QUANTUM PHYSICS

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Are the Quantum World and The Real World the Same Thing?

By **Andrew Friedman** on Thu, 07 May 2015

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While quantum mechanics is arguably our most successful theory of nature, it is perhaps best known for its strangeness. Quantum theory—and its key mathematical tool, the wave function—excels at predicting *probabilities* for the outcomes of experiments. Yet, after nearly a century of debate, physicists and philosophers of science can agree only that there is no real consensus on what quantum theory actually says about the world. This has led to a cottage industry of interpretations of quantum theory, which now number in the hundreds if not the thousands.

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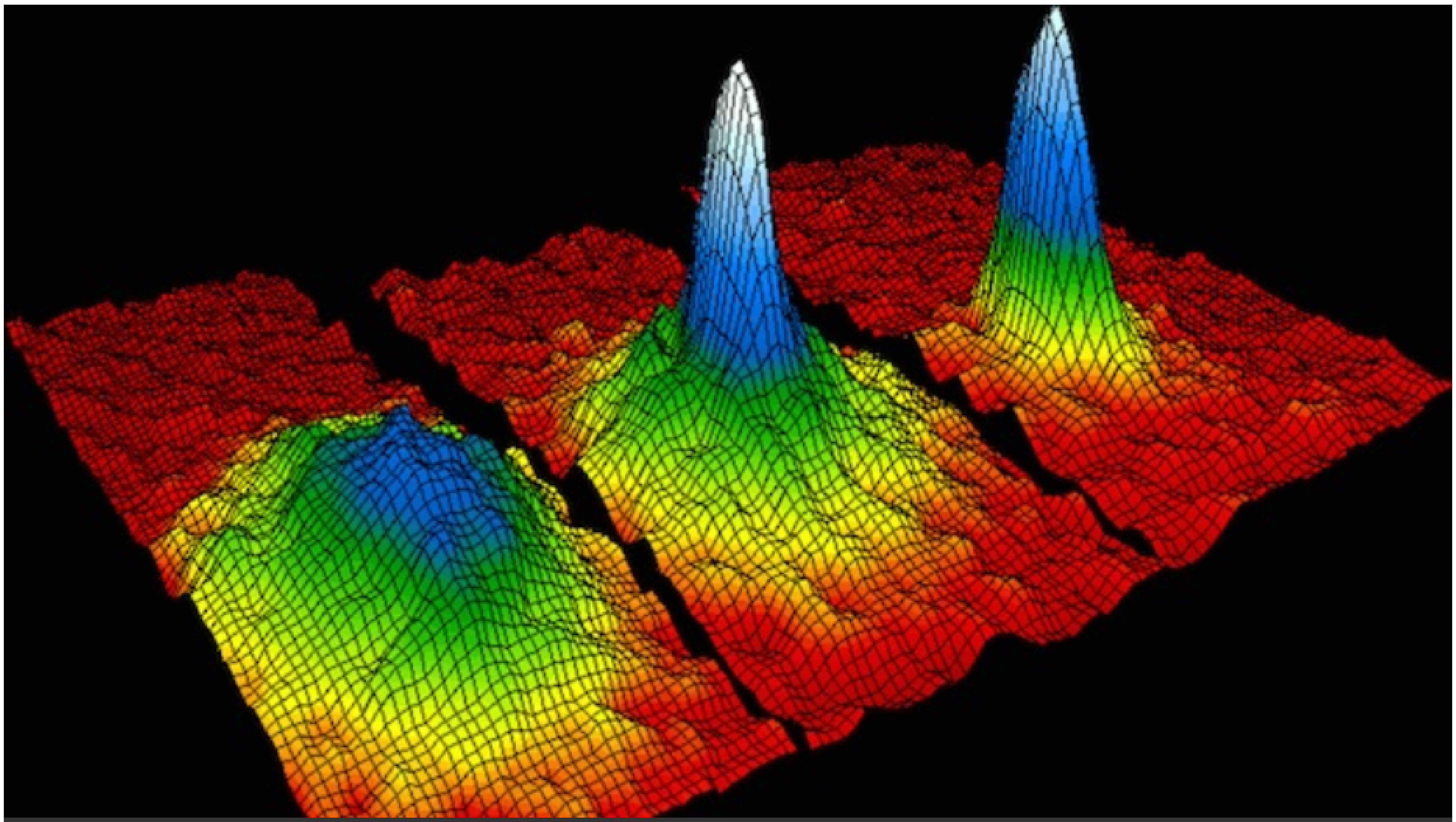


Visualization of a quantum wave function for a Bose-Einstein condensate of Rubidium atoms. Credit: NIST/JILA/CU-Boulder via Wikimedia Commons

At the center of this quagmire is the "wave function." Using the wave function, better known by its mathematical nickname, ψ ("psi"), physicists can calculate the probability that a quantum measurement will have a particular outcome. The success of this procedure has allowed us to control the subatomic world with unprecedented precision: You can thank (or curse) quantum theory for your iPads, smartphones, and laptops. Yet, unlike classical physics, quantum mechanics can't deliver a single, definite answer to a simple question about the outcome of a measurements. Instead, it returns a probability distribution representing many different possible outcomes. It's only after you make a measurement that you observe a stable, predictable, classical outcome. At this point, the wave function is said to have "collapsed."

