done. For instance, he notes that in liquid-state NMR, "the size of the ensemble has to grow exponentially in order for the system to work. If that doesn't happen, then very quickly the signal-to-noise ratio makes it impossible to see an output." And the nonentangled algorithm for searching through N objects requires a system of size N—exponentially more resources than the $\log_2 N$ needed in a fully entangled quantum computation.

Scaling issues are fundamental to the discussion of quantum computers, explains David Cory (MIT). "For a quantum computer, the resources needed for a computation have to scale appropriately," he told us. "Liquid-state NMR can certainly process information—the dynamics are great—but it does not scale as a quantum computer, so it's a mistake to call liquid-state NMR implementations of quantum information processors, quantum computers." Many scaling concerns were raised early on, including in the original papers on NMR implementations.[5,13] Braunstein and company have clarified the issues, says Gershenfeld, by showing the cost of being unentangled due to very low polarization.

Braunstein and his colleagues speculate that, as the number of qubits increases, entanglement will eventually appear. But there are other, fundamental obstacles to scaling the current room-temperature liquid-state NMR techniques beyond about 10 qubits. Researchers are therefore exploring other alternatives that might still take advantage of the coherent control and long coherence times in magnetic resonance. Possibilities include optical pumping and various solid-state NMR schemes.

Andrew Steane (University of Oxford) warns, however, that NMR is restricted to looking at an ensemble average instead of measuring individual qubits. "This is the essential limitation of NMR," he explains. In addition to causing scaling problems, "it means that you can't do certain experiments where measurement is an essential part of the process, like when you're looking for nonlocal correlations."

In the end, efforts to implement quantum logic using NMR may find an unexpected beneficiary—NMR spectroscopy.[14] The questions raised by the work of Braunstein and company could also have significant long-term impact on what mixed states are good for. Work on quantum error correction and distillation (see John Preskill's article in PHYSICS TODAY, June 1998, page 24) has examined the behavior of systems in the vicinity of pure states. Attention is now being paid to states near the maximally mixed states—the opposite extreme. "The domain of mixed states between these two extremes is incredibly big and largely unexplored," notes Jeff Kimble (Caltech). "It is an extremely important endeavor to understand the nature of entanglement for general mixed states and to harness this power for various tasks in quantum information science."

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Experts Dismiss Doomsday Scenarios for RHIC

A panel of particle physicists has examined concerns that high-energy collisions of gold nuclei might trigger the formation of black holes, vacuum instabilities, or voracious strangelets.

The Relativistic Heavy Ion Collider (RHIC) recently completed at Brookhaven National Laboratory is expected to produce a plasma of quarks and gluons—the state in which matter is thought to have existed in the first microseconds of the Big Bang, before matter coalesced into the neutrons and protons that characterize our universe today (see PHYSICS TODAY, October 1999, page 20). Before entering any such new territory, explorers naturally speculate on what unknowns might be encountered. In this case, the speculations have included a few scenarios—recognized to be extremely remote even by those physicists who have raised them—that could possibly spell danger. Concerns over those scenarios were voiced last summer in the general press. To examine their likelihood, Brookhaven director John Marburger appointed a panel of particle physicists consisting of Wit Busza (MIT), Robert Jaffe (MIT), Jack Sandweiss (Yale University), and Frank Wilczek (Institute for Advanced Study). Their report concludes that "the candidate mechanisms for catastrophe scenarios at RHIC are firmly excluded by existing empirical evidence, compelling theoretical arguments, or both." (www.bnl.gov/bnlweb/rhicreport.html)

The panel evaluated three exotic concerns: that heavy-ion collisions might (1) generate black holes that would consume ordinary matter; (2) initiate a transition from our current vacuum to some lower-lying, more stable vacuum; and (3) produce an unlikely type of particle known as a strangelet, which just might convert ordinary matter into strange matter without limit.

To conjure up any of these scenarios, one must invoke hypotheses that run counter to expectations based on our current knowledge of physics—but that are not absolutely excluded by it. To evaluate them, the four panelists looked both at current theoretical knowledge and at empirical evidence.

