sors form large oxide particles and large, clustered metal particles after reduction. Different temperatures, gas exposures, and modes of drying can make a large difference in particle formation, as evidenced by the preparation of uniform cobalt on silica particles by using fluid bed drying at 100°C in a nitrogen rather than air flow (7). These approaches, which have been led by de Jong, de Jongh, and their co-workers are also scalable. However, for each system, the particular technique (NO addition, drying variations, etc.) must be empirically determined.
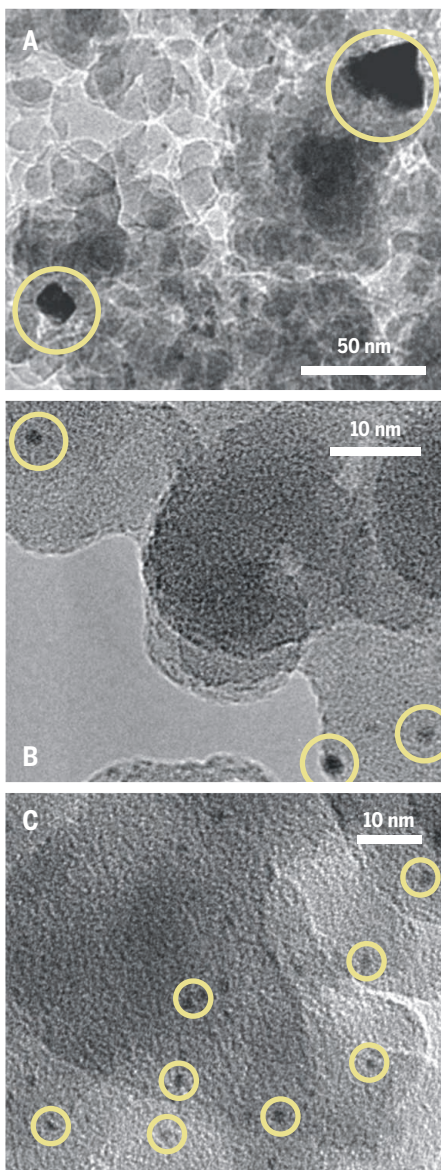
Size selection on silica. (**A** and **B**) Transmission electron micrographs (TEMs) show a sample prepared with an aqueous tetraamine platinum hydroxide solution and calcined at 350°C followed by reduction. The result is a distribution of metal particle sizes. (**C**) The TEM shows a platinum-arginine preparation with air calcination at 425°C. Small, uniformly distributed metal crystals form upon reduction.

A third approach involves using simple water-soluble bifunctional organics—amino alcohols or amino acids—to form impregnates that interact strongly with silica. These bifunctional organics (such as tri-ethanolamine and arginine) provide major advantages compared to using simple organic acids, which have served as more commonly used dispersion aids. With supported ruthenium and iridium, the preparation of optimal catalysts requires partial decomposition of the impregnate to form an anchored complex, which is then reduced and cleaned by hydrogenolysis to remove the organic fragment (8). In this way, ruthenium or iridium oxides, which are mobile on the silica surface, never form.

Other noble metals that do not have mobile oxide phases, such as platinum, palladium, and rhodium, can have their organic complex oxidized and reduced (see the figure). This technique has the advantage of keeping the two metals mixed and is well suited for making bimetallic alloy particles. It is widely applicable to most transition metals, but at high metal loadings and for large-scale preparations, the oxidation of organics must be controlled to avoid runaway exothermic reactions. In that regard, it is probably more suitable for noble metals that are generally kept at low loading levels.

These new approaches and our increased understanding of the scientific basis of controlling impregnations, metal nanostructures, and site homogeneity on silica-supported catalysts portend a wider use of these catalysts in the future. The present state of knowledge also allows a reassessment of processes where alumina has been used but may not be optimal. Increasing efforts to learn to control textural properties (surface areas, pore sizes, and pore volumes) on physically strong extrudates will also help propel this area forward, as most applications require this type of support particle. ∎

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Classical entanglement?

Entanglement is a property of the quantum world; classical systems need not apply

By **Ebrahim Karimi**[1] and **Robert W. Boyd**[1,2]

Since the inception of quantum theory, scientists and philosophers have been puzzled by the apparent indeterminacy of physical properties prior to the measurement process. These problems suggest that quantum mechanics might ultimately be incompatible with basic notions of "realism"—that is, the view that a physical system possesses inherent properties that are independent of procedures used to measure them. This issue lies at the core of the famous gedanken experiment of Einstein, Podolsky, and Rosen (EPR) (1) and of attempts to develop a conceptual understanding (2–4) of EPR correlations.

The concept of entanglement was initially introduced by Schrödinger (2) in his response to EPR. Entanglement refers to the strong, nonclassical correlations that can exist between two spatially separated quantum systems. Over the past 40 years or so, numerous studies have confirmed that nature does behave in the manner described by Schrödinger (5). In particular, the laws of physics have been found to be inherently nonlocal: The results of a measurement at one position in space can dictate the possible outcome of a measurement performed at a different position.

In recent years, the term entanglement has come to be used in a more general context, including single-particle entanglement (6, 7) and classical entanglement (8–11). We do not endorse this new nomenclature. Ascribing a new meaning to a term that has been in wide use in quantum physics for more than 80 years can only lead to confusion. But more deeply, these new situations lack the key feature—nonlocality—that led to the concept of entanglement in the first place. For example, single-particle

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entanglement refers to correlations of two different degrees of freedom of an individual particle; this situation cannot lead to nonlocal correlations. Moreover, a classical system cannot possess any quantum correlations (classical correlations are incapable of describing quantum correlations).