To some, this suggests that there is a gap between the real, physical universe and whatever it is that the wave function is describing. So, what does the wave function actually represent? And what, if anything, is actually collapsing? Now, theorists and experimenters are bringing new insight (and new data) to this devilishly complex debate.

The wave function debate

Philosophers use the word “ontic” to describe real objects and events in the universe, things that exist regardless of whether anyone observes them. If you think of the universe as a video game, the so-called “ψ-ontic” view holds that the wave function is the source code. From this perspective, the wave function does indeed correspond directly to physical reality, containing a complete description of what philosophers call “the furniture of the world.” For these “ψ-ontologists” (as their opponents playfully call them), quantum theory, and reality itself, is ultimately about how the wave function unfolds over time, according to the Schrödinger Equation. In the quantum realist view, ψ is, in some sense, “all there is.”

To many thinkers in this camp, nothing extraordinary happens at the moment the wave function collapses. The apparently instantaneous collapse is actually just a very rapid process that occurs as a formerly-isolated quantum system interacts with its surrounding environment.

By contrast, the alternative “ψ-epistemic” view holds that the wave function represents at most our limited knowledge of the state of the system—not the source code, but just what you can learn about the source code, if it exists, from a particular round of the game. Some ψ-epistemologists believe an actual ontic state still exists even if the wave function is just a convenient computational tool that doesn’t capture all of the underlying reality. Others in the ψ-epistemic camp contend that the physical ontic state may not even exist in a meaningful way without an observer present: the game doesn’t exist if there’s no one there to play it. Most of the following discussion will adopt a “realist” position, which holds that there is a real, physical, world that exists independent of the observer, regardless of whether or not the wave function captures the whole story.

In the ψ-epistemic view, wave function collapse is not an actual physical process. Instead, it represents the near-instantaneous updating of our knowledge about the state of the system. This seems to give the observer some kind of special status, which may or may not be desirable, depending on your perspective. As a bonus, in this view, uncomfortable quantum superpositions, like those that put Schrödinger’s cat into mortal purgatory, are mere mathematical mirages, sums of possibilities, not actualities. Even if we are temporarily ignorant of it, there may really be only one actual fact of the matter, at a given time, about the questionable vital status of

Schrödinger's cat. It is only our knowledge that seems to change discontinuously, not the cat's actual state.

New insights

Is the wave function objective reality or just subjective knowledge? With such diametrically opposing views, it is no wonder that the two camps can't "collapse" onto the same meaning for ψ. Now, recent theoretical work by the British physicists Matthew Pusey, Jonathan Barrett, and Terry Rudolph (PBR) has presented the strongest theoretical evidence to date in favor of the ψ-ontic view. The trio of theorists have shown that—with certain assumptions—the ψ-epistemic view contradicts the predictions of quantum mechanics. In light of the astounding empirical success of quantum theory, this seems to suggest that the wave function really does correspond to an objective physical reality, and the ψ-epistemic team is out of luck.

Not so fast, say the skeptics. Remember those "certain assumptions" I mentioned? One of those assumptions is that systems prepared independently have independent physical ontic states; that is, that a photon in Vienna, for example, has absolutely nothing to do with a photon in Cambridge. But almost everything we have ever been able to access experimentally has a fairly recent shared causal history. Even if you agree that, in practice, a quantum system prepared in Vienna is approximately independent of a quantum system prepared in Cambridge, the Earth is a cosmically small place and light takes only a few milliseconds to cross it. Furthermore, the atoms in everything on Earth all emerged from a shared cosmic causal past, stretching all the way back to the big bang, nearly 14 billion years ago.

So, how can we know for sure that no parts of each experimental apparatus or quantum system are quantum mechanically entangled with one another, even if only to a tiny degree? Each system is certainly entangled with its local environment, and by considering larger and larger parts of the surrounding environment, it doesn't take long until the wider environment encompasses both experiments.

