

Mesoscopic wave physics in fish shoals

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Ultrasound scattered by a dense shoal of fish undergoes mesoscopic interference, as is typical of low-temperature electrical transport in metals or light scattering in colloidal suspensions. Through large-scale measurements in open sea, we show a set of striking deviations from classical wave diffusion making fish shoals good candidates to study mesoscopic wave phenomena. The very good agreement with theories enlightens the role of fish structure on such a strong scattering regime that features slow energy transport and brings acoustic waves close to the Anderson localization transition.

Since the late 1980's, physicists have achieved great progress in the fabrication of strongly disordered materials that would allow for Anderson localization of 'classical' waves (e.g., light, microwaves, sound) in three dimensions¹⁻³. Anderson localization is a halt of propagation due to disorder^{4,5}. Although very few experiments have succeeded⁶⁻⁸, these studies have revealed the 'mesoscopic' interference phenomena^{9,10} that are analogous to that of low-temperature electrical transport^{10,11} (for instance weak localization^{12,13}, strong fluctuations and long-range correlations of scattered intensity^{14,15}). Such a set of mesoscopic phenomena have never been observed apart from laboratory experiments, and even less with living matter, as they require carefully designed disordered samples. In acoustics, three-dimensional mesoscopic phenomena have been observed exclusively in so-called 'mesoglasses'^{6-8,14}. Many studies have considered coated particles suspended in a host matrix in both optics and acoustics^{16,17} because of their interesting scattering properties. However arduous synthesis and weak stability make those particles rarely employed. Can natural complex media be inspiring for the design of such model systems? Do they scatter waves strongly enough to observe non diffusive wave transport?

Here, we show that shoals of fish trapped in large cages—an example of live, active matter—allow the examination of various mesoscopic interference phenomena in ultrasound scattering for fish densities that are comparable to those encountered in natural fish schools at sea. Fish swim bladder (an organ which allows fish to control their buoyancy) is analogous to an air bubble with radius about 5 mm and thus strongly scatters ultrasonic waves. This strong scattering has been useful for several decades for fish counting with ultrasounds in the single scattering regime (which is valid for low fish density)¹⁸. The present study focuses on dense shoals in which single scattering assumption is irrelevant. Comparison with multiple scattering theories reveals the impact of the complex fish structure that can be seen as a coated air scatterers (and not as a simple air bubble anymore). For different fish densities, the scattering strength of fish shoals is demonstrated *via* the measure-

ments of long-range correlations or non-Rayleigh distribution of the intensity speckle, as well as *via* the dynamic coherent backscattering effect, revealing the lowest energy velocity observed in underwater acoustics. Indeed, although dramatically low values of phase velocity have been observed with ultrasound in porous media¹⁹, we here consider the average *local* velocity of energy transport in the diffusion process²⁰. Because of their quasi-random movement, fish are also interesting for configurational averaging where spatial ergodicity (the averaging over probed positions) is usually assumed for laboratory experiments.

To ensure fish shoal control and to prevent avoidance reactions of the fish at sea²¹, we perform acoustic measurements in large ($\sim 5 \text{ m} \times 5 \text{ m} \times 5 \text{ m}$) open-sea fish cages that are typical of fish farms (Fig. 1a, b). A cage typically contains several tens of thousands of fish at a mean density of 10–100 fish per m^3 . The fish fry are raised in in-shore tanks and transferred to the open-sea cages when their weight is about 5 g. The feeding procedures are controlled to obtain a calibrated fish size. The individual fish mass ranges from 10 g for fish larvae up to 1 kg for mature fish. The corresponding fish volume fraction ϕ ranges from 1% to 10%. Much higher ϕ , up to 30%, can be reached with fish farms that practice intensive fish farming.

