QUANTUM GASES

At the edge of mobility

Laurent Sanchez-Palencia

A new experiment with ultracold quantum gases measures the mobility edge of the Anderson transition in a controlled disordered potential.

Nearly sixty years ago, Anderson has shown that a gas of quantum particles without mutual interactions in a disordered medium can remain localized in a finite region of space while its classical counterpart would diffuse away[1]. After some latence period, Anderson localization has attracted a huge attention and it has been observed in a variety of systems[2]. It is now understood that this effect results from the coherent interference of diffusion paths in the disordered medium. In three dimensions (more precisely in dimension $d>2$), it is characterized by a phase transition between a localized regime at small energy and a diffusive regime at high energy[3]. While this universal behavior is now well understood, the determination of the transition point, the so-called the mobility edge, remains a challenge. Owing to their high degree of control, ultracold atoms in disordered potentials are particularly promising for quantitative studies of Anderson localization[4,5,6], in particular of the critical regime, where no exact quantitative theory exists. Evidence of the Anderson localization of ultracold matterwaves in a three-dimensional optical speckle potential were reported recently[7,8]. Writing in *Nature Physics*, Semeghini *et al.*[9] now report the first measurement of the mobility edge.

Realizing the conditions to observe Anderson localization is not an easy task. One should first isolate the system to maintain the phase coherence on sufficiently long times, suppress the interactions, and find a precise probe of transport properties. In addition, quantitative measurements require a precise control of both the disorder and the initial state of the matterwave injected in the disorder. These requirements are met in ultracold quantum gases. These systems consist in atomic gas samples cooled down to temperatures of the order of the nanoKelvin and confined in optical traps far from the atomic resonance. It suppresses dissipative effects and allow coherence times of a few seconds. Interactions are almost cancelled by the use of Fano-Feshbach resonances induced by a controlled magnetic field. The disordered potential is an optical speckle field, which is realized by passing a laser beam through a ground-glass diffuser. The main advantages of speckles are that they are easily realized and their statistical properties are very well known from the basic laws of optics[10]. These features are now well mastered and have been used previously to show evidence of the Anderson transition in 3D7,8. It was, however, not possible in these experiments to measure the mobility edge mainly due to insufficient energy resolution. Semeghini *et al.*9 now go an important step further and control the energy distribution, which allows them to find precise values of the mobility edge.

The experiment follows the standard scheme of for observing localization of a matterwave[11] (see Fig.1) : An interacting quantum degenerate gas -here a Bose-Einstein condensate- of a tens of micrometer long is first created in a laser trap. One then switches on the disorder and switches off both trap and interactions a the initial time. The gas starts to freely expand in the disorder on hundreds of micrometers. In three dimensions, the expanding gas is made of two distinct components : those with energy $E<E$C, which localize, and those with energy $E>E$C, which diffuse away. The gas is finally imaged at different times, which allows to distinguish an immobile part (the localized component) and an expanding part (the diffusive component). Most importantly one can count the number of atoms in each component by simple analysis of intensity profile of the image, which is the comment of the density profile. In principle, the distinction of the two components permits to measure the mobility edge EC. It is the solution of the equation

$$N_{\mathrm{loc}}=\int_{-\infty}^{E_c} n(E) \quad , (1)$$

where *N*loc is the measured number of localized atoms and *n*(*E*) is the energy distribution of the exanding gas in the disorder. In order to realize this programme, two major issues must be overcome. On the one hand, one should determine *n*(*E*), which cannot be directly measured in the experiment. On the other hand, one should design *n*(*E*) with a sharp maximum around the mobility edge *E*C, in order to have sufficient precision.

Semeghini *et al.*9 proceed in two steps. The first step consists in switching on the disorder and switching off the trap as slowly as possible to minimize the kinetic energy transfered to the gas at the beginning of the expansion stage. The energy distribution is then determined from the measurement of the matterwave momentum distribution by standard time-of-flight imaging and from the numerical calculation of the spectral function, which gives the energy distribution of a wave with a given momentum. The second step consists in realizing a controlled coherent transfer of a portion $0<p<1$ of the population of the component of energy *E* to the energy $E+\hbar\omega$ by modulation of the disordered potential at a adjustable frequency $\omega/2\pi$. This process consists in changing the energy distribution into

$$\mathrm{n}'_{\omega}(E)=(1-p)n(E)+\mathrm{pn}(E-\hbar\,\omega) \quad , (2)$$

as shown in Fig.2. By varying the value of ω, Semeghini *et al.* were able to significantly populate energy states close to the mobility edge. It remains to determine the value of *E*C from equation (1) after replacing *n*(*E*) by *n'ω*(*E*) [see equation (2)]. The precision of the measurement was further improved by fitting the behavior of *n'ω* (*E*) as a function of w with E_C as the unique fitting parameter. The same measurement is then repeted for various values of the disorder strength.

These results constitute the first experimental measurement of the behavior of the mobility edge for a 3D matterwave versus the disordered potential strength. They usefully complete recent exact numerical calculations performed for similar systems[12,13]. Here, theory is largely incomplete. We are now able to calculate the mobility edge with good accuracy using various improvements of the self-consistent theory[14,15] but only for very weak disorder12. The measurement by Semeghini *et al.*9 provides values of the mobility edge in a regime of stronger disorder where present theory breaks down. It should stimulate further improvement of the theory.

