Physicists investigate onset of effective mass

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(Phys.org) —Although mass may seem to be a fairly straightforward concept, from a physics perspective it can be much more complex than weighing an object and reading off a number in grams. For instance, an object's mass can be modified by putting it in a different medium.

The familiar type of mass, also called the "inertial mass" or "bare mass," is a fundamental property of an object that is determined by an object's resistance to acceleration when subject to a force, for example gravity.

When an object's mass is modified by putting it in a different medium, the modified mass is called the "effective mass." Effective mass is distinctly different than bare mass, as it is not a fundamental property of an object, but changes depending on the material it is in. For practical purposes, effective mass plays an important role in electrical conductivity and electronic devices.

"The effective mass description is incredibly powerful because it allows one to sweep away a lot of the complex physics, which describes the interactions between the electron and the medium, replacing it with an intuitive 'classical' description, while burying the details within a modified mass," physicist Rockson Chang, currently at the Institut d'Optique at the Université Paris-Sud, told *Phys.org*.

"Effective mass behavior is well established, both in fundamental science and modern electronic engineering," he said. "An example of the latter is in the use of the semiconductor gallium arsenide (GaAs). Electrons in GaAs turn out to have a very small effective mass, just

0.067 times that of the bare electron mass. This very small mass means that when the electrons are subjected to a potential difference, they move significantly faster than outside this medium, making them ideal for high-speed electronic devices. "

While working at the University of Toronto, Chang and his coauthors investigated what happens to effective mass when an external force is applied very abruptly. In the simplified theory of effective mass, which is often used in research, the assumption is that the forces are applied slowly. The researchers wanted to find out what happens when this assumption is not met.

To do this, the researchers used a Bose-Einstein condensate (BEC)—a large number of atoms cooled to near absolute zero temperature. These atoms were trapped in an artificial crystal made of light called an optical lattice. Although this system contains atoms rather than electrons, it exhibits many of the same fundamental properties as a semiconductor. However, because BECs exist on larger length and time scales, they have the advantage of being much more easily accessed experimentally than semiconductors. As the researchers explained, this idea of using one well-controlled quantum system to "simulate" the properties of another is called "quantum simulation."

After trapping the BEC in an optical lattice, the researchers abruptly (in about 20 µs) applied a force on the atoms with an external magnetic field. This force results in an oscillation of an atom's motion in the crystal, and from this motion the researchers were able to extract the particle's mass.

The researchers' most important finding was that the initial response of the atoms to this applied force is characterized not by the effective mass as expected, but by the bare mass. Shortly after this initial time period, the atoms response undergo rapid oscillations and the onset of effective mass occurs.

"For over 50 years, the observed effective mass behavior has been well described by theory," Chang said. "However, the popular and intuitive description is based on some fundamental assumptions, in particular that the external force is applied relatively slowly. In our work we probe what happens when this assumption is invalidated. Our work shows that if one were to apply a force sufficiently quickly, the effective mass description falls apart. Interestingly, the initial response of the particle is that of a particle with its bare mass—or in other words, the particle responds as if the medium wasn't there at all. Only over longer time does the medium have a chance to catch up, again modifying the behavior of the particle and gradually returning to the usual effective mass response."

To give a loose analogy, Chang explains that the onset of effective mass is somewhat like walking through a muddy field. Because of the mud, you tend to walk slower than you would otherwise. This is like having an effective mass larger than a bare mass. However, if you started off by running into the mud, you would at first move very quickly. At this point, effective mass is still low. But as you sink deeper and deeper into the mud, it becomes more and more difficult to maintain that speed, and you eventually slow down. Likewise, it takes some time for the effective mass behavior to arise when subjected to a force.

"It's not that our work is the first observation of the effective mass," Chang said. "Rather, our experiment demonstrates that the simple and intuitive picture of effective mass can actually break down, while revealing a conceptually very satisfying transition between two different behaviors, from a response in free space (described by the bare mass) to in a medium (described by an effective mass). Our work explores a new regime of dynamics, fast compared to the characteristic timescale of the material-particle interaction."

By showing how effective mass develops on short time scales, the results shed light on some of the most fundamental properties of solid state systems.

"This regime is increasingly of interest for researchers looking to continually push the speed of electronic devices," Chang said. "For example, there has been recent interest in using ultrafast laser pulses (femto-second and shorter) for fast electronic switches. Our results show that the speed and effectiveness of this switching may be affected since the effective mass description may no longer be valid."

More information: Rockson Chang, et al. "Observing the Onset of Effective Mass." *Physical Review Letters.* DOI: 10.1103/PhysRevLett.112.170404