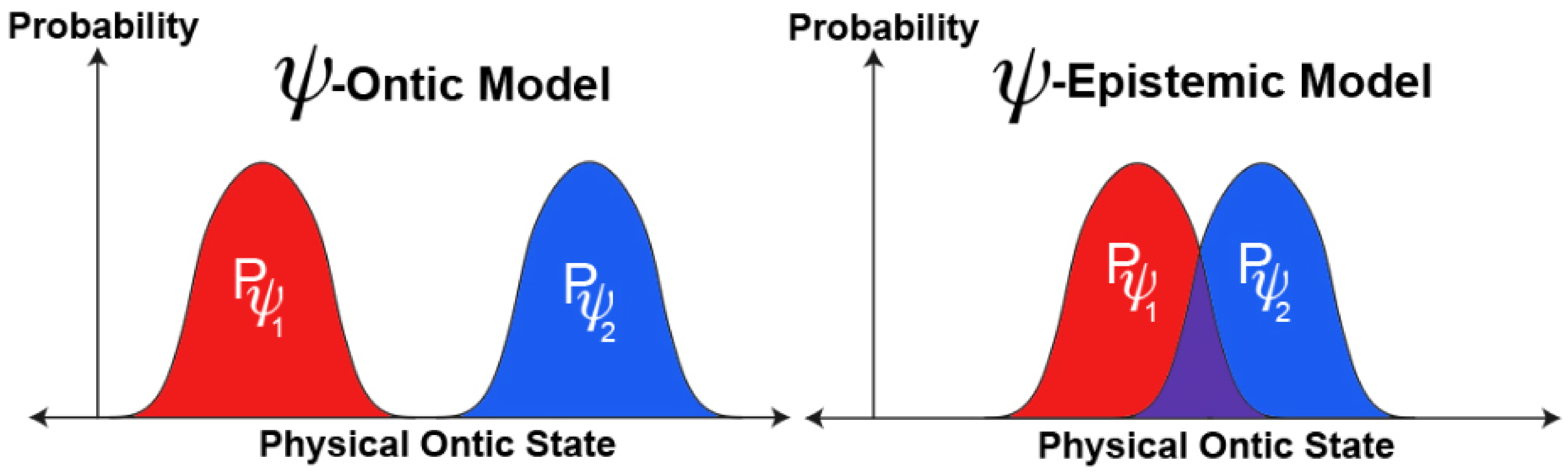
While these concerns might not affect the results of most quantum experiments in a noticeable way, the PBR theorem requires that they be prepared completely independently. Any tiny violation of this, no matter how small, would invalidate the conclusions. In fact, questioning the seemingly reasonable assumption of preparation independence, and even whether scientists have complete free will to set up their experiments, is one of the main motivations that led my colleagues at MIT and I to propose an experiment to use causally disconnected quasars to choose experimental settings in a test of Bell's inequality.

Back to the laboratory

Late last year, a team of experimental physicists including lead author Martin Ringbauer, working in the group of Professor Andrew White at the University of Queensland, performed an experiment designed to test whether the ψ-ontic or ψ-epistemic picture gives the best explanation for certain quantum experiments, without having to make the same assumptions that PBR did. The key issue is that certain quantum states called "orthogonal" are relatively easy to distinguish experimentally: for example a photon with "horizontal" polarization versus another with "vertical" polarization. Other "non-orthogonal" quantum states, like two different combinations of both horizontal and vertical polarization, cannot be distinguished perfectly, even if the experimenter knows what the possibilities are in advance.

The ψ-ontic and ψ-epistemic views tell very different stories about why non-orthogonal quantum states are so hard to tell apart in the lab. In the ψ-ontic view, the quantum state is uniquely determined by the ontic state. But in the ψ-epistemic picture, more than one quantum wave function can represent the same ontic reality. Think of the old chestnut about the tree falling in the forest: assuming for the moment that the tree does have an ontic state even in the absence of an observer, that ontic state can be either "fallen" or "not fallen," and the quantum state can be "sound" or "no sound." A quantum state of "no sound" can correspond to two different realities—one in which it didn't fall, and one in which no one was there to hear it—so knowing the quantum state alone doesn't tell you the true ontic state.

We can show this visually using a graph like the one below. Assuming that there really is some underlying "reality" (a subject for another day), the ψ-ontic model says that the wave functions of two independent states can't overlap. But in the ψ-epistemic model, on the right, two different wave functions can correspond to the same ontic state, represented by the purple area where the curves of the wave functions *do* overlap.



Now, imagine that, instead of overlapping two-dimensional curves, we had overlapping three-dimensional spheres. (For extra credit, and a guaranteed headache, you can even try imagining four-dimensional overlapping hyperspheres.) The more dimensions you add, the smaller the relative size of the overlap. In quantum mechanics, this means that as you measure more parameters of your system—not just polarization but the direction of motion, for instance—it's harder to find two wave functions that represent the same ontic reality.

