OVERLINE

Is Quantum Mechanics Tried, True, Wildly Successful, and Wrong?

A skeptical physicist charges that his field has been wandering in a philosophical wilderness for 80 years. The good news: He thinks he knows the way out

Antony Valentini has never been happy with quantum mechanics. Sure, it's the most powerful and accurate scientific theory ever devised. Yes, its bizarre predictions about the behavior of atoms and all other particles have been confirmed many times over with multi-decimal-place exactitude. True, technologies derived from quantum mechanics may account for 30% of the gross national product of the United States. So what's not to like?

Valentini, a theoretical physicist at Imperial College London (ICL) and the co-author of a forthcoming book on the early history of quantum mechanics, believes that shortly after the theory's birth some 80 years ago, a cadre of influential scientists led quantum physics down a philosophical blind alley. As a result of that wrong turn, Valentini says, the field wound up burdened with paradoxical dualities, inexplicable long-distance connections between particles, and a pragmatic "shut up and calculate" mentality that stifled attempts to probe what it all means. But there is an alternative, Valentini says: a long-abandoned "road not taken" that could get physics back on track. And unlike other proposed remedies to quantum weirdness, he adds, there's a possible experiment to test whether this one is right.

"There isn't a more insightful or knowledgeable critic in the whole field of quantum theory," says Lee Smolin, a theoretical physicist at the Perimeter Institute for Theoretical Physics in Waterloo, Canada. Smolin, who researches a subfield known as quantum gravity, has long held that current quantum theory is incomplete at best.

In a book to be published later this year by Cambridge University Press, Valentini and co-author Guido Bacciagaluppi, a philosopher of physics at the University of Aberdeen, U.K., reassess a pivotal and contentious meeting at which 29 physics luminaries—including Louis de Broglie, Niels Bohr, Werner Heisenberg, Erwin Schrödinger, and Albert Einstein—butted brains over how to make sense of quantum theory.

The book, *Quantum Theory at the Crossroads*, includes the first English translation of the proceedings of the historic 1927 Solvay conference. The gathering was the fifth in an ongoing series of invitation-only conferences in Brussels, Belgium, launched in 1911 by the Belgian industrialist Ernest Solvay. At the meeting, blandly titled "Electrons and Photons," attendees grappled with issues that were—and remain—among the most perplexing ever addressed by physicists. Quantum mechanics confounds commonsense notions of reality, and the physicists in Brussels disagreed sharply about the meaning of the theory they had created.

"Quantum physics ... is a special case of a much wider physics, with many new possible phenomena that are just there waiting to be explored."

—ANTONY VALENTINI
IMPERIAL COLLEGE LONDON

A classic experiment demonstrates the sheer strangeness of the new physics they were struggling to understand. Light—a stream of photons—shines through two parallel slits cut in a barrier and hits a strip of film beyond the slits. If the experiment is run with detectors near each slit so physicists can observe the passing light particles, the result is unsurprising: Every photon goes through either one slit or the other, just as particles should, leaving two distinct clusters of dots where the individual photons strike the film.

Remove the detectors, however, and something exceedingly strange happens: A pattern of alternating light and dark stripes appears on the film. The only explanation is that photons sometimes behave like waves. As light waves emerge from the two slits, bright lines form on the screen where wave crests overlap; dark lines, where a crest and trough cancel each other. As long as no detectors are present, the same pattern appears even if the photons hit the screen one by one. Over the decades, physicists have tried the experiment with photons, electrons, and other particles, always with the same bizarre results.

The experiment highlights two of the conundrums that dominated discussions at the 1927 Solvay conference: How can photons, electrons, and all other bits of matter and energy behave like waves one moment, particles the next? And how does one explain that the mere act of observation seems to affect physical reality—at least on the quantum level?

