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Cracow, 6 November 2025

Nonlocality inherent in the nature of identical particles

At its deepest physical foundations, the world appears to be nonlocal: particles separated in space behave not as independent quantum systems, but as parts of a single one. Polish physicists have now shown that such nonlocality – arising from the simple fact that all particles of the same type are indistinguishable – can be observed experimentally for virtually all states of identical particles.

All particles of the same type — for example, photons or electrons — are entangled with one another, including those on Earth and those in the most distant galaxies. This surprising statement follows from a fundamental postulate of quantum mechanics: particles of the same type are, in their very nature, identical. Does this mean that a universal source of entanglement — underlying the peculiar, nonlocal features of the quantum world — is at our fingertips? And can we somehow outsmart quantum theory, which so carefully guards access to this extraordinary resource? Answers to these questions have been provided by two Polish theorists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow and the Institute of Theoretical and Applied Informatics of the Polish Academy of Sciences (IITiS PAN) in Gliwice. Their findings, published in *npj Quantum Information* (Nature Publishing Group), show how the very identity of particles gives rise to observable quantum nonlocality.

Theorists from the IFJ PAN and the IITiS PAN have analysed the fundamental entanglement of identical particles, drawing directly on John Bell's concept of nonlocality. While entanglement is a concept firmly rooted in the abstract framework of quantum theory, locality is much more intuitive and universal. It reflects the common-sense idea that events follow a chain of causes and effects that propagate through space at a finite speed — never faster than light. When no such explanation exists, we enter the realm of nonlocal phenomena. This was the essence of the breakthrough made by Northern Irish physicist John Stewart Bell, who pointed out an experiment that cannot be explained within a local framework. The key element of this experiment is the quantum entanglement between separate systems on which researchers — traditionally named Alice and Bob — can perform arbitrary and independent measurements.

"At first glance, the problem seems simple: entangled systems violate Bell's inequalities, so all you need to do is perform a well-designed experiment. Indeed, but this applies only to distinguishable systems that can be labelled and sent to two distant laboratories. With identical particles, this framework breaks down," says Dr. Pawel Blasiak (IFJ PAN), and goes on to explain: *"Quantum mechanics is clear: identical particles are indistinguishable by their very nature. In practice, we do not measure 'this particular' particle, but 'some' particle at a given location. Quantum physics consistently resists any attempt to assign them individual labels — and that is precisely why the classical Bell scenario cannot be applied here."*

Dr. Marcin Markiewicz (IITiS PAN), co-author of the article, clarifies: *"This seemingly subtle difference introduces new ground rules for describing the world: it requires the symmetrization or antisymmetrization of the wave function in systems with multiple particles. It is precisely the principle of particle identity that leads to the division into fermions and bosons — two worlds that underpin the structure of atoms and their nuclei, and determine the nature of interactions. Indistinguishability also blurs the very concept of entanglement: in the case of identical particles, it no longer behaves* *as we are used to — and loses some of its practical meaning. This is where the real challenge lies in addressing the question of nonlocality arising from the fundamental indistinguishability of particles."*

Contemporary experiments on entanglement typically involve its artificial creation through interactions between particles within a quantum system. Yet quantum mechanics also points to another, more fundamental mechanism: entanglement — and perhaps nonlocality itself — may arise directly from the identical nature of particles of the same type. From this perspective, nonlocality could even manifest between particles that have never interacted with one another before.

It is this primordial form of nonlocality that captured the interest of physicists from the IFJ PAN and the IITiS PAN. They set out to determine whether it could be demonstrated in experiments composed solely of simple, passive linear optical elements: mirrors, beam splitters, and particle detectors. Such systems can be arranged so that the propagating particles never meet at any point. Yet if Bell's inequalities could still be violated under these conditions, it would imply that the observed nonlocality is not a by-product of experimental interactions, but a manifestation of something truly fundamental.

The researchers posed a simple yet remarkably general question: for which quantum states of identical particles can one identify a classical optical system in which nonlocal correlations become manifest? The challenge lies in the fact that both the number of possible optical configurations and the diversity of identical-particle states appear virtually limitless. The scientists managed to tame this complexity using an arsenal of sophisticated tools: the Yurke-Stoler interferometer, clever post-selection, the concept of 'quantum erasure', mathematical induction, and extensive experience in constructing hidden-variable models.

In their article, the Polish theorists presented a criterion that enables the clear identification of nonlocality for any state containing a fixed number of identical particles. The conclusions are surprising: all fermionic states and almost all bosonic states turn out to be nonlocal resources (in the latter case, except for a narrow class of so-called states reducible to a single mode). Notably, the proof is entirely constructive: it demonstrates, step by step, how to design optical experiments that reveal the nonlocality of the state under investigation.

"Our research reveals that the very indistinguishability of particles hides a source of entanglement we can access. Could nonlocality, then, be woven into the fabric of the Universe itself? Everything seems to suggest that this is indeed the case, with the source of this extraordinary property lying in the seemingly simple postulate of the identical nature of particles of the same type," concludes Dr. Blasiak, whose research was co-funded by a Fulbright Senior Award (2022-23) at the Institute for Quantum Studies (IQS), Chapman University, California.

As always, much remains to be understood, and questions about the nature of reality and the interpretation of quantum mechanics gain new resonance. Physicists Charles W. Misner, John A. Wheeler, and future Nobel laureate Kip S. Thorne expressed this insight eloquently in their 1973 book Gravitation: *"No acceptable explanation for the miraculous identity of particles of the same type has ever been put forward. That identity must be regarded, not as a triviality, but as a central mystery of physics."* This enduring puzzle will likely continue to inspire researchers for many decades to come.

The Henryk Niewodniczański Institute of Nuclear Physics (IFJ PAN) is currently one of the largest research institutes of the Polish Academy of Sciences. A wide range of research carried out at IFJ PAN covers basic and applied studies, from particle physics and astrophysics, through hadron physics, high-, medium-, and low-energy nuclear physics, condensed matter physics (including materials engineering), to various applications of nuclear physics in interdisciplinary research, covering medical physics, dosimetry, radiation and environmental biology, environmental protection, and other related disciplines. The average yearly publication output of IFJ PAN includes over 600 scientific papers in high-impact international journals. Each year the Institute hosts about 20 international and national scientific conferences. One of the most important establishments of the Institute is the Bronowice Cyclotron Centre (CCB), which is an infrastructure unique in Central Europe, serving as a clinical and research centre in the field of medical and nuclear physics. In addition, IFJ PAN runs four accredited research and measurement laboratories. IFJ PAN is a member of the Marian Smoluchowski Kraków Research Consortium: "Matter-Energy-Future", which in 2012-2017 enjoyed the status of the Leading National Research Centre (KNOW) in physics. In 2017, the European Commission granted the Institute the HR Excellence in Research award. As a result of the categorization of the Ministry of Education and Science, the Institute has been classified into the A+ category (the highest scientific category in Poland) in the field of physical sciences.

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SCIENTIFIC PUBLICATIONS:

“Identical particles as a genuine non-local resource”
P. Błasiak, M. Markiewicz
npj Quantum Information 11, 171 (2025)
DOI: 10.1038/s41534-025-01086-x

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Nonlocality seems to be enchanted into such a fundamental property of our Universe as the indistinguishability of quantum particles. (Source: IFJ PAN, AI)