When Image Noise is your Friend

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Application Note

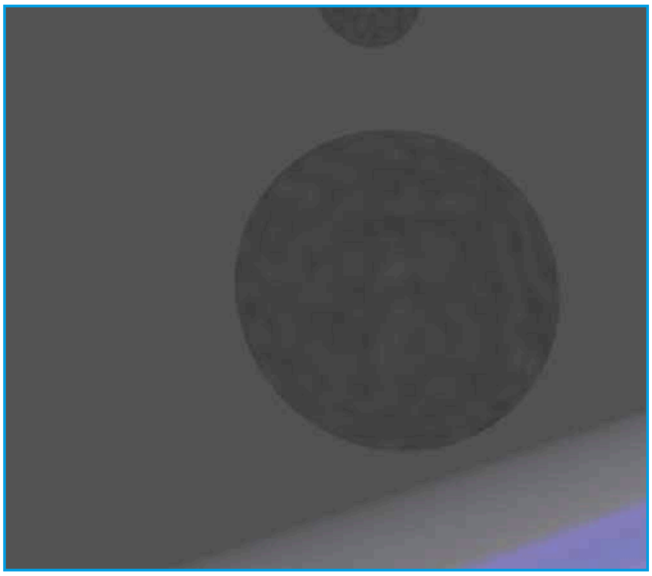

Figure 1: A cloud of atoms is released from a trap and expands while it is falling. When it is illuminated by a laser beam, the shadow cast by the cloud can be imaged by a CCD camera. In this way, each pair of pixels of the CCD serves as a pair of detectors for atoms within the beams of light (red and blue) that hit those specific pixels.

Ultracold atoms in optical lattices are a novel way to explore a diverse range of physical models in physics. Recently, one major focus of cold atom research is the implementation of condensed-matter like systems. To simulate effects which occur in materials with a crystalline structure, the atoms are subjected to a periodic potential created by optical standing waves. In this way, the atoms model electrons which move in the periodic potential created by the regular lattice of ions in the crystal – but on a 1000 fold larger scale. In such a lattice, the movement of the particles can then be strongly influenced by the interactions between the electrons, or, in our case, atoms.

The common way of making measurements on ultracold atom ensembles is to plainly photograph them with a CCD camera. For this, the atoms are released from the trap, and this cloud of up to one million atoms expands while falling. It is then illuminated form one side, and the shadow created is projected onto a CCD camera chip. In this way, the density distribution of the cloud is obtained in two dimensions. Since this distribution reflects how far the atoms have moved since they have been released from the very small trapping region, this reflects the velocity distribution of the particles prior to release.

In the strongly interacting regime, a specific feature of the velocity distribution is that it has none – its basic features are: The velocity distribution typically has a Gaussian shape like the one of a normal, thermal gas, and does not contain any visible information about the distribution of the atom inside the lattice.

Surprisingly, however, it can be shown that there is much more information in such images than just the overall shape – and that this information is contained in the noise. This noise consists of the fluctuations which show up when comparing several images taken under identical conditions. When other noise sources such as electronic readout noise or fluctuations in the imaging light due to interference are low enough, the shot noise which results from the low number of atoms per pixel of the camera can be the dominating source of noise in the absorption images. This regime can be reached with low noise Peltier-cooled EMCCD cameras such as the ANDOR iXon DV885-JCS-VP. Statistical correlations between the individual particles can then be identified as correlations in the shot noise pattern present.

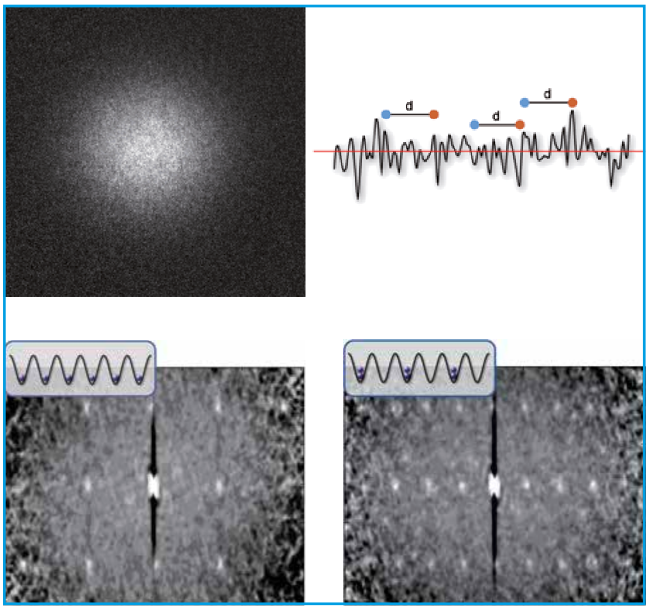

Figure 2: The images obtained when releasing atoms from a deep optical lattice always look the same: A featureless cloud with a Gaussian density distribution (a). By analyzing the density correlations between different points (red and blue in (b)) at a specific relative distance d, information about the cloud's structure in the trap can be obtained. This allows for distinguishing atom configurations where every site (c) or only every second site (d) is filled.

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The correlations between the individual particles dropping out of the trap originate from atom-atom correlations inside the trap. The analysis, which is conducted mathematically using many images taken under the same conditions, therefore effectively allows for the probing of in-trap correlation functions. For regular patterns of atoms such as those in an optical lattice, a regular pattern is obtained in the correlation function. Since many important complex many-body phases for atoms in optical lattices are characterized by patterns emerging in the lattice which differ from the simple lattice structure, this method can allow for probing of such phases in momentum space, where the averaged density distribution does not contain any information about the pattern. A so-called charge density wave, where the number of atoms on the lattice sites is modulated in a plane wave structure, would for example be characterized by the appearance of additional peaks in the momentum correlation function.

Since the noise correlation analysis method relies only on one very basic property of quantum mechanical particles – the fact that they are indistinguishable when in the same state – it can be applied to a broad array of situations. As a method of probing in-trap higher-order correlations between atoms it is therefore a powerful way probing complex ordered quantum states such as quantum magnets or spin waves, which are at the focus of current research.

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