Unreality rules

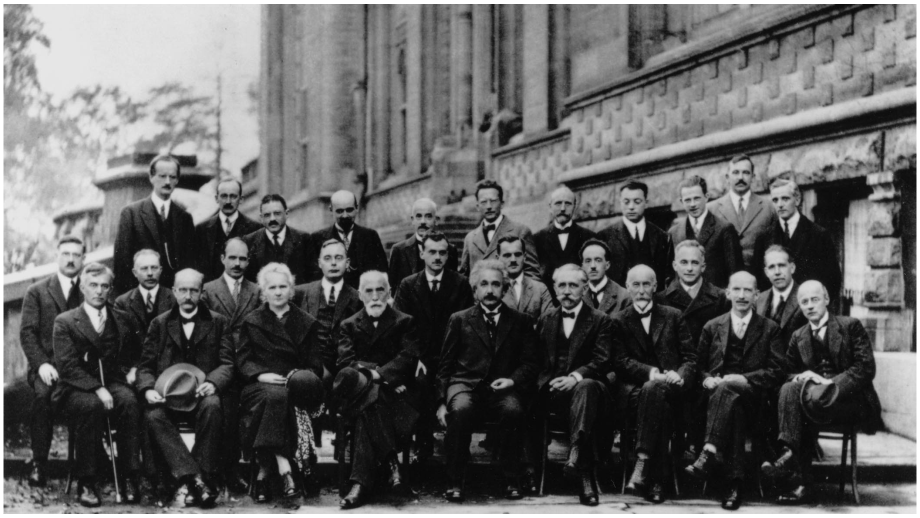
Bohr and Heisenberg answered such questions with an austere vision of the theory now called the Copenhagen interpretation. With no observer present, they said, any given particle exists here, there, and everywhere in between, dispersed like a wave. Introduce an observer to measure the wave, however, and the quantum wave "collapses" into a single particle. Before the measurement, the particle could be described only by an equation that specified the probability of finding it in one location rather than another. The act of measurement itself forces a particle to assume a single, definite position. The sharp boundary between an objective world "out there" and subjective observations blurs in this version of quantum theory.

"Bohr believed that it was meaningless to try to describe the quantum world because we have no direct experience of it," says Valentini. "Bohr and Heisenberg thought that quantum mechanics showed we had reached the limits of human understanding. … Physics no longer told us how things *are*—it only told us how human beings perceive and measure things."

Some conference participants, most notably Einstein, de Broglie, and Schrödinger, rejected Bohr's arguments. Physicists today remember Einstein as Bohr's chief antagonist. But their famed disputes over the validity of quantum theory must have taken place off the record, Valentini says; the published conference proceedings don't mention them at all.

The proceedings do, however, contain 24 pages of discussion of a rival interpretation by de Broglie. Unlike Bohr, who viewed the quantum wave equation describing a particle as a mathematical abstraction, de Broglie

CREDIT: COURTESY OF A. VALENTINI



Bold lead-in. Caption goes here caption goes here caption goes here caption goes here caption goes here caption goes here caption goes here caption goes here caption goes here.

thought such waves were real—he called them pilot waves. In de Broglie's picture, particles never exist in more than one place at the same time. All the mysterious properties of quantum theory are explained by pilot waves guiding particles along their trajectories. In the two-slit experiment, for example, each particle passes through only one slit. The pilot wave, however, goes through both slits at once and influences where the particle strikes the screen. There is no inexplicable wave collapse triggered by observation. Instead, Valentini says, "the total pilot wave, for the particle and the detectors considered as a single system, evolves so as to yield an *apparent* collapse."

Bohr, Heisenberg, and their supporters at the Solvay conference were unimpressed. The details of the particle trajectories were unobservable, and Bohr insisted that physicists shouldn't traffic in hidden, unmeasurable entities. "De Broglie wasn't happy with the Copenhagen interpretation," says Valentini, "but he gave up trying to argue about it."

Bohr and Heisenberg's vision of quantum theory prevailed; de Broglie's languished. David Bohm, a prominent American physicist, rediscovered de Broglie's work in the early 1950s and expanded on it. But Bohm's work, like de Broglie's, failed to attract much support, because it could not be distinguished experimentally from conventional quantum mechanics.

