Infinite-dimensional symmetry opens up possibility of a new physics—and new particles

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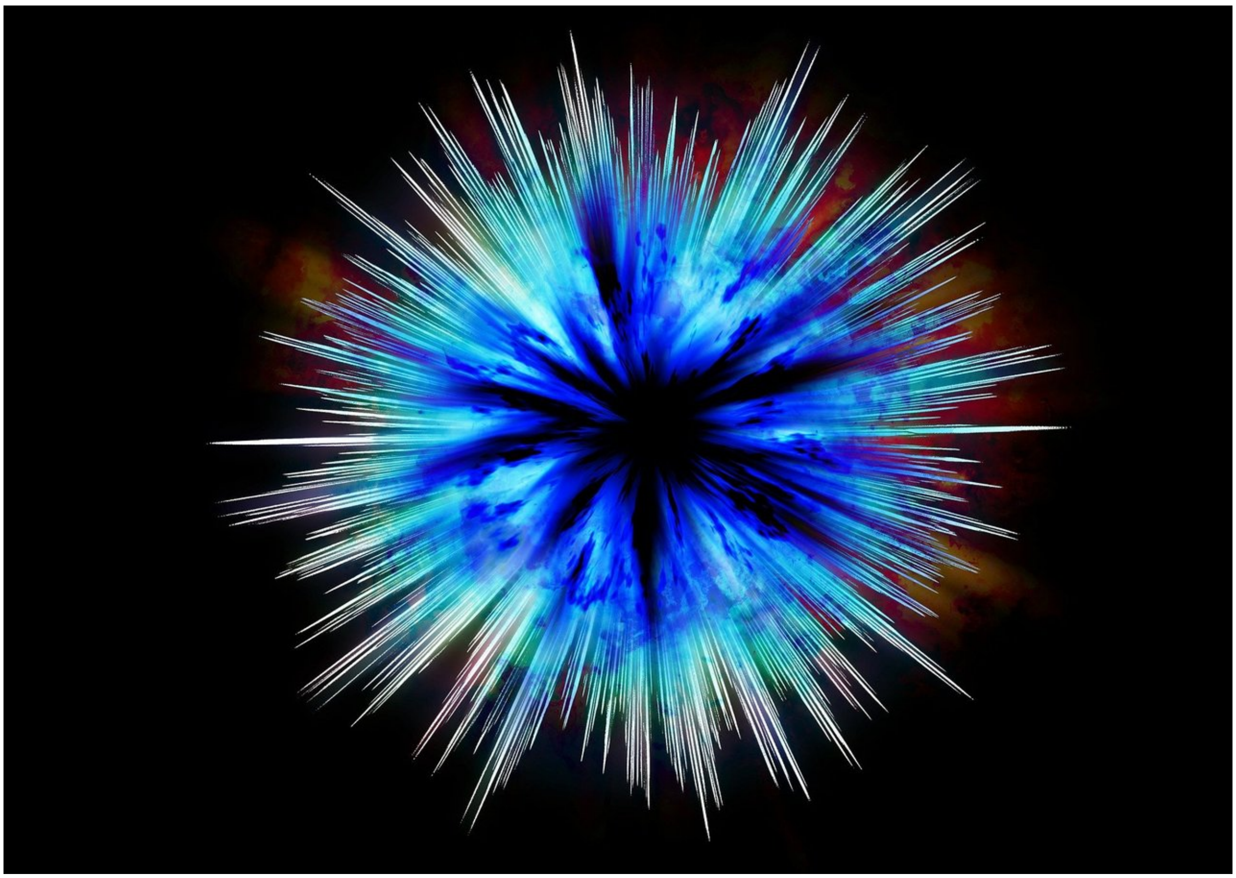

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The symmetries that govern the world of elementary particles at the most elementary level could be radically different from what has so far been thought. This surprising conclusion emerges from new work published by theoreticians from Warsaw and Potsdam. The scheme they posit unifies all the forces of nature in a way that is consistent with existing observations and anticipates the existence of new particles with unusual properties that may even be present in our close environs.

For a half-century, physicists have been trying to construct a theory that unites all four fundamental forces of nature, describes the known elementary particles and predicts the existence of new ones. So far, these attempts have not found experimental confirmation, and the Standard Model—an incomplete, but surprisingly effective theoretical construct—is still the best description of the quantum world. In a recent paper in *Physical Review Letters*, Prof. Krzysztof Meissner from the Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, and Prof. Hermann Nicolai from the Max-Planck-Institut für Gravitationsphysik in Potsdam have presented a new scheme generalizing the Standard Model that incorporates gravitation into the description. The new model applies a kind of symmetry not previously used in the description of elementary particles.

In physics, symmetries are understood somewhat differently than in the colloquial sense of the word. For instance, whether a ball is dropped now or one minute from now, it will still fall in the same way. That is a manifestation of a certain symmetry: the laws of physics remain unchanged with respect to shifts in time. Similarly, dropping the ball from the same height in one location has the same result as dropping it in another. This means that the laws of physics are also symmetrical with respect to spatial operations.

