Twisting neutrons may reveal their internal structure

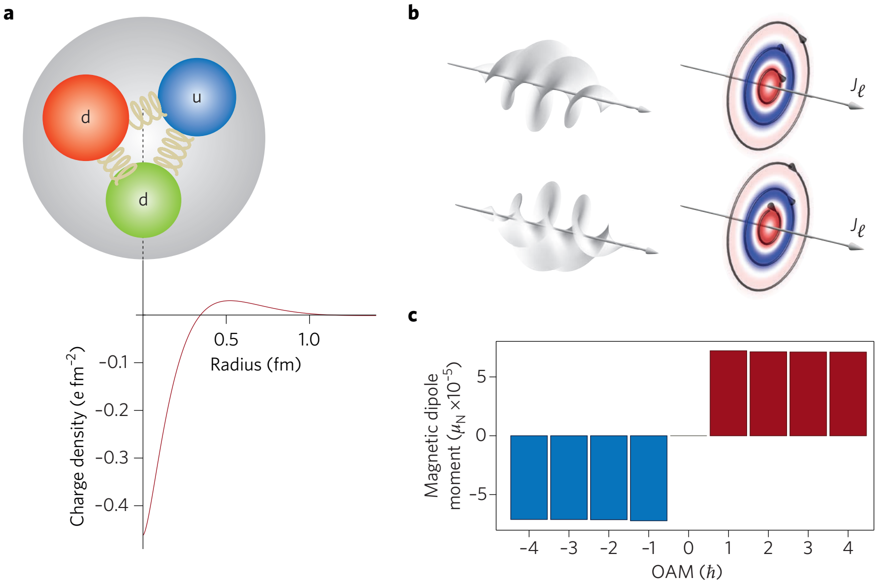

Figure 1 | Charge and current densities of OAM-carrying neutrons. **a**, Schematic of the quark composition of the neutron and the experimentally observed neutron's transverse charge density. **b**, Wavefronts of neutron wavepackets carrying ±2$\hbar$ units of OAM along with the associated transverse charge distributions, displayed in red and blue colours, and the direction of the resulting current density, represented by black arrows. Red represents a positive charge density while blue represents a negative one. **c**, Magnetic dipole moment of OAM-carrying neutron wavepackets resulting from the currents shown in **b** expressed in terms of the nuclear magneton μ_N for a neutron wavepacket with a beam waist of 20 fm.

To the Editor — According to quantum mechanics, matter can be described by a wavefunction that can be modified, just like a wave, through processes such as interference. Under certain conditions, specific forms of interference can result in the formation of a vortex. Vortices are defined by some form of coiling motion around a stagnation point. In the case of matter waves, this coiling motion is attributed to the probability density associated with the wavefunction — that is, its probability density current[1]. Within a quantum context, this motion often translates to a wave with twisted wavefronts that describes a quantized form of azimuthal motion known as orbital angular momentum (OAM).

Electromagnetic or optical waves are now well-known examples of waves carrying OAM[2], and their use has been explored in several fields of modern science such as microscopy, optical tweezing and communications[3]. Similarities between the equations describing optical waves and the wavefunction of a free particle[1,3] have also led to the generation of OAM-carrying matter waves, especially electron waves[4,5]. In particular, the interest surrounding these 'twisted' electrons arises from the electron's charge, which, in conjunction with the wave's coiling motion, causes them to form loops of electrical current characterized by magnetic properties. Due to these properties, OAM-carrying electrons are now starting to find applications as nanoscale magnetic probes for characterizing materials[3,5].

Prospective applications of OAM-carrying particles have recently been discussed at this year's International Conference on Optical Angular Momentum (ICOAM) in Capri, Italy. Some of the proposed applications are based on more massive and non-elementary particles such as neutrons. In fact, a method to generate OAM-carrying neutron waves has recently been reported[6]. However, these neutron waves are not as coherent as optical waves and, unlike electrons, they do not carry a net charge. These properties suggest that neutrons would perform poorly in applications relying on OAM-carrying photons or electrons. On consideration of these factors, one might wonder whether neutrons or other OAM-carrying particles have any distinct properties that would make it possible to take advantage of their OAM in modern science. Interesting proposals have been put forward, one of them suggesting that shaping the wavefunction of a particle could increase its lifetime[7]. We are of the opinion that twisted neutron waves can additionally be used to provide information pertaining to their subatomic structure.

Unlike photons and electrons, neutrons are not elementary particles. More specifically, they consist of one up quark and two down quarks, which have different colours, bound together by the strong force, and whose charges add up to zero. This compound structure can to some extent complicate the formalism describing their physical states. For instance, for a free neutron, this internal structure manifests itself as a non-zero transverse charge density that must usually be obtained through the use of theoretical models with various fitting parameters[8,9]. This approach, however, often yields charge densities that vary from one model to another due to the different assumptions made concerning the neutron's internal structure. For this reason, information regarding this quantity must often be extracted by means of experimental methods — typically scattering experiments[10]. As shown in Fig. 1a, this experimental approach reveals that neutrons are negatively charged at their centre and have a transverse charge density that varies between positive and negative values. The amplitude of these oscillations decreases as radial distance increases.

When a free neutron wave is imparted with OAM, it acquires a doughnut-shaped transverse profile along with a form of azimuthal motion. In conjunction with the neutron's internal charge distribution, we predict the appearance of OAM-dependent charge and current distributions, as shown in Fig. 1b. These transverse charge and current distributions make OAM-carrying neutrons exhibit several interesting electromagnetic properties.

The charge distribution resulting from the addition of OAM is directly determined by the doughnut-shaped profile of OAM-carrying waves. For regular (non-shaped) neutrons, which are modelled as Gaussian waves that do not carry OAM, the neutron wave's charge distribution directly corresponds to that of the neutron scaled to the relative (coherent) size of the beam. Unlike waves with a Gaussian transverse profile, an OAM-carrying wave is brightest at a certain radial distance from its centre — where the beam holds the negative charge attributed to the centre of the neutron. As we move away from this region, the outer charge distribution of the neutron starts to be more noticeable. Interestingly, the dominant terms describing the electric field at more distant regions have no dependence on the OAM carried by the neutron and depend solely on the neutron's internal charge density.

The current density of the neutron wave comes from its charge distribution experiencing a form of azimuthal motion. In the case of a Gaussian neutron wave, in the absence of OAM there will be no current. However, for OAM-carrying neutrons, the azimuthal motion of its charge distribution ultimately amounts to a sequence of loops of current whose direction alternates from loop to loop. Surprisingly, this alternation does not completely cancel out the magnetic fields that the current generates, resulting in a net magnetic field for OAM-carrying neutrons, as shown in Fig. 1c. Unlike particles that carry a net charge, such as electrons[1,3] or protons, the magnetic field of an OAM-carrying neutron wave does not increase with its OAM, as it gets quickly washed away when the transverse extent of the neutron wave becomes much greater than that of its internal charge density.

The neutron wave's OAM-dependent charge density could prospectively provide new means for probing the internal charge density of neutrons in scattering experiments, which rely on bombarding neutrons with charged or magnetized particles. Because these particles are scattered off the neutrons in a way that is determined by the neutron's internal charge and current densities, imparting OAM on neutrons could provide additional information on the neutron's internal structure by observing how it influences the outcome of the scattering experiment.

Our analysis and its applications can potentially be extended to other types of OAM-carrying free particles with non-trivial internal charge densities, including atoms. In particular, it could motivate the development of methods that can more efficiently characterize atomic and nuclear structure. However, the study of the interaction between such particles and external fields might be complicated by the type of interaction that binds the particle's constituents. ❐

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