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QUANTUM-MATTER PHYSICS

Quasiparticles on a collision course

Emergent quanta of momentum and charge, called quasiparticles, govern many of the properties of materials. The development of a quasiparticle collider promises to reveal fundamental insights into these peculiar entities. SEE LETTER P.225

DIRK VAN DER MAREL

Electrons and atomic nuclei in solids are bound together by their electric charges. If an electron is moved to a new position inside a metal, then the other electrons and nuclei respond by shifting their own positions. An electron that is accompanied by this response of the surrounding electrons and nuclei is an example of a quasiparticle (Fig. 1). It would be fascinating to prepare and manipulate the trajectories of quasiparticles to make them collide and then to study the effect of the collision, similar to experiments in a particle accelerator. On page 225 of this issue, Langer *et al.*[1] report the realization of such an experiment.

The authors studied an electrical insulator, tungsten diselenide (WSe_2). They generated pairs of quasiparticles in the material, one negatively charged and the other positively charged, using an ultrashort light pulse (10–100 femtoseconds in duration; 1 fs is 10^{-15} seconds). The light pulse's energy, intensity and duration were precisely adjusted so that the initial distance of the quasiparticles from each other, and their relative speeds, were well defined.

Langer and colleagues then launched the quasiparticles along a linear track. This track was created with the help of the electric field from a second light pulse; the field strength, duration and oscillation period of the light pulse were adjusted to direct the quasiparticles into a head-on collision. The collision caused mutual annihilation of the quasiparticles and the emission of a photon, which the authors detected. The experiment is therefore similar to studies of electron–positron annihilation in high-energy particle accelerators (positrons are the antiparticles of electrons, which means that they have opposite charge and equal mass to an electron).

The researchers can tune the conditions of their system in many ways by adjusting the aforementioned experimental parameters and the time interval between the generation of the pulses and their detection. They particularly examined the effect of the electrical (Coulomb) interaction between the two oppositely charged quasiparticles. Under stable conditions, this interaction would bind the quasiparticles into a neutral composite particle called an exciton. Excitons are another example of a collective state that can exist in solids, somewhat like positronium atoms (which form from one electron and one positron). The authors obtained material-specific information such as the exciton binding energy, and observed an enhancement of the collisional cross-section (a quantity that governs the rate at which the quasiparticles collide) as a result of the Coulomb force between the oppositely charged quasiparticles.

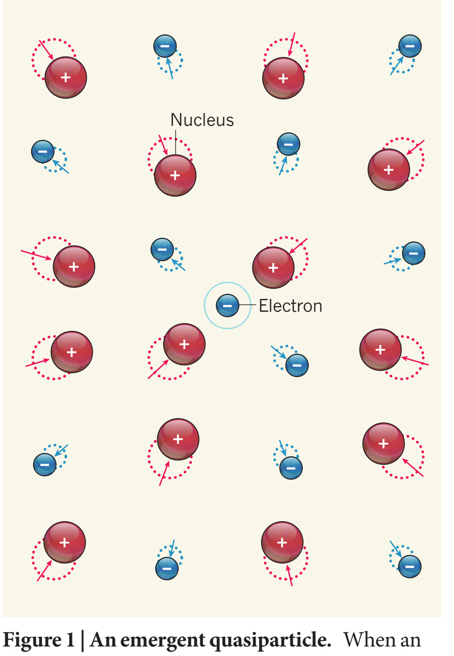

Figure 1 | An emergent quasiparticle. When an electron moves to a new position inside a metal, the other electrons and atomic nuclei shift their own positions in response (empty circles show original positions of the surrounding electrons and nuclei; electrons are negatively charged, nuclei are positively charged). The combination of the electron and the movement of the surrounding electrons and nuclei is an example of a quasiparticle — a collective phenomenon that behaves like a single particle. Langer *et al.*[1] describe a system that allows quasiparticle collisions to be studied.

The beauty of Langer and colleagues' experimental toolkit is that it might finally allow quasiparticles and their mutual interactions to be studied in the materials in which they arise. The negative and positive quasiparticles in the authors' experiment are similar to electrons and positrons in a vacuum, but a rich variety of unconventional quasiparticles could also be studied, for which no equivalent elementary particles are known. For example, when an electron is introduced into an insulating transition-metal oxide such as strontium titanate ($SrTiO_3$), the electron slightly attracts the positive ions in the material (Ti^{4+} and Sr^{3+}), but slightly repels the negative oxide ions (O^{2-}). When the electron moves around the compound's lattice, the ionic displacements move with the electron. The resulting object — the electron plus the co-moving lattice distortion — is called a polaron[2,3]. Its properties and behaviour are different from those of an electron; for example, its mass is typically two or three times higher.

Quasiparticles that are even more bizarre emerge in two-dimensional gases of interacting electrons in a strong magnetic field. The charge on these quasiparticles is a fraction of that for an electron: it can be one-third (the same as for elementary particles called quarks), one-fifth, one-seventh, or smaller[4,5].

When a magnetic field is applied to certain superconductors, peculiar topological states known as vortices appear, equivalent to tubes of magnetic flux. Vortices and antivortices form spontaneously[6,7] in 2D superconductors, but it might also be possible to generate them using light pulses. This would open the way to studies of their interactions using Langer and colleagues' approach, including the annihilation of vortex–antivortex pairs.