Ringbauer and his colleagues tested this out by measuring several states of specially-prepared photons, each with either three or four parameters. Adding a new quantum state is like adding an extra sphere to the set. When adding more spheres, and/or increasing the number of dimensions, it becomes even harder to find places where all the spheres overlap. With this analogy in mind, the Queensland group found that as they increased the number of parameters for each quantum state and increased the number of states they were trying to distinguish between, their experimental results increasingly diverged from the predictions of a well defined ψ-epistemic model. Their experimental results thus strongly conflict with the ψ-epistemic picture's "overlap" model—a major strike against the ψ-epistemic viewpoint.

The new results aren't totally free of controversial assumptions, though. For example, Ringbauer and colleagues have to assume that there are such things as objective physical properties, independent of observers. (That is, that the moon exists even when you're not looking at it, as Einstein once said.) Their argument also hinges on the specific way they define a physical model to be ψ-ontic or ψ-epistemic, adapting an expanded framework originally developed by John Bell in 1964 when deriving his famous Bell's theorem. But they do avoid the assumption of preparation independence that was required for the PBR theorem. Overall, this is an elegant approach to attacking a deep foundational issue with experimental data.

If new results like these help us to better understand the nature of reality, many physicists will undoubtedly utter a ψ of relief. In all seriousness, I expect (and hope) that a combination of new theoretical ideas and real-world experiments will help reconcile these two seemingly incomparable views on the wave function. Both camps have many points in their favor and both seem to be at least partially right.

In the quest to understand the true Nature of Reality, we must continually question our most basic assumptions, admit and quantify our ignorance, and be explicit about what we are assuming. All of this is required in order to edge ever closer to finally grasping the meaning of the complex mathematical workhorse of quantum theory: the century-old, yet still misunderstood, wave function.

Go Deeper

Author's picks for further reading

arXiv: Measurements on the reality of the wavefunction
In this preprint of their Nature Physics paper published in 2015, Martin Ringbauer and his colleagues in the group of Andrew White (Queensland) describe their experiment bolstering the ψ-ontic view of the wave function.

arXiv: QBism, the Perimeter of Quantum Bayesianism
A broad overview of Quantum Bayesianism, both philosophical and technical, by one of its leading proponents, Christopher Fuchs (UMass Boston).

arXiv: On the reality of the quantum state
In this 2012 paper, later published in Nature Physics, Matthew Pusey (Perimeter Institute), Jonathan Barrett (Oxford) and Terry Rudolph (Imperial) present their novel "PBR" no-go theorem supporting the ψ-ontic view.

arXiv: A Synopsis of the Minimal Modal Interpretation of Quantum Theory
Jacob Barandes (Harvard) and David Kagan (UMass Dartmouth) present a synopsis of an explicitly realist quantum interpretation with both ψ-ontic and ψ-epistemic features.

Matt Leifer: Can the Quantum State be Interpreted Statistically?
An excellent explanation of the PBR theorem, and the basic issues surrounding ψ-ontic and ψ-epistemic models, by quantum foundations expert Matt Leifer (Perimeter Institute).

Nature News: Physics: QBism puts the scientist back into science
An accessible article by eminent quantum theorist, and converted Quantum Bayesian, N. David Mermin (Cornell) about how one of the most prominent ψ-epistemic views, QBism, helps demystify both quantum mechanics and classical physics, including our subjective perception of time.

Quanta: Is the Quantum State Real? An Extended Review of ψ-ontology Theorems
A thorough recent review article also by Matt Leifer (Perimeter Institute) on the most important results regarding ψ-ontic and ψ-epistemic models in the technical literature.

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Andrew Friedman is a recent National Science Foundation Science, Technology & Society postdoctoral fellow at the Massachusetts Institute of Technology and currently a Visiting Research Scientist at the MIT Center for Theoretical Physics. Before MIT, he received a Ph.D. in Astronomy and Astrophysics from Harvard University and a B.A. in Physics and Astrophysics from the University of California, Berkeley. He is currently working on several theoretical and observational cosmology projects, including devising fun experiments that leverage cosmology to help test fundamental physics. His research background is primarily in observational astronomy and cosmology, specifically cosmological studies of Gamma-Ray Bursts and infrared observations of Type Ia Supernovae which can be used to measure the expansion history of the universe, cosmic acceleration, and dark energy. He is very interested in projects at the intersection between astrophysics, cosmology, and the philosophy of science, and is excited to continue bringing some of these fascinating scientific questions to the public through science writing, art, animation, and other media.

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