Speeding particles in the sights of a laser

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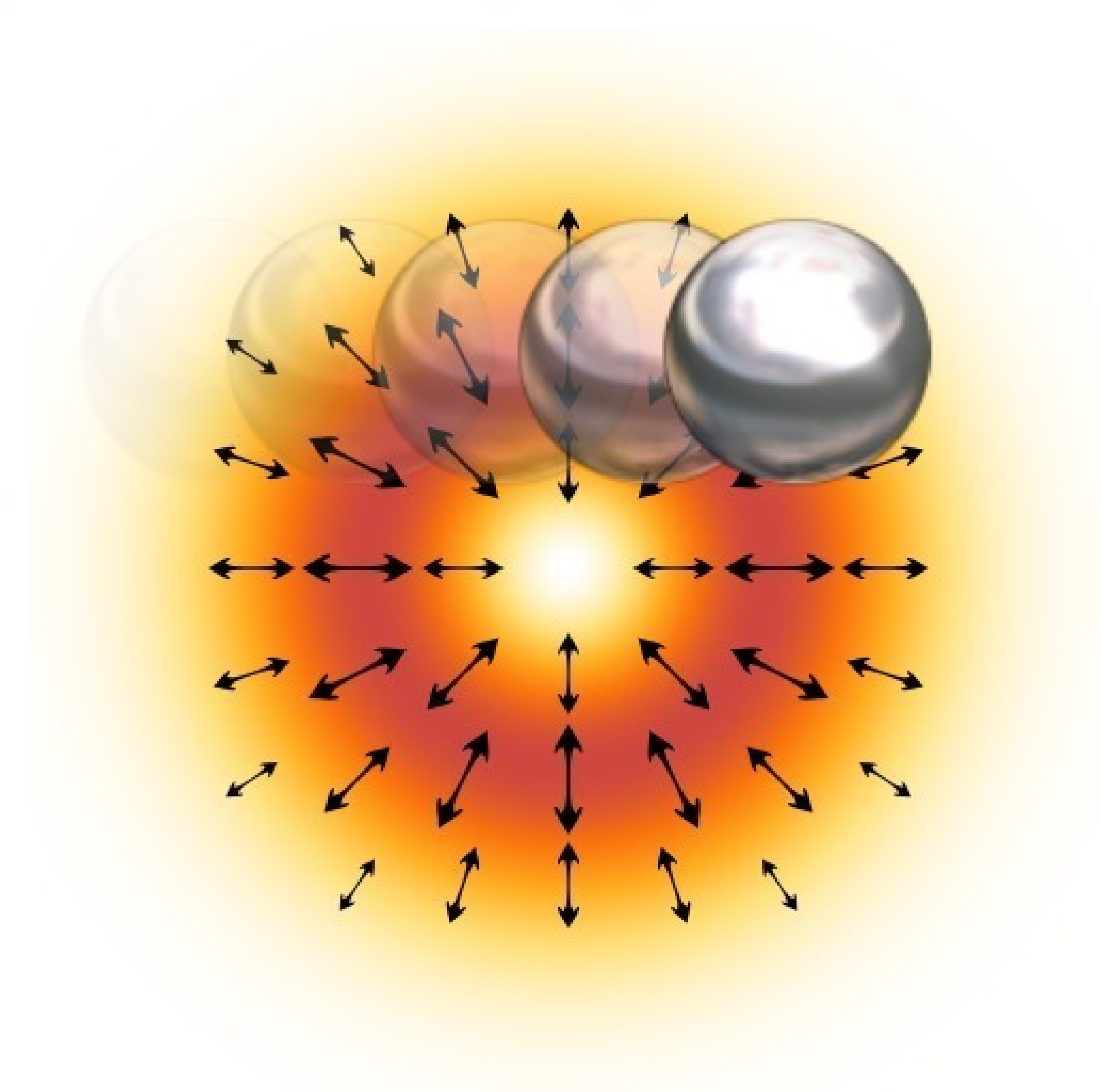

Tracked in flight: Physicists at the Max Planck Institute for the Science of Light track the path of a one-millimetre metal sphere that flies through a radially polarized laser beam in which the polarizations symbolized by arrows are arranged like the spokes of a wheel. In this kind of laser light, the polarization and information on the spatial structure of the beam are classically entangled. The position of the tiny sphere can therefore be determined by measuring the polarization. Credit: Optica 2015, MPI for the Science of Light

It might be easier to track tiny particles in the future – even when they hurtle along with the speed of a rifle bullet. This is thanks to researchers working with Christoph Marquardt and Gerd Leuchs at the Max Planck Institute for the Science of Light, who have discovered that these particles can be tracked with a radially polarized laser beam. In radially polarized light, the oscillation planes of the light waves arrange themselves like the spokes of a wheel. When the researchers cause a particle to fly through such a laser beam, they are able to determine its position several billion times per second by measuring the polarization of the beam. The physicists exploit the fact that the polarization of the laser beam and its spatial structure are classically entangled with each other. Up to now, the path of very fast objects, for example, can only be observed with expensive high-speed cameras. And these run for only a fraction of a second before they have to be restarted.