Quasiparticles are not only of academic interest — they also determine many of the properties and functionalities of materials, such as electrical resistivity, heat capacity and magnetism. There are thus many reasons to study quasiparticles in the materials in which they are manifested. Langer and co-workers have provided a fresh strategy with which condensed-matter physicists can tackle such studies. This promises fundamental insights, but also offers ways to control and handle the quasiparticles characteristic of the various states of matter that can be realized in solids.

That said, only a few experimental facilities will have the combination of technologies required to study quasiparticles that have fractional charges, or vortex–antivortex annihilation in two dimensions. But for those that do, Langer and colleagues' approach can be readily applied to investigate the properties of polarons in strontium titanate or other transition-metal oxides, or the 'heavy electrons' that occur in several materials owing to the coupling of mobile electrons to fluctuations of magnetic polarization[8–10]. According to some schools of thought, the quasiparticle concept does not apply in certain materials or under special conditions[11]. Collision experiments might therefore help to identify the boundaries of the quasiparticle concept. ■

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CELESTIAL MECHANICS

Fresh solutions to the four-body problem

Describing the motion of three or more bodies under the influence of gravity is one of the toughest problems in astronomy. The report of solutions to a large subclass of the four-body problem is truly remarkable.

DOUGLAS P. HAMILTON

The study of the orbital motions of bodies that are subject to their mutual gravitational attractions is crucial for understanding the movements of moons, planets and stars, and for navigating spacecraft to distant planets. The central problem is to determine the motions of n point masses interacting through gravitational forces that vary with the inverse square of their separation distances. This n-body problem is famous among astronomers and mathematicians, and is known to have no general analytical solution (that is, no solution that can be written down in terms of simple mathematical functions). Nevertheless, specific solutions have been eagerly sought and occasionally discovered. Writing in *Celestial Mechanics and Dynamical Astronomy*, Érdi and Czirják[1] report analytical solutions for a broad class of four-body configurations.

Isaac Newton solved the two-body problem in his 1687 masterwork, the *Principia*, but the three-body problem proved surprisingly complex and occupied many distinguished mathematicians over the next two centuries. Leonhard Euler and Joseph-Louis Lagrange found all analytical solutions to an important subclass of the three-body problem known as central configurations, but work by Heinrich Bruns and by Henri Poincaré in the late 1880s showed that a general arrangement of three or more bodies admits no analytical solution. Although the set of all possible central configurations of four bodies remains unknown, Érdi and Czirják have taken a large stride forward by solving all of those in which two of the bodies lie along an axis of symmetry.

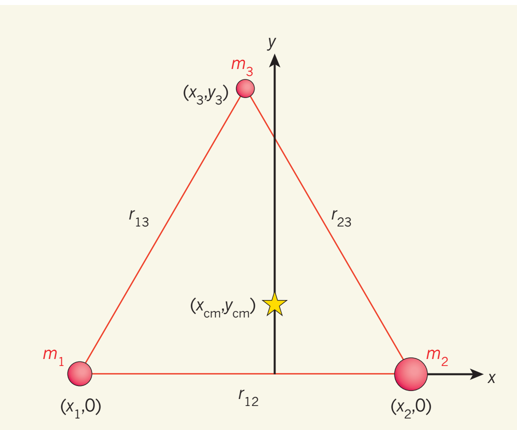

Figure 1 | A subclass of the three-body problem. The motions of three bodies with masses m_1, m_2 and m_3 under the influence of gravitational forces can be described analytically — that is, in terms of simple mathematical functions — for the special case in which the bodies are placed at the vertices of an equilateral triangle. Proof of this involves considering the accelerations in the y direction of two masses placed on the x axis. It emerges that the bodies orbit in such a way that the triangle rotates, expands or shrinks, and always remains in the xy plane. The yellow star represents the centre of mass of the three-body system. Distances between the masses are represented by the symbol r, with subscripts representing the masses; coordinates for masses and for the centres of mass are given as (x,y) pairs.

In central configurations, each body must be subject to an acceleration directed towards the centre of mass of the system with a magnitude that is proportional to its distance from the centre of mass. All orbits of two bodies are central configurations, in which the objects each orbit their common centre of mass along ellipses that have identical shapes and orbital periods. Euler's solutions for linear arrangements of three bodies are also central configurations, as are Lagrange's solutions in which the three masses are placed at the vertices of an equilateral triangle. In the latter system, Lagrange showed that the vertices of the triangle can move in such a way as to preserve relative distances between the masses; the triangle can rotate around the centre of mass, expand or shrink, but must remain in its initial plane.

It is easy to show that equilateral triangles are the only possible planar central configuration of a three-body system by placing two of the masses (m_1 and m_2) on an x axis, and considering their accelerations in the perpendicular y direction (Fig. 1). The y acceleration on m_1 is due solely to the gravity of the third mass (m_3) and equals Gm_3y_3/r_{13}^3 — where G is the gravitational constant, y_3 is the coordinate of m_3 along the y axis and r_{13} is the distance between m_1 and m_3. The corresponding y acceleration on m_2 is Gm_3y_3/r_{23}^3. According to the definition of central configurations, these accelerations must separately equal λy_{cm} (where y_{cm} is the y coordinate of the centre of mass and λ is the common proportionality constant). By cancelling like terms in the two y accelerations, it immediately becomes apparent that r_{13} must be the same as r_{23}.

If the symmetry of the equilateral-triangle system is then exploited by choosing a new x axis to run along the line connecting m_1 and m_3, repeating the above argument shows that r_{12} must also be the same as r_{23}, and thus all three sides of the triangle must be equal in length. This proof extrapolates directly to four bodies: the only fully three-dimensional central configurations for