observed interferometrically. The signal delay of the same wavefront arriving at two stations forming a baseline is determined in a correlation process. In the particular experiments, four 1-GHz-wide frequency bands in the 6–13 GHz range were observed. Due to their limited sensitivity, the small node telescopes could not detect the weak signals of the radio sources. That's where the large hub telescope came in: by exploiting the triangle-closure in the three-station interferometric network, the delay observations between the two small radio telescopes could be derived in an indirect way. The authors call this innovative strategy "node-hub style observations". As common in VLBI, the receiving systems of all three telescopes were connected to hydrogen frequency standards (H-masers). For the node telescopes in Medicina and Koganei, these H-masers were linked via optical fibres and frequency combs to highly precise clocks located at the Italian and Japanese national time and frequency laboratories. Finally, the VLBI data post-processing analysis of the indirectly measured delay observations between the node stations allowed to derive the frequency ratio between the two optical clocks located at about 9000 km distance with an uncertainty that is superior to other techniques using global navigation satellite system observations.

The strategy put forward by Pizzocaro and colleagues paves the way for a routine and highly precise clock comparison on an intercontinental scale. But there is still room for improvement. Longer observation times (and thus longer averaging periods), dual polarization observations with the node stations, and an increased observation bandwidth could all lead to better performance. The latter two aspects will require developments of the next-generation VLBI system. Comparing clocks on global and intercontinental scales is important for time keeping and metrology as well as space geodesy. Usually, space geodesy today still works in a post-Newtonian framework employing Newtonian formulations and corresponding relativistic corrections. However, in the framework of general relativity, clocks measure local proper time of events in spacetime, a four-dimensional manifold. By comparing clocks located on different continents, the difference in gravity potential at these locations can be measured. These gravity potential differences are influenced by relativistic effects. Thus, this work opens the door for a potential further development of classical physical geodesy towards advanced relativistic geodesy[6].

In order to compare optical clocks worldwide, maintain timekeeping and perform advanced research in geodesy and astrometry, one could envisage the international network of national metrology institutes to collaborate with the International VLBI Service for Geodesy and Astrometry (IVS)[7]. Assuming that more such small radio telescopes and broadband VLBI receiving stations become available, these could then be placed at national metrology institutes all over the world and could be connected to the corresponding optical clocks as illustrated in Fig. 1. This would enable regular node–hub-style clock comparisons as described by Pizzocaro and colleagues in close cooperation with the VLBI global observing system stations in the IVS. The remaining main challenges in establishing the new technique are astrophysical effects that cause the quasars to appear extended instead of being point-like sources[8], as well as interference from artificial radio frequency sources[9] both on ground and in space. Ways to mitigate these disturbances have to be developed in order to further improve performance of the presented approach. ❐

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## Competing interests

The author declares no competing interests.



HELIUM DIMERS

# Gently stirred not shaken

Manipulating weakly bound helium dimers with ultrafast laser pulses reveals their quantum behaviour. This method opens a route towards studying the low-energy dynamics of other exotic and fragile quantum states.

Daniel Rolles

Her Majesty's most famous secret agent (whose latest movie, like everything else, has been delayed by the COVID-19 pandemic) will only accept his martini shaken, not stirred. But some physicists prefer to have their helium dimers gently swirled, not shaken — and the result affords them exquisite experimental control worthy of our movie superhero. Writing in *Nature Physics*, Maksim Kunitski and co-workers report that they have used short laser pulses to gently manipulate a fragile helium dimer, bound by only 150 neV (corresponding to a temperature of 1.7 mK), in such a way that allows them to control, observe and study its delicate quantum behaviour by wave packet interferometry[1].