For the situations just described, we prefer to use the term "nonseparable states." To see why, we must examine the relation between entanglement and nonseparability. A basic tenet of quantum mechanics is that the wave function of any entangled state is necessarily nonseparable. For example, consider the quantum state $|\psi\rangle = (|a\rangle_1|b\rangle_2 - |b\rangle_1|a\rangle_2)/\sqrt{2}$, where $|a\rangle_1$ means that particle 1 is in quantum state a, the other (spatially separated) particle 2 is in state b, and similarly for the other quantities. The state ψ has the property that if a measurement of particle 1 shows it to be in state a, then a measurement of particle 2 will certainly show it to be in state b, and vice versa. Nonetheless, before any measurement is performed, there is an equal probability for each particle to be in either state a or b. Although all entangled states are nonseparable, it is not true, in our view, that all nonseparable states are entangled (see the figure). We prefer not to describe nonseparable states in terms of entanglement, because there is no sense of nonlocality for this situation. In fact, no classical system can produce true quantum entanglement, of the sort that Einstein called "spooky action at a distance."

Let us next recall the work of John Bell (3), who examined whether correlations in the EPR form could be explained in terms of "local hidden variables." The idea here is that these correlations could be the consequence of some classical random process involving a degree of freedom that is unknown to (hidden from) the experimenters. These variables are local, in the sense that they are carried separately by each of the particles. Bell was able to show that if a certain inequality involving directly measurable quantities were violated, then this violation would rule out the possibility of interpretation in terms of local hidden variables. To date, experimental studies (5) have produced evidence in favor of conventional quantum mechanics and have ruled out alternative local and crypto-nonlocal statistical interpretations (3, 4).

Turning now to some deeper issues involving single-particle and classical entanglement: In the single-particle case, nonseparability among different degrees of freedom of a single particle can be used to test other statistical models, such as noncontextual realistic models (7). However, several studies have recently reported

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(9–11) the violation of a Bell inequality for nonseparable classical systems, and some have even suggested this violation would shift the quantum-classical boundary (10). If such a paradoxical interpretation were to be valid, it would indicate basic flaws with the current understanding of quantum mechanics.

However, in our view such an interpretation is not correct. These violations do not indicate quantum behavior, as they occur only at a purely formal level. Expressions derived to describe nonlocal, two-particle entanglement (that is, Bell inequalities) have been evaluated with laboratory results obtained from an entirely different physical system, which involve various degrees of freedom of a classical (9–11) system. It is not surprising that these expressions can take on meaningless values, as argued already in (8). It should also be clear that these tests cannot provide information on the nature of quantum theory, because there is no need to invoke quantum mechanics to describe classical physics. We point out, however, that even though these nonseparable classical states cannot be used to address any fundamental questions in quantum mechanics, they are proving to be useful in applications such as quantum metrology (12) and quantum information.∎

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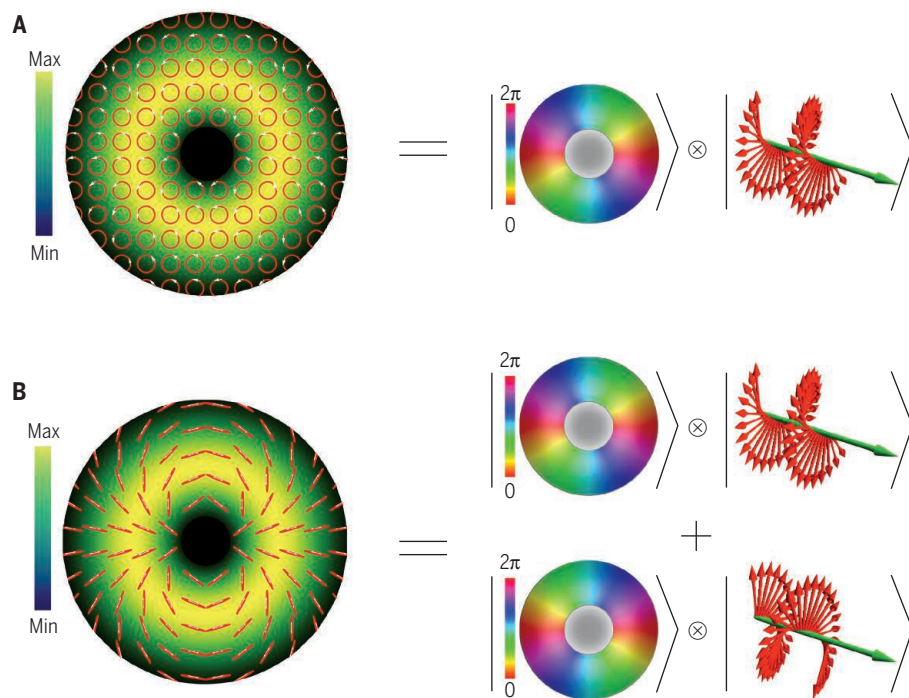
Separable and nonseparable states of a classical light field. (**A**) A circularly polarized light beam with an azimuthally varying phase distribution. Such a state is said to be separable, as it can be represented as the product of a spatially varying phase distribution and a polarization state vector. (**B**) A linear superposition of the state of (A) with another state with the opposite phase variation and the opposite circular polarization (7). In this case, the state of polarization varies as a function of position across the light beam, and the state cannot be described as the separable product of a function of position and a state of polarization.

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