mm) is significantly smaller than the wavelength  $\lambda$  ( $\sim 0.66$  mm), it is reasonable to expect that interference effects, which can eventually lead to Anderson localization, will play an important role in modifying the transport in this sample, consistent with the observation of sub-diffusive behavior seen in this experiment.

#### IV. CONCLUSIONS

The all-fluid model system of disordered resonant scatterers presented here has many advantages for the study of ultrasonic wave transport through strongly scattering media. First, the fabrication process that we used (robotics) is simple and efficient for producing calibrated resonant emulsions. Second, our two-fluid-phase material (fluorinated oil and water-based gel) is almost non-absorbent for ultrasound in the MHz range. Our transverse confinement measurements have evidenced two ultrasonic wave transport regimes revealing diffusive and sub-diffusive behaviors. Our preliminary calculations performed in the framework of the self-consistent theory fit quite well with the experimental data. Additional experiments, e.g., in more concentrated resonant emulsions, as well as further calculations, will be conducted to investigate more completely the nature of wave transport in this system and continue the search for potential Anderson localization effects.

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