Regarding the formation of black holes, the panel first argues that the relevant parameter is not the total center-of-mass energy of RHIC's colliding gold nuclei (which, at 200 MeV per nucleon, exceeds the center-of-mass energy of any previous accelerator), but the energy density. The energy of the gold nuclei is concentrated in their constituent quarks and gluons, which have collided at higher energies in some existing accelerators. Even if all the mass in the gold nuclei were somehow compressed to the size of an individual proton (and there's no known mechanism for accomplishing that), the strength of gravity would still be at least 10^{22} times less than the nuclear force. Stated purely in terms of classical effects, the escape velocity from the surface of this clump of matter would be 10^{11} times smaller than the speed of light c; For a black hole, it's exactly c.

The second possibility considered by the panel is the vacuum instability. The ordinary vacuum we know is recognized to be a highly structured medium, which can theoretically exist in various states or phases. Some researchers have postulated that the ordinary vacuum is only metastable—although there is no *a priori* reason to expect this—and that a sufficiently violent collision, such as one of those at RHIC, might trigger its decay into a different, more stable vacuum. The panel rules out this possibility because it has not happened yet, despite the innumerable collisions between gold nuclei over the past billions of years in the vacuum of space at energies as high and higher than those achieved at RHIC. The panel reviewed a calculation of the number of collisions of various types that have occurred in our past light cone,[1] and concluded that, even if the abundance of gold nuclei in space were many orders of magnitude lower than our best current estimate, the number of gold–gold cosmic-ray collisions that have occurred safely greatly exceeds those expected during the lifetime of RHIC.

The panel devotes most of the space in its report to the issue of strangelets. Theorists have predicted that strangelets might form when matter is subjected to high enough pressures; such high baryon densities might prevail in the core of neutron stars. Under these conditions, normal matter becomes a gas of freely moving quarks and gluons. It might be energetically favorable for some of the up and down quarks of normal matter to become strange quarks through weak interactions. The resulting strange matter, a clump of which is termed a strangelet, typically has a very low charge-to-mass ratio.

Some theorists have postulated that, once formed at high pressure, strangelets might remain stable at a lower pressure and zero temperature. But to date, they haven't been seen either in neutron stars or in accelerator collisions.

Strangelets are expected to be positively charged and hence quite benign: They should be quickly surrounded by a sea of electrons and prevented from further interaction with other matter.

The disaster scenario envisions the formation, somehow, of a negative strangelet. If captured by a nucleus, it might convert some of the up and down quarks to strange quarks. The resulting nucleus would become positive and hence harmless. But there's a remote possibility that a negative nucleus is more stable. Then the strangelet might capture some orbital electrons to become negative again and repeat the cycle without limit.

Wilczek outlined for us the chain of (unlikely) hypotheses that would have to be true for such runaway strangelets to be let loose. First, strangelets would have to represent the lowest energy, stable configuration of matter, even at zero external pressure and at small sizes. Available evidence from theory and experiment points against this. Second, the strangelet would have to be negatively charged to be able to "eat" ordinary matter. Yet this beast is overwhelmingly more likely to be positive. Third, one would have to be able to produce it in the RHIC environment, and there's no known mechanism for that. Furthermore, Wilczek and his colleagues have argued, the Moon has not yet turned into strange matter, despite billions of years of bombardment by energetic iron and gold atoms in cosmic rays.

Three CERN theorists—Arnon Dar, Alvaro de Rújula, and Ulrich Heinz—recently undertook an independent analysis of the possibility that heavy ion colliders, such as RHIC or CERN's planned Large Hadron Collider, might unleash destructive strangelets.[2] Adopting a worst-case approach, they ask: What if strangelets are produced with a higher probability in center-of-mass collisions, such as those at RHIC, than in fixed-target collisions, such as those of cosmic rays with the Moon? Dar and his colleagues estimated how many collisions there have been in outer space between gold nuclei rushing at one another with equal speeds without producing strangelets. They conclude that it is safe to run RHIC for 500 million years. **Barbara Goss Levi**

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