"Symmetries play a huge role in physics because they are related to principles of conservation. For instance, the principle of the conservation of energy involves symmetry with respect to shifts in time, the principle of the conservation of momentum relates to symmetry of spatial displacement, and the principle of the conservation of angular momentum relates to rotational symmetry," says Prof. Meissner.

Developing a supersymmetric theory to describe the symmetries between fermions and bosons began back in the 1970s. Fermions are elementary particles whose spin, a quantum property related to rotation, is expressed in odd multiples of the fraction 1/2, and they include both quarks and leptons. Among the latter are electrons, muons, tauons, and their associated neutrinos (as well as their antiparticles). Protons and neutrons, common non-elementary particles, are also fermions. Bosons, in turn, are particles with integer spin values. They include the particles responsible for forces (photons, carriers of the electromagnetic force; gluons, carrying the strong nuclear force; W and Z bosons, carrying the weak nuclear force), as well as the Higgs boson.

"The first supersymmetric theories tried to combine the forces typical of elementary particles, in other words the electromagnetic force with a symmetry known as U(1), the weak force with symmetry SU(2) and the strong force with symmetry SU(3). Gravity was still missing," Prof. Meissner says. "The symmetry between the bosons and fermions was still global, which means the same at every point in space. Soon thereafter, theories were posited where symmetry was local, meaning it could manifest differently at each point in space. Ensuring such symmetry in the theory required for gravitation to be included, and such theories became known as supergravities."

Physicists noticed that in supergravity theories in four spatiotemporal dimensions, there cannot be more than eight different supersymmetric rotations. Each such theory has a strictly defined set of fields (degrees of freedom) with different spins (0, 1/2, 1, 3/2 and 2), known respectively as the fields of scalars, fermions, bosons, gravitinos and gravitons. For supergravity N=8, which has the maximal number of rotations, there are

48 fermions (with spin 1/2), which is precisely the number of degrees of freedom required to account for the six types of quarks and six types of leptons observed in nature. There was therefore every indication that supergravity N=8 is exceptional in many respects. However, it was not ideal.

One of the problems in incorporating the Standard Model into N=8 supergravity was posed by the electrical charges of quarks and leptons. All the charges turned out to be shifted by 1/6 with respect to those observed in nature: the electron had a charge of -5/6 instead of -1, the neutrino had 1/6 instead of 0, etc. This problem, first observed by Murray Gell-Mann more than 30 years ago, was not resolved until 2015, when Professors Meissner and Nicolai presented the respective mechanism for modifying the U(1) symmetry.

"After making this adjustment we obtained a structure with the symmetries U(1) and SU(3) known from the Standard Model. The approach proved to be very different from all other attempts at generalizing the symmetries of the Standard Model. The motivation was strengthened by the fact that the LHC accelerator failed to produce anything beyond the Standard Model and N=8 supergravity fermion content is compatible with this observation. What was missing was to add the SU(2) group, responsible for the weak nuclear force. In our recent paper, we show how this can be done. That would explain why all previous attempts at detecting new particles, motivated by theories that treated the SU(2) symmetry as spontaneously violated for low energies, but as holding in the range of high energies, had to be unsuccessful. In our view, SU(2) is just an approximation for both low and high energies," Prof. Meissner explains.

Both the mechanism reconciling the electric charges of the particles, and the improvement incorporating the weak force proved to belong to a symmetry group known as E10. Unlike the symmetry groups previously used in unification theories, E10 is an infinite group, very poorly studied even in the purely mathematical sense. Prof. Nicolai with Thibault Damour and Marc Henneaux had worked on this group before, because it appeared as a symmetry in N=8 supergravity under conditions similar to those during the first moments after the Big Bang, when only one dimension was significant: time.

"For the first time, we have a scheme that precisely anticipates the composition of the fermions in the Standard Model—quarks and leptons—and does so with the proper electric charges. At the same time it includes gravity into the description. It is a huge surprise that the proper symmetry is the staggeringly huge symmetry group E10, virtually unknown mathematically. If further work confirms the role of this group, that will mean a radical change in our knowledge of the symmetries of nature," Prof. Meissner says.

Although the dynamics is not yet understood, the scheme proposed by Professors Meissner and Nicolai makes specific predictions. It keeps the number of spin 1/2 fermions as in the Standard Model but on the other hand suggests the existence of new particles with very unusual properties. Importantly, at least some of them could be present in our immediate surroundings, and their detection should be within the possibilities of modern detection equipment. But that is a topic for a separate story.

More information: Krzysztof A. Meissner et al, Standard Model Fermions and Infinite-Dimensional R Symmetries, *Physical Review Letters* (2018). DOI: 10.1103/PhysRevLett.121.091601

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