In the Beginning Was Quantum Mechanics

Cosmologists take a chance on a quantum universe

BY DIETRICK E. THOMSEN

In principio erat verbum. It seems appropriate to add the first few words of St. John's gospel to the Latin quotations that were bandied about at the beginning of the recent Workshop on Quantum Cosmology, which was held at the Fermi National Accelerator Laboratory in Batavia, Ill. This outburst of Latinity and classical scholarship, which even included a dispute over whether the word *apparatus* belongs to the second or the fifth declension, seemed an appropriate beginning for a conference on a subject – the origins of the universe – that has fascinated scholars ever since classical times.

In the beginning was the word, *en arche hen ho logos.* One of the meanings of "logos" in this context is a word descriptive of the basic structure of the universe and, more than descriptive, a dynamical word that outlines and perhaps even determines the course of the history that follows the beginning. From the philosophers of ancient Hellas to the professors of physics in modern universities, most have expected that this word would be mathematical. It is the last generation or two that has expected it to be quantum mechanical.

"Quantum mechanics has to describe everything," said Murray Gell-Mann of Caltech in Pasadena in the opening talk of the workshop. And it became clear that by "everything" he meant the work of historians and crime detectives and the songs of birds as well as the motions of galaxies. But he added: "The questions are all murky and border on the philosophical."

The main reason for the dominance of quantum mechanics was cited by James Hartle of the University of California at Santa Barbara: "The laws of physics are quantum mechanical; quantum cosmology is the proper framework." Nevertheless, the large objects that dominate the universe as we now see it operate according to classical mechanics. The serious problem for all of physics, and for quantum cosmology in particular, is to find some kind of linkage by which classical physics can be generated out of quantum mechanics.

A similar question occurs historically: If we trace the expansion of the universe backwards we eventually come to a point in history when the universe was so small that it had to behave as a whole as a quantum mechanical system. Figuring out how the present came out of the past is the problem.

The initial state from which the universe evolved has always been a sticking point for expanding-universe cosmologies. Naively tracing the expansion back leads to a point when the universe had zero diameter, space was infinitely curved, and by definition the laws of science failed to hold. This point is known as a singularity. One singularity is bad enough, but general relativity, the theory of gravity that nearly all physicists believe in, allows the universe to have many of them, one in the center of each black hole.

We expect the laws of physics to hold everywhere and at all times, Stephen Hawking of Cambridge University in England reminded the workshop, yet for more than two decades we have tolerated a Big Bang cosmology that not only begins at a singularity but also expects the universe to be salted with a great number of other singularities. "We cannot predict what comes out of a singularity," he says. "It is a disaster for science." Hawking has spent 25 years working on the physics of singularities and their surroundings and has become quite famous for it, but in spite of his investment in singularities, he told the meeting, "I have changed my mind."

Hawking then presented to the meeting a picture of a universe without singularities, where the laws of science truly hold everywhere. It can be so, he says, if it was and is in its quantum mechanical "ground state." In quantum mechanics a physical system, say an atom, can exist in a hierarchy of discrete states characterized by different amounts of energy. Each state involves different arrangements and activities of the atom's internal parts. The atom can go from one state to another by losing or gaining energy. The ground state is the lowest-energy state available to any system, usually involving the least amount of internal activity.

If the universe as a whole is a quantum mechanical system like an atom and is in its ground state, then, according to Hawking, it no longer needs a singularity at the beginning, and the centers of black holes are no longer singularities but little separate universes connected to ours by passages that topologists call wormholes.

Things that happen to fall into the black hole eventually pass into these little universes. However, if the universe, our universe, is in one or another of its energetically excited states rather than in its ground state, the existence of these separate little universes with their connecting wormholes provides channels by which information from outside the system may enter. "God may know what this information is; we don't," Hawking says. "If the universe is not in the ground state, science cannot predict the universe. The rest is up to God."

In a quantum mechanical universe, whether in the ground state or not, it seems science can predict much less than people whose expectations are conditioned by classical physics (or perhaps by Calvinist theology) might expect. In classical physics, causality is absolute. A given cause leads to a given effect. In any case the probability of a given result is either 1 (it must happen) or 0 (it must not happen). Quantum mechanical causality is statistical, and traditionally it applies to large ensembles of individuals. Its probabilities are usually between 0 and 1, and the customary interpretation of them is that a certain fraction of the individuals will do one thing and a certain fraction something else.

The traditional way of regarding quantum mechanics, the Copenhagen interpretation, regards the theory as intrinsically inexact. In this view quantum mechanics cannot make predictions about individual objects, and the way in which it connects to classical physics is left vague. Gell-Mann declares that we need a new interpretation of quantum mechanics as an exact science so that it can make predictions about the whole universe, which is after all a single system.