Unlike ultrasonic probe usually employed for aquaculture purpose (piston like transducers), the device used here²² is a reversible mills-cross multi-beam antenna capable of volume scanning. This characteristic is indeed essential for spatial or angular-resolved measurements of the wavefield detailed in this study. We measure the reflection of short acoustic pulses ($\sim 0.1 \text{ ms}$) that are emitted by a cross-shaped antenna of 2×64 acoustic transducers (based on Seapix technological brick, iXblue La Ciotat), as shown in Fig. 1a, at a central frequency of $f = 150 \text{ kHz}$ (see Supplemental Material for details of the experimental setup and the description of data processing and fitting). This is far from the swim-bladder resonance. For all of the measurements, the duration of the emitted pulse is about 0.1 ms and the backscattered waves are recorded over 25 ms immediately after emission. After each acquisition cycle, the system remains inactive for 10 ms to ensure that no residual acoustic signal is detected at the beginning of the next cycle. The natural fish motion at a speed of the order of 5 cm/s is sufficiently slow to ensure that the fish can be considered as immobile during a single shot. At the

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FIG. 1. (a, b) Photographs taken underwater (a) and at the surface (b) of an open-sea cage used in our experiments (*courtesy of S. Pasta*). (c) Intensity (dashed line) and mean intensity (symbols) of the backscattered acoustic signal after emission of a short pulse. Solid line, diffusion theory fit.

same time, the fish motion produces independent fish configurations over time, effectively providing us with a huge number of statistically independent measurements that correspond to different configurations of the fish in the cage. Averaging is performed over 2,000 to 20,000 acquisitions (roughly 10-min-long acquisitions), to ensure that many different independent spatial configurations of the fish in the cages are probed. For a single incident pulse, the backscattered acoustic pressure field $\psi(\mathbf{r}, t)$ and the intensity $I(\mathbf{r}, t) = |\psi(\mathbf{r}, t)|^2$ measured by a transducer at a position \mathbf{r} fluctuate widely (see Fig. 1c, dashed line, for typical experimental data), whereas the mean over many shots (and hence many different fish configurations) and over all of the transducers yields a smooth *coda*, as shown by the symbols in Fig. 1c. This is a direct signature of the multiple scattering, and it can be understood by viewing wave transport as a random walk with a velocity v , a step length ℓ (the scattering length, or mean free path), and an isotropization distance $\ell^* \geq \ell$ (the transport mean free path). For propagation distances greater than ℓ^* , the ensemble mean intensity $\langle |\psi(\mathbf{r}, t)|^2 \rangle$ obeys a diffusion equation with diffusivity¹⁰ $D = v\ell^*/3$. This equation provides an excellent description of $\langle I(\mathbf{r}, t) \rangle$ in Fig. 1c (solid line). This diffuse behavior of $\langle I(\mathbf{r}, t) \rangle$ is accompanied by circular Gaussian statistics of $\psi(\mathbf{r}, t)$.

Mesoscopic effects manifest as deviations from the diffusion picture of propagation, due to interference of waves scattered along different paths inside the disordered fish aggregation^{10,11}. We first analyze the statistics of the time-integrated (stationary) wave field $\psi(\mathbf{r})$ and intensity $I(\mathbf{r}) = |\psi(\mathbf{r})|^2$. Correlation functions of the field and intensity fluctuations respectively, are expressed as:

$$C_\psi(\Delta r) = \langle \psi(\mathbf{r})\psi(\mathbf{r} + \Delta\mathbf{r})^* \rangle / \langle |\psi(\mathbf{r})|^2 \rangle \quad (1)$$

and

$$C_{\delta I}(\Delta r) = \langle \delta I(\mathbf{r})\delta I(\mathbf{r} + \Delta\mathbf{r}) \rangle / \langle I(\mathbf{r}) \rangle^2, \quad (2)$$

