PHYSICS

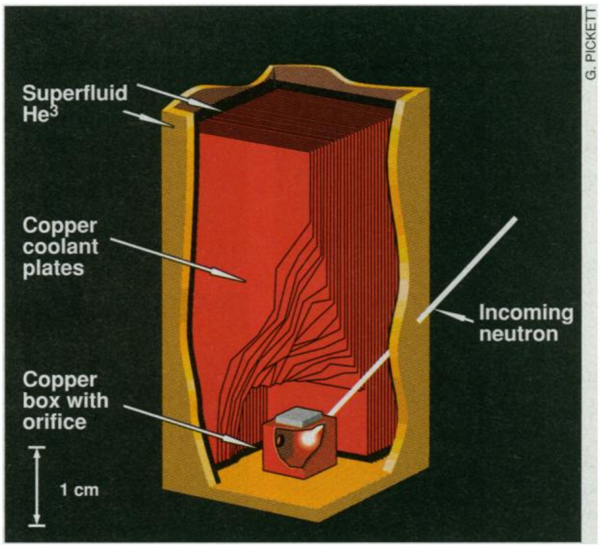
Experiments Mimic Infant Universe in Superfluid Helium

A flask of liquid helium at a temperature a hair above absolute zero might seem an odd place to simulate the universe a fraction of a second after its birth in the cosmic fireball of the big bang. But this unlikely medium has provided a critical test for one of cosmologists' more esoteric theories: the notion that infinite stringlike fractures, which appeared in the fabric of space-time as the early universe began to cool, seeded the formation of the galaxies and larger scale structures we see today.

Two international teams report in the 25 July issue of *Nature* that they have measured the rate at which strings form in bottles of superfluid liquid helium-3 and found that it matches theoretical predictions for what might have occurred in the early universe. "It is very nicely consistent, given how simple the theory is and how controversial it used to be," says Wojciech Zurek, the Los Alamos National Laboratory physicist who proposed the theory of string formation from phase transitions. As for the experiments themselves, Zurek calls them "spectacular."

Behind the concept of cosmic strings is the idea that as the universe cooled from the first moments of the big bang, it went through a series of phase transitions, much like steam condensing into water and then freezing into ice. The phase transitions in the neonatal universe, says physicist Tom Kibble of Imperial College, London, involved the universe's fundamental forces. At the moment of creation there would have been one highly symmetric unified force, but as the universe cooled and expanded, this symmetry broke, resulting in the four forces seen today—electromagnetism, the weak and strong forces, and gravity. As the symmetry broke, space-time took on a preferred "direction," akin to the direction that the magnetic field in a ferromagnet assumes when the magnet cools from a disordered state at high temperature to an ordered state in which all the magnetic moments of the individual atoms align.

On the scale of the early universe, however, the analogy is stretched a bit thin, explains Kibble. The phase transition from disorder to order in a magnet is slow enough that the direction of magnetization is likely to be the same throughout the magnet. But in the early universe, the phase transition would have happened much too fast for a consensus to be reached, and different domains of the universe would have settled into different orientations, trapping between them regions where the different orientations couldn't be reconciled. The result would have been topological defects in the fabric of space-time.



Little big bang. In a bath of superfluid helium-3, heat from an incoming neutron triggers a phase transition like one that took place a fraction of a second after the big bang.

Kibble showed in 1976 that under certain conditions these defects could take a variety of forms, among them one-dimensional strings. These cosmic strings would stretch across the universe, says physicist Matti Krusius of the Helsinki University of Technology (HUT). "They would be very massive, and some people think they would have a superconducting core. They would fluctuate in time and create ripples in the vacuum state, and this would then be a way to create galaxies" by forming density perturbations that would induce matter to begin collapsing under gravity.

While this picture had rivals as a theory of galaxy formation, it was the only one that could be tested in the laboratory, as Zurek suggested in 1985. He pointed out that the mathematics of the phase transition for liquid helium when it cools from a normal fluid into a superfluid—a condition in which it "basically behaves like a vacuum, which means you can move an object and find no resistance," says Henri Godfrin of the Center for Very Low Temperature Research in Grenoble—should be the same as that of phase transitions in the early universe. "The whole idea of phase transitions is that they're universal," says Zurek. "It doesn't matter if the transition is happening at 1 K or 10 gigaelectron volts. The mathematics is essentially the same, so we should be able to test out our ideas of the early universe in the lab." This phase transition would create strings in the laboratory whose rate of formation could be measured experimentally and compared with the theoretical prediction.