These predictions about the single universe, which Gell-Mann and his collaborator Hartle call "a priori" probabilities, tell us that there is a certain percent chance that the single universe will be in this state or that state. From these a priori probabilities it is necessary to be able to predict both statistical probabilities (that is, those of ordinary quantum mechanics) for the large ensembles and classes of similar objects, such as galaxies, stars or white-headed woodpeckers, and also to get the absolute yes-or-no predictions of classical physics, which still apply to certain individual cases. In the completed system, Gell-Mann says, "When we do have an ensemble, a priori probability yields statistical probability. However, an a priori probability close to 0 or 1 yields a classical prediction."

To get to that point, to get past the usual vaguenesses of ordinary quantum mechanics, Gell-Mann puts the probabilities through a process he calls "decoherence." In ordinary quantum mechanics fundamental uncertainties arise because probabilities are linked to each other, they interfere with each other, leading to uncertainty about what is going on. The classic double-slit diffraction experiment, in which the probability of detecting light as a particle going through one slit or the other and the alternate probability of detecting it as a wave going through both slits at the same time are so linked, is Gell-Mann's example. Decoherence will separate these linked probabilities, allowing us to concentrate on the ones that affect us and ignore the rest.

Decoherence involves throwing away a lot of information and literally ejecting a lot of probabilities from our universe, for the thrown-away probabilities belong to other parallel universes. People working on this idea believe in the so-called many universes solution to cosmological problems: that there are or at least can be a lot of different universes with different physical characteristics that do not communicate with each other.

The word "universe" can be used in two senses, to mean all the material reality that exists or to mean as much of material existence as we can know about, which may not be the whole thing. These many parallel universes are all part of *the* universe taken in the grand sense (one attempt at visualization likens them to bubbles within it), but although they may be philosophical existents, they are physically inaccessible to us. We have no evidence for their existence, only arguments.

In our own little bubble this winnowing out of probabilities means that even though sometimes definite predictions based on probabilities of 1 or 0 can be made and sometimes statistical predictions based on fractional probabilities, a lot doesn't get predicted that some people might want to predict. As Hartle puts it, it doesn't predict that our solar system should have nine planets and not eight or 10. Nor does it say why a population of white-headed woodpeckers in San Mateo County sing one variation of the species' song, while those in Contra Costa County sing another. At one moment in time there are a lot of alternatives in both past and future, and so there are in another moment in time. Gell-Mann hinted that the human sense of having free will might be related to this profusion of alternatives.

That raises the problem of how we get a history. The universe as we know it obviously has a history. So does classical physics. As Hartle reminded the meeting, in classical physics time is a preferred variable: The clock runs majestically and regularly along, independent of the physical system under consideration. Any classical physics theory automatically has a history. In quantum mechanics the clock is part of the system.

A great deal of complicated physics and mathematics is being done to solve the difficulties caused by this linkage and to put quantum mechanically determined events in some kind of temporal sequence. The decoherence process does it automatically to some extent, says Gell-Mann, and in addition he can appeal to the principle of simplicity — that the universe began in a simple state and that things get more complicated as they move in temporal sequence.

"Fifteen billion years ago, the universe was in a simple condition," he says. "We call the direction to that condition 'ago.' "

Given all this, Gell-Mann and Hartle can start with an array of probabilities, a density matrix, for the beginning, bring it down to us and our measurements, and then to the probability that we will have certain data in our memories. Here the theory becomes very much an information theory. Gell-Mann seems to agree with the authors of *1066 and All That* (Sellar & Yeatman, Dutton, 1958), that history is what you remember. If you talk to professional historians, he says, they will tell you that they make a history from data available now—coins, monuments, documents, etc. — and what is in our memory banks depends on probability. The historians did not experience the past. Likewise the crime detective, who "knows the quantum mechanical formula intuitively, constructs a variety of scenarios and evaluates the probability that they predict what will be found." So in science also, we make a cosmology from the data probability has given us.

At this point Yakov B. Zeldovich of the Institute for Cosmic Investigations of the USSR Academy of Sciences in Moscow, objected: "What has all this got to do with observable reality?"

Gell-Mann replied that this procedure could turn a random statistical fluctuation of the density of the early universe into a specific galaxy "that we all know and love," reminding Zeldovich that Zeldovich himself is famous for proposing that such statistical fluctuations become observable galaxies.

Some cosmologists have proposed that our bubble, our universe, underwent a period of rapid, inflationary expansion in the past. This expansion would obviate the necessity of worrying about the beginning, as it would erase the memory of the earliest conditions and guarantee the present appearance of our universe no matter what the beginning was. Hartle argues that inflation won't do this for every possible case, nor can we assume, as some of these cosmologists do, that our universe is necessarily in the most probable state that it might be in. And he quotes Cato: *Delenda est Carthago.* Zeldovich, who seems to favor inflationary schemes, and who is critical of the Gell-Mann-Hartle-Hawking efforts, replied with a quote from Julius Caesar: *Divide et impera.* □