where $\delta I(\mathbf{r}) = I(\mathbf{r}) - \langle I(\mathbf{r}) \rangle$. Those correlation functions are shown in Fig. 2 for two representative shoals that feature weak (gray asterisks) and strong (red circles) scattering. Weak scattering occurs for the fish fry (i.e., sea bream with mean weight $W = 10$ g and shoal density $\eta \sim 6$ kg/m³), whereas strong scattering occurs for the dense shoal of adult sea bream ($W = 284$ g; $\eta \sim 23$ kg/m³). $C_\psi(\Delta r)$ is short-range for both shoals and can be reasonably well fitted according to theory that takes into account the finite size of our acoustic transducers (see supplementary text) and yields the scattering lengths $\ell \sim \lambda \simeq 1$ cm as the best-fit parameters. These small ℓ suggest that the Anderson localization of sound expected for $2\pi\ell/\lambda \lesssim 1$ (the Ioffe-Regel criterion)^{1,4,5} would be reachable in denser fish shoals. In contrast to $C_\psi(\Delta r)$, the intensity correlation function $C_{\delta I}(\Delta r)$ features a long-range component C_0 that does not vanish even for $\Delta r \gg \lambda, \ell$. In our notation,

C_0 incorporates contributions from wave interference in the bulk [denoted as C_2 and C_3 in the literature^{10,11}] as well as the near transducers (the genuine C_0 ²³) because our experiments do not allow these to be distinguished. $C_0 \simeq 0.4$ for the dense fish shoal indicates a breakdown of wave diffusion where $C_{\delta I}(\Delta r) = |C_\psi(\Delta r)|^2$ would be expected. This breakdown is also confirmed by an analysis of the intensity probability density function, as shown in the inset of Fig. 2a. Fitting of the data to theory¹¹ allows an effective dimensional conductance g to be attributed to each fish shoal. The variance of the intensity fluctuations is given by $\langle \delta I(\mathbf{r})^2 \rangle / \langle I(\mathbf{r}) \rangle^2 = 1 + 4/3g$ ¹¹. Thus, g is a measure of deviations of the scattered field $\psi(\mathbf{r})$ from the Gaussian statistics, which implies $\langle \delta I(\mathbf{r})^2 \rangle / \langle I(\mathbf{r}) \rangle^2 = 1$. The large $C_0 \simeq 0.4$ and small $g \simeq 2$ for the high-density fish shoal signal substantial deviations from the diffusion picture of wave propagation and confirm the proximity of the Anderson localization regime, for which $g < 1$ is expected²⁴.

Coherent backscattering (CBS) represents a mesoscopic effect *par excellence* that has been measured for light^{12,13}, ultrasound²⁵, matter²⁶ and seismic²⁷ waves. This is due to constructive interference of waves following time-reversed pairs of paths, and manifests as the doubling of the mean scattered intensity in a narrow angular range $\Delta\theta \sim \lambda/\ell^*$ around the back-scattering direction²⁸. Examples of our stationary CBS measurements are shown in Fig. 3a, for two cages that contain either adult sea bream at a low density ($W = 320$ g; $\eta \sim 15$ kg/m³) or a dense shoal of croaker fish ($W = 886$ g; $\eta \sim 24$ kg/m³). The theoretical fits to the data provide the best-fit values of $\ell^* = 1.7$ cm and $\ell^* = 0.7$ cm for the lower and higher fish densities, respectively. These small values of ℓ^* support our conclusion on the strong multiple scattering of ultrasound in the considered fish shoals.

The diffusivity D can be estimated from the *dynamic* CBS profile, as shown in Fig. 3b. The CBS cone width $\Delta\theta(t)$ follows the theoretical behavior $\Delta\theta^{-2} \propto Dt$ expected for wave diffusion^{10,25} up to $t \simeq 5$ ms (Fig. 3c). The linear growth of $\Delta\theta^{-2}$ with time slows at longer times, again indicating strong mesoscopic interference effects and the closeness to the Anderson localization transition⁷.