The helium dimer, consisting of two helium atoms held together by only weak van der Waals forces, is quite a popular target for studying quantum effects in simple matter. Because of its shallow binding potential, which can only support a single vibrational and rotational state, the helium dimer has the longest bond length of all diatomic molecules in their ground state,

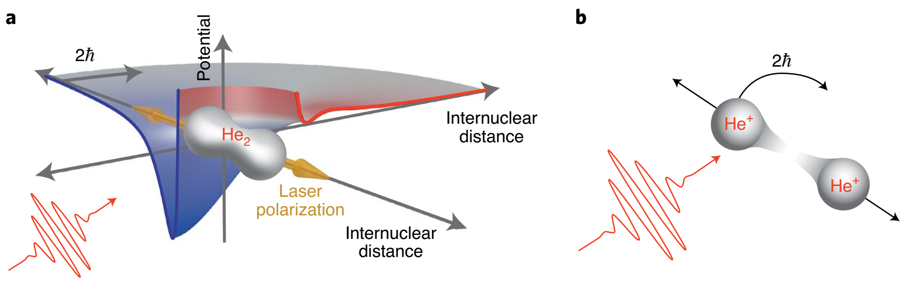


**Fig. 1 | Helium dimer manipulated and ionized by short laser pulses. a**, The potential of a weakly bound helium dimer is modified by a short laser pulse that dissociates the dimer and sets it into a swirling motion by imparting an angular momentum of $2\hbar$ on the dissociative wave packet (where $\hbar$ is the reduced Planck's constant). **b**, The time evolution of the quantum wave packet is probed via Coulomb explosion imaging using a second, more intense laser pulse that doubly ionizes the dimer and breaks it into two $He^+$ ions, whose momentum vectors are then detected in coincidence.

with a separation of 5,200 pm (or 52 Å) between the two atoms — 70 times larger than the bond length of a hydrogen molecule. The wave function of a helium dimer extends far beyond the bound range of the potential well and deep into the classically forbidden tunnelling region, creating a situation known as a 'quantum halo'[2]. Quantum halos are studied across many areas from nuclear physics to quantum optics and are characterized by an exponentially decreasing tunnelling wave function with non-zero probability density that reaches out to infinity. In the case of the helium dimer, 80% of the probability distribution resides in this quantum halo.

In their experiment, Kunitski and colleagues applied a short (310 fs) near-infrared laser pulse to an ensemble of helium dimers prepared as a cold molecular beam, dissociating the dimers without ionizing them. The laser pulse imparted an angular momentum onto the initially spatially confined dissociative wave packet, essentially setting each dissociating dimer in rotation (Fig. 1a). A second, more intense laser pulse was used to doubly ionize and 'Coulomb explode' the dissociating dimer. That is, two electrons were removed, causing the two resulting singly charged helium ions to rapidly accelerate because of the internal Coulomb repulsion, as illustrated in Fig. 1b.

The two ions were then detected in coincidence, meaning that by working at very low count rates and making use of the momentum conservation that governs such a half-collision process, the measurement was able to unambiguously identify ion pairs that resulted from the same dimer. Both the orientation of the internuclear axis and the internuclear separation at the time of arrival of the second laser pulse was retrieved from the ions' momentum vectors using a method called 'Coulomb explosion imaging'[3]. This method takes advantage of the fact that the kinetic energy of the detected ions is almost exclusively due to their Coulomb energy at the moment they were created, and thus proportional to the inverse of their internuclear distance at the moment the second laser pulse arrived.

The angular momentum transferred to the dimer by the first laser pulse resulted in a partial rotation alignment, determined by the angle between the internuclear axis and the polarization direction of the first laser pulse[4]. This alignment only affected the dissociating part of the wave function, leaving the rest to maintain its spherical symmetry. As a function of the time delay between two laser pulses, the experiment thus resulted in a movie of an 'alignment wave' that spread out to larger and larger distances, while the inner part returned to its initial spherical symmetry. Furthermore, the interference between the dissociative wave packet and the highly delocalized 'quantum halo' wave function of the helium dimer in its ground state were used to determine the phase and density of the dissociating wave packet, which, at large internuclear distances, describes the time evolution of a propagating (quasi-)free particle.

The study combines concepts of low-energy quantum physics and strong-field and ultrafast laser physics, and builds a bridge between these two traditionally separate areas of atomic, molecular and optical physics. In doing so, it provides a new tool to image and characterize ultrafast field-induced wave packet dynamics in weakly bound, low-energy, few-body quantum systems by wave packet interferometry and tomography, and to experimentally observe, for example, the quantum phase of a propagating free-particle wave packet. These capabilities open the door to the investigation and manipulation of other low-energy systems, such as the helium trimer. They also afford the possibility of observing and characterizing the dynamics of exotic quantum systems, such as the birth of an Efimov state[5,6], that have so far eluded detailed experimental realization. ❐

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