Zurek's proposition has already been put to the test in liquid crystals, which go through a phase transition from a disordered to an ordered state (*Science*, 18 February 1994, p. 921) and in superfluid helium-4. While both tests confirmed that strings form during the relevant phase transitions, neither matched the mathematics of the early universe as well as the new results—from groups at HUT and Grenoble—using superfluid helium-3.

Both groups first cooled helium-3 into the superfluid state, which exists at just two or three thousandths of a kelvin above absolute zero. They then flipped the superfluid back and forth through the phase transition almost instantaneously by shooting a single neutron into it. The neutron, says Zurek, "creates a fat cigarlike region which is heated above the phase transition of superfluid helium-3. Since this is still sitting in this relatively huge container of helium-3, it gets the heat sucked out of it very quickly and comes back to the broken symmetry phase. If the theory is right, you can estimate the rate this comeback happens, and then use that rate to estimate the density of topological defects formed after this trip back and forth." Because the energy from a single neutron drives the heating and cooling, adds Krusius, the experiment is "crystal clear to interpret. There is not much space for speculation anymore."

Of the two experiments, the Helsinki one comes closest to actually seeing the strings, with the aid of the world's first rotating nuclear demagnetization cryostat. "Imagine," says Lancaster physicist George Pickett, who works with the Grenoble group, "a Coke can that's revolving along its axis and going at very low speed." The can, containing superfluid helium-3, is kept spinning at a rate just below that which would generate stringlike vortices in the superfluid without a phase transition, explains Krusius. Add the neutron, and a fat cigar of superfluid flips through the phase transition, creating a vortex that first appears as a small ring. If the can weren't spinning, the ring would contract and quickly vanish. Instead it expands into a single line, parallel to the of axis rotation and extending from the top to the bottom of the container. The extended vortex can be spotted with magnetic resonance imaging, says Zurek, enabling the group to "pull out vortex lines and count them one by one." The Helsinki group went on to measure vortex formation at varying temperatures and pressures, and the results, says Kibble, "seem to fit [Zurek's predictions] very well."

Lacking such sophisticated imaging apparatus, the Grenoble researchers cool their superfluid liquid helium-3 to 130 microkelvin, a temperature five times lower than the Helsinki group reached and a world record. That's cold enough to stabilize the vortices formed in the liquid helium, enabling the Grenoble group to measure their density by determining how much energy they absorb from the surrounding superfluid. The researchers know exactly how much energy the neutron deposited in the helium-3—"a very well-known 764 kiloelectron volts [KeV]," says Godfrin—and they can measure the energy of the system before and after the entry of the neutron. Inevitably the difference comes to less than 764 KeV. The missing energy has no place to go but into the formation of vortex lines. "We don't actually see any vortices," says Pickett. "All we do is infer they're there from the energy deficit. But if we agree they're there, we can work out how far apart they are, and the distances agree very well with this scenario of cosmic-string formation."

The two experiments lend considerable credence to the idea that topological defects formed in the early universe. But the next step in cosmologists' postulated chain of events—the idea that cosmic strings provided the "seeds" for galaxy formation—is less amenable to a test. "The experiments allow us to estimate the initial number of defects that might have formed in the early universe," says Kibble, but then cosmologists have to follow the strings through a few billion years of cosmic evolution to see if they end up with the right properties to seed galaxy formation. "That's a long chain of reasoning," he says, "and the experiments in helium-3 don't help us with that." But at least they strengthen the first step in this cosmic chain.

–Gary Taubes

BEHAVIORAL GENETICS

Does Nature Drive Nurture?