The past decade has seen renewed interest in understanding the foundations of quantum mechanics, and physicists have devised several competing interpretations of the theory (*Science*, 25 June 2004, p. 1896). Valentini has been in the thick of this quantum renaissance. In the early 1990s, as a graduate student studying with the late Dennis Sciama, a cosmologist who also mentored Stephen Hawking, he learned about the work of de Broglie and Bohm and became convinced that it had the potential to resolve all the mysterious paradoxes of quantum mechanics. He has spent most of his career almost single-handedly building on their work.

His single-mindedness has cost him. Although Valentini's colleagues acknowledge the originality and importance of his research, spadework on the foundations of quantum theory has not been a fast track to tenure. For years, he has survived from grant to grant in a succession of temporary positions; his current one at ICL ends this year.

"I used to do private teaching just to get by," Valentini says. "Things have changed in recent years, but I'm still just living year by year. It is a field where there are these wide-open, in-your-face problems with interpretation[s?] that are staggeringly fundamental, with virtually nobody in the world really dedicating the bulk of their time and attention to working on them. So how do you expect there to be much progress?"

Beyond the quantum?

In Valentini's physics, the "laws" of quantum mechanics are not really laws at all but accidents of cosmic history. Particles in the universe today conform to the supposed rules of quantum mechanics, Valentini suggests, because they settled into a sort of quantum equilibrium immediately after the big bang, in a process roughly analogous to the way a mixture of hot and cold gases gradually reaches a uniform temperature. Immediately after the big bang, particles could have existed in states not allowed by the normal rules of quantum mechanics but permitted in pilot-wave theory.

Bold lead-in. Caption goes here caption goes here caption goes here caption goes here caption goes here cap

"Quantum physics is not fundamental; it's a theory of a particular equilibrium state and nothing more," says Valentini. "To my mind, pilot-wave theory is crying out to us that quantum physics is a special case of a much wider physics, with many new possible phenomena that are just there waiting to be explored and tested experimentally."

The place to look, Valentini says, is in the cosmic microwave background (CMB), the remnant radiation from the big bang that fills all of space. The radiation is almost perfectly uniform, with only slight variations in temperature. Theorists think those small temperature differences resulted from quantum fluctuations that were magnified as the universe expanded. In a paper Valentini has submitted to *Physical Review D*, he argues that if his pilot-wave theory is correct, some of those temperature variations will not have the distribution that standard quantum theory predicts. Deviations are more likely to survive at long wavelengths, he says. CMB measurements by the WMAP probe have revealed "intriguing" anomalies in precisely that domain, Valentini says, but pursuing them will take time and effort. "I need to do a lot more work to refine my predictions," says Valentini. "Part of the problem is that I'm the only person working on it. It is a difficult thing."

Confirmation of Valentini's idea would be one of the biggest advances in physics in decades. The Planck spacecraft, launched in May by the European Space Agency (*Science*, 1 May, p. 584), will take a closer look at the CMB and could conceivably find evidence supporting Valentini's predictions.

"One of the most attractive features of Antony's proposals is that they're testable," says David Wallace, a philosopher of physics at the University of Oxford in the United Kingdom. "If tomorrow there is some experiment that Antony's theory gets right and quantum mechanics gets wrong, then end of story."

Valentini knows he faces steep odds. "Maybe in 200 years people will look back and say the time wasn't right to reexamine the foundations of quantum mechanics," he says. "Or it might be that they'll say, 'My God, it opened up a whole new world.' We can't tell. One thing is certain: We won't find out if we

CREDITS (FROM TOP): PHOTOGRAPH BY BENJAMIN COUPRIE, INSTITUT INTERNATIONAL DE PHYSIQUE SOLVAY; W. F. MEGGERS GALLERY OF NOBEL LAUREATES; PHOTOGRAVURE BY A. BORTZELLS TRYCKERI, WEBER COLLECTION; (ALL) COURTESY AIP EMILIO SEGRE VISUAL ARCHIVES

overset p.1513 (quantum)

don’t try.”

–TIM FOLGER

Tim Folger is a contributing editor at *Discover* and the series editor for *The Best American Science and Nature Writing*.