Combining D estimated above with ℓ^* from the static CBS, we obtain a surprisingly low energy transport velocity $v = 3D/\ell^* \simeq 35$ m/s. This value is much lower than the speed of sound in either water ($v_0 \simeq 1500$ m/s) or air (340 m/s)—the two values that might serve as a reference for scattering by an air-filled swim bladder in (possibly) bubbly water. While it has been demonstrated that resonant scattering can slow down diffusive wave transport^{20,29,30}, narrow-band resonance effects are not clear here since low v values are obtained for any fish size. The only possibility to explain this is to consider the solid multi-layer structure of a fish (see supplementary text) and, in particular, to invoke the slow speed $v_s \sim 10$ m/s of the shear waves in the fish flesh. By assuming

FIG. 2. Spatial correlations (Eqs. 1 and 2) of field ψ (a) and intensity fluctuations δI (b) for weakly (gray asterisks) and strongly (red circles) scattering fish shoals. The lines show the theoretical fits to the data. While $C_\psi(\Delta r)$ rapidly decays to zero for both shoals, $C_{\delta I}(\Delta r)$ is long-lasting and remains appreciable even for $\Delta r = 5\lambda$, especially for the stronger-scattering shoal. The colored area in (b) represents the noise level. (a) inset: the probability density of the normalized intensity $I/\langle I \rangle$ (symbols) that deviates from the Rayleigh law $P(I) = \exp(-I/\langle I \rangle)/\langle I \rangle$ expected for weak scattering (dashed line). Solid lines are theoretical fits¹¹ with the dimensionless conductance g as a free-fit parameter.

FIG. 3. (a) Stationary coherent backscattering (CBS) profiles for weakly (gray asterisks) and strongly (red circles) scattering fish shoals. The lines are the theoretical fits. (b) Dynamic CBS profile for the strongly scattering shoal. (c) Time evolution of the cone width $\Delta\theta(t)$ of the dynamic CBS peaks. The linear increase in $\Delta\theta^{-2}$ that is expected from diffusion theory is shown by the dashed lines.

equipartition of energy between longitudinal and shear waves in fish³¹, we consider that the wave speed is v_s in the fish body and v_0 in between two fish. Then, averaging this along a path that traverses the fish shoal yields:

$$v = \frac{1 + \phi^{1/3}/(1 - \phi)^{1/3}}{1/v_0 + \phi^{1/3}/(1 - \phi)^{1/3}/v_s}. \quad (3)$$

From Eq.3(3), we obtain $v \simeq 30$ m/s for the fish volume fraction $\phi \simeq 10\%$, which is in agreement with independent measurements provided by the sea-farm manager. We emphasize that this dramatic slowing down of the ultrasound is not related to the scattering resonances of the fish, and thus cannot be explained by known, resonant mechanisms^{20,32}.

From an applied standpoint for aquaculture, determination of v via dynamic CBS measurements allows the estimation of the shoal density through the fish volume fraction ϕ . Similarly, measurements of $C_\psi(\Delta r)$ and the stationary CBS yield ℓ and ℓ^* , which are related to the scattering and transport cross-sections σ and σ^* of an individual fish, from which a mean fish length can be estimated. The knowledge of both the mean fish length and the fish shoal density opens new perspectives for noninvasive biomass estimation of dense fish shoals.

In conclusion, ultrasound scattering in fish shoals under conditions close to those encountered in nature show such mesoscopic wave phenomena as long-range correlations of scattered wave intensity, CBS, and the slowing down of the diffusion. These phenomena indicate that transition to the Anderson localization might be within reach in experiments with denser fish shoals. The extremely slow energy transport velocity emphasizes the importance of the fish solid structure in the multiple scattering of ultrasound—a phenomenon that has been overlooked up to now. Furthermore, the alliance of mesoscopic wave physics and fisheries acoustics has the potential of being used for monitoring fish biomass, which at present is restricted to the single scattering regime. When transposed to the open sea, CBS measurements might also be applied to study strong fish density variations during day-night schooling transitions²¹.

SUPPLEMENTARY MATERIAL

See the supplementary material for details about experiments (fish farming and ultrasonic setup) and theories employed for data fitting. Additionally, a multi-layered model of

scatterer is suggested to explain slow wave energy transport in schools of fish.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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