Entanglement is usually considered to be a prime example of the fantastic challenges which our imagination must master when dealing with quantum mechanics, the non-classical physics. The properties of two entangled particles influence each other without any time delay – and this takes place even over large distances. However, classical physics also has an analogue to quantum mechanical entanglement: "In a radially polarized light beam, the polarization is linked with the spatial distribution of the electromagnetic field," says Christoph Marquardt, who leads a Research Group in Gerd Leuchs' division at the Max Planck Institute for the Science of Light. "Surprisingly, the mathematical description of this relationship is similar to that of quantum mechanical entanglement."

But classical entanglement is not quite as spooky as the quantum mechanical version. Although the two properties of the radially polarized light beam are inseparably dependent on each other, they do not seem to show a mutual influence over large distances, which is what happens with quantum mechanical entanglement. In contrast, classical entanglement applies only within a light beam. It nevertheless has a practical use: the physicists in Christoph Marquardt's Group determine the position of a particle which races at right angles through a laser beam via the relationship between polarization and position. And since the polarization of a light beam can be measured more than a billion times per second, the Erlangen-based researchers can track the flight of even a very fast particle via the laser beam. "We can track objects moving at any terrestrial speed by measuring the polarization," says Christoph Marquardt.

Experiments prove how well the motion sensor works

What happens here can also be illustrated without having to resort to the mathematical equations of classical entanglement. A detailed look at radial polarization is sufficient: physicists like to represent polarized light waves by arrows. For a radially polarized light beam, the arrows are arranged around the centre of the beam like a garland. For every arrow which protrudes from the beam centre, there is another arrow precisely cancelling it out, i.e. all polarizations average out to zero.

If polarization directions are now shielded at one point, the corresponding arrows have no counterpart – a net polarization remains, and this will be different for each particle trajectory through the light beam. A laser beam can be used to unequivocally determine the trajectory only when the approximate size of the particle is known, however. This is because a small sphere which flies close to the centre of the beam leaves the same trace in the polarization as a larger sphere which passes the beam at a greater distance from the centre.

The researchers in Erlangen used experiments to prove how well their optical motion sensor works. They used a metal sphere one millimetre in diameter and recorded its trajectory through the laser beam with high temporal resolution, i.e. in a rapid succession of snapshots. Finally, they also tested how fast the sensor reacts to an object which appears in the beam. They did this by shooting a knife blade into the laser beam with a speed of 27 metres per second. The laser beam darkened within 92 nanoseconds - in 92 billionths of a second - which the physicists recorded in steps of fractions of a nanosecond.

Classically entangled laser beams could improve LIDAR technology

"In these tests, the new technology shows that it is superior in some respects to the methods currently used to track very fast objects," says Christoph Marquardt. Although high-speed cameras freeze objects which race through their field of vision in billions of images per second, they are not only very expensive, but also run for only fractions of a second. Also short pulses of light are already being used to record particle trajectories and even have a very high temporal resolution. This is done by varying the delay with which a laser pulse takes an image after a particle sets off in very small increments. It not only means it must be known when the particle is setting off; to record its complete trajectory, the process has to be repeated very often in exactly the same way.

The technology developed by the Erlangen-based physicists does not have these kinds of disadvantages. "We can therefore imagine several applications for our method primarily in research, not least because it is comparatively simple and low cost," says Stefan Berg-Johansen, who worked on the project. "And if we were to use additional or different types of laser beams, we can even track the motion of a particle in three dimensions." The to and fro of a particle that is held more or less tightly with a pair of optical tweezers can be tracked with radially polarized laser beams, for example, as can the path taken by a particle because of its thermal motion. And ultimately, today's LIDAR technology, which is already being used to measure distances and speeds in science and engineering, could be improved with classically entangled laser beams. A LIDAR measures distances and motions in the direction of the laser beam; the Erlangen method could provide a simple way of tracking the transverse motions as well.

More information: Stefan Berg-Johansen et al. Classically entangled optical beams for high-speed kinematic sensing, *Optica* (2015). DOI: 10.1364/OPTICA.2.000864

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