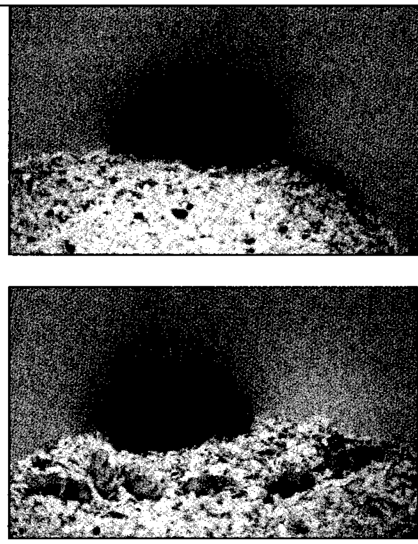
Researchers who create "knockout" mice by inactivating specific genes in the animals sometimes get less than they bargained for. The mice show fewer abnormalities than expected, or even none at all. But sometimes the researchers get much more. Take the knockout mice created by Jennifer Brown.

When Brown first bred the mice, in which she had inactivated a gene called *fosB* that is known to play a critical role in controlling the expression of other genes, she noticed something odd: Most of the pups were born healthy, but quickly died. "Only one or two [of a handful of mothers] had surviving pups. It was enough to pique my interest and provoke me to do a larger experiment, but not enough to make me think there was that much going on," recalls Brown, an M.D.–Ph.D. student who works in the lab of neuroscientist Michael Greenberg at Harvard Medical School.

A few months later, in the spring of 1995, she knew that her first impression was wrong. Something important was going on. By this time, two dozen pairs of parents with the *fosB* knockout had had litters. Again, most of the pups died. "Even the people in the animal facility were asking me what was happening with these mice," says Brown.

As Brown, Greenberg, and co-workers report in the 26 July issue of *Cell*, what appears to be happening is that *fosB* heavily influences—if not downright controls—whether a mother mouse nurtures her offspring. "This is among the first bit of evidence that nurturing in mammals has a genetic component," says Greenberg, who has long studied the relationship between the *fos* family of genes (there are four in all) and neurons.

The study, which merges molecular genetics and behavioral science, is winning plaudits from researchers in both fields. "I think it's a lovely piece of work, and it really shows the power of molecular genetics to analyze interesting behavioral problems," says Eric Kandel of Columbia University, who works in both areas. As Brown and Greenberg are the first to acknowledge, however, they haven't completely ruled out the possibility that the altered behavior of the mother knockout mice is caused by a physiologic or anatomical defect resulting from the *fosB* deletion, rather than from altered neuronal responses. "We need to do more work to really resolve whether this involves direct action of *fosB* in neurons," says Greenberg.



Mother inferior. A normal mouse mother *(top)* cares for her pups, while a *fosB* knockout *(below)* ignores hers.

BROWN ET AL., *CELL*, VOL. 86 NO. 2, JULY 26, 1996

Still, the link between *fosB* and behavior does not come as a complete surprise. During the past few years, many molecular geneticists have shown that the *fos* gene family is one of several turned on in neurons shortly after an animal receives some kind of environmental stimulus, such as contact with a pup. The proteins produced by these so-called "immediate early genes," in turn, kick other genes into action, leading ultimately to a neuronal response to the stimulus. And among the brain areas where *fos* family members are active are ones that other researchers have shown to be necessary for normal nurturing behavior.

Still, given the uncertainties of working with knockouts, Brown began the current work not knowing what she would find—if anything. But when she noticed how poorly the knockout mothers cared for their pups, ignoring them until they died, the team began an extensive study to see how *fosB* inactivation might be causing the problem.

The researchers ran several tests to make sure that the knockout mothers really were poor nurturers. For example, they removed pups from their mothers for an hour, put three back, and timed how long it took the mothers to move them to the nest. Wild-type mothers retrieved their first pup within 20 seconds and all three within 4 minutes. In contrast, only one of 10 knockout mothers retrieved all her pups within the 20-minute observation period, and the rest took more than 16 minutes to retrieve their first pup.

But the failure of the pups to survive may have had less to do with this behavior than with possible non-neuronal problems—if, for example, loss of *fosB* made it impossible for the knockout mothers to produce milk. Their mammary glands showed no abnormalities, however. The researchers next examined levels of hormones, such as progesterone and oxytocin, that are known to affect nurturing behavior. Again, wild-type and mutant mothers showed no differences. A check of several brain regions showed no obvious physical abnormalities in the knockouts, either.

Nor did the mutants appear to have olfactory abnormalities that might prevent them from recognizing their young through smell. Using an "aversive conditioning paradigm," the researchers showed that the mutants had