A major challenge is now to observe the critical behavior and measure the critical exponent of the Anderson transition, which has been shown to be universal[16,17]. Presently, the method developed by Semeghini *et al.* is not sufficiently precise to determine the value of th exponent and new strategies should be developed. Two approaches have been proposed that are promising but challenging. The first approach consists in measuring the large-distance decay of the localized wavefunction, which can be directly related to the critical exponent[18]. It, however, requires to separate the localized and diffusive compenents, which is not easy due to very slow diffusion close to criticality. The second approach consists in using energy-selective radio-frequency field transfer from an atomic state insensitive to the disorder with a well determined energy to another state at the same energy in the disordered potential[19]. It, however, requires the transfer a significant number of atoms to have sufficient signal. In spite of these difficulties, the impressive progress realized in the last years on control of disordered matterwave make the critical regime with reach.

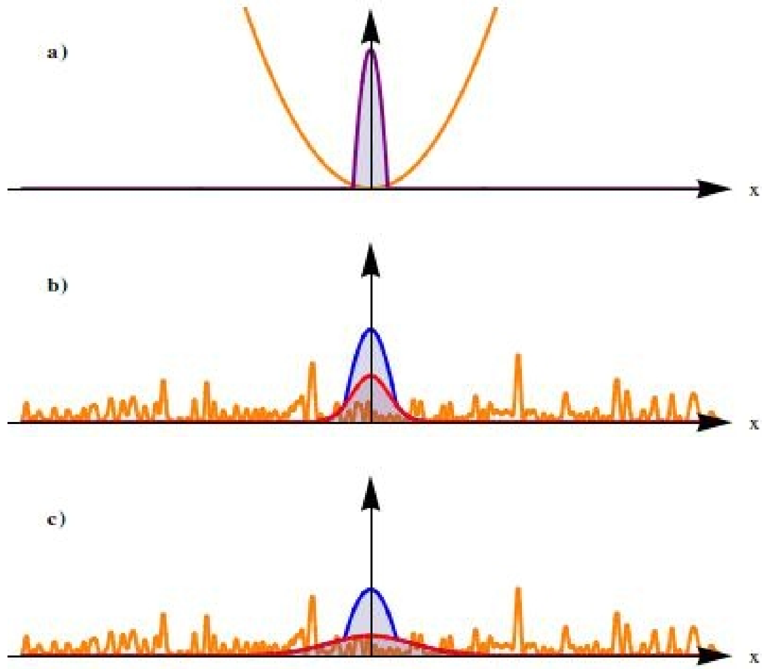
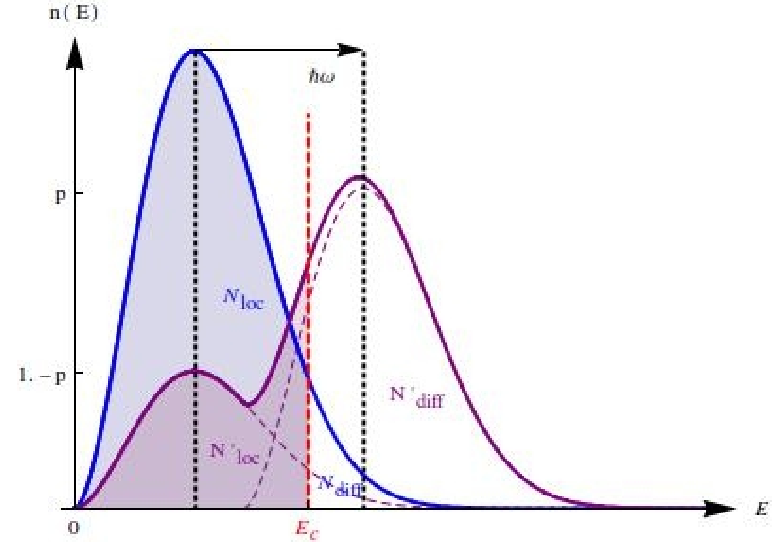


Figure 1 : Principle of the localization experiment for a matterwave. a. A quantum gas (purple) is first created in a trap (in orange). **b.-c.** Then, the trap and the interactomic interactions are switched off and the disordered potential (in orange) is switched on slowly. In the presence of the disorder, the gas is formed of a localized component (in blue) and a diffusive component (in red). When the gas expands in the disordered potential, the localized component stops after a short expansion while the diffusive component spreads unbounded.



Figuse 2 : Measurement of the mobility edge. After the loading of the gas in the disordered potential (see Fig. 1), the atoms are spread in many states with a certain energy distribution (in blue), containing the mobility edge E_C. Then, using a coherent transfer technique, the energies of a portion p of the atoms are increasing by a variable amount $\hbar\omega$ while those of the portion 1-p of the other atoms are unchanged, hence creating a new energy distribution (in purple). The numbers of localized, N_{loc}, and diffusive, N_{diff}, atoms are then changed to N'_{loc}, and diffusive, N'_{diff}, respectively. By studying the variations of N'_{loc} and N'_{diff} as a function of ω, one finds a precise of value of the mobility edge E_C using the numerically-calculated initial energy distribution.

Laurent Sanchez-Palencia is in Laboratoire Charles Fabry, CNRS, Institut d'Optique, and Univ. Paris-Saclay, F-91127, Palaiseau, France.
e-mail: lsp@institutoptique.fr

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