Nuclear Squeeze at Lawrence Berkeley Lab

High-energy collisions at the Bevalac between niobium nuclei yield the first direct evidence that nuclear matter can be compressed

Physicists from the Laboratory for Heavy Ion Research (GSI) in Darmstadt, West Germany, and the Lawrence Berkeley Laboratory (LBL) have come up with experimental evidence for the proposition that nuclear matter can be significantly compressed. "We have made the first direct observation of compressed nuclear matter," Arthur Poskanzer of LBL told *Science*.

Even more important, the likely mechanism whereby the compression took place and its attendant experimental signature strongly suggest that physicists will eventually be able to construct a nuclear "phase diagram" spanning a wide range of temperatures and densities. If theorists are correct, lying in wait are one or more phase transitions to new states of nuclear matter, such as the so-called quark-gluon plasma or quark soup that characterized the earliest moments of the universe.

The compression itself is not surprising. Physicists know that nuclei shiver and shake. In the monopole or breathing-mode giant resonance, the entire nucleus alternately expands and contracts, implying a limited compressibility. Moreover, astrophysicists calculate that neutron stars, the superdense remnants of some kinds of burned-out stars, have a density about three times that of ordinary nuclear matter, which is close to 2.5×10^{14} grams per cubic centimeter.

However, it is one thing to conjecture about inaccessible neutron stars and another to measure properties of nuclei under similar conditions in the laboratory. Theorists have calculated that the maximum density achieved in the GSI-LBL experiment is three to four times normal, although the dense state lasted only 10^{-22} second at most.

THE GSI-LBL collaboration did its work with Berkeley's heavy ion accelerator, the Bevalac. With recent improvements, the Bevalac can create relativistic beams of nuclei as heavy as uranium that collide with stationary target nuclei. The accelerator boosts heavy nuclei up to 1 billion electron volts (GeV) per nucleon (proton or neutron).

In the course of the collision, nuclei disintegrate. In general, fragments derived from portions of the projectile and target nuclei that are farthest from the collision center respectively race away in the direction of the incident beam or sit at rest. A much hotter and more dense "nuclear fireball" comprising nucleons from both the projectile and target near the collision center also moves forward in the beam direction but at a speed intermediate between those of the projectile and target fragments.

To detect the outcome of the collisions, the physicists used a special instrument, the Plastic Ball detector, that identifies hydrogen and helium isotopes and positively charged pions emanating from the collision point and measures their energy. The Plastic Ball comprises 815 modules covering almost the entire 4π solid angle surrounding the collision point and can thereby make a detailed map of the spatial distribution of the energy flow. A companion Plastic Wall measures properties of the collision products downstream along the beam direction.

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The colorful term "side-splash" describes the main effect seen by the collaboration, headed by Hans Gutbrod and Hans-Georg Ritter of GSI and Poskanzer of LBL, when the beam of niobium-93 nuclei of energy 0.4 GeV per nucleon struck niobium nuclei in a thin metal target. "Side-splash" refers to a sideways leap that is superimposed on the forward motion of the fireball. It is also an example of "collective flow." Collective means that the nucleons act in concert rather than as independent particles, even when they are not bound together.

Several years ago, theorist Walter Greiner of Frankfurt University, West Germany, and several co-workers at Frankfurt and GSI predicted that "side-splash" would be a principal signature for nuclear compression. The theorists calculated from a hydrodynamic model of the nucleus, which treats continuous nuclear density and velocity fields rather than discrete nucleons.

With regard to compression in nuclear collisions, the differences between the independent particle and hydrodynamic models are quite significant. A "gas" of nucleons, which is what the former treats, can clearly be compressed, but because the nucleons are independent (the potential energy they have does not depend on the exact positions of the neighboring nucleons), the model yields no collective effects and no "side-splash," in particular.

Greiner and his co-workers also found that the predicted collective effects would be most plainly revealed for collisions between heavy nuclei of nearly the same mass. The reason for the heavy nuclei requirement is not mysterious. "If you want to see collective effects, you have to have lots of nucleons," says Horst Stöcker, who has migrated to Michigan State University from GSI.

In the hydrodynamic model, the collision sets up a shock wave that compresses nuclear matter in the central fireball for the briefest of instants. The compressed matter then expands, giving rise to the "side-splash." The degree of "side-splash" then depends partly on the maximum compression.

Until the upgrade of the Bevalac and the construction of the Plastic Ball detector, it was not possible to test this finding in detail. Nuclear compression can and probably does occur without noticeable "side-splash," but there had been no way to measure density changes before. For example, work reported last year by another GSI-LBL collaboration under the leadership of Reinhard Stock found indirect evidence for nuclear compression in a lower than expected number of pions emanating from nuclear collisions. The energy associated with the missing pions was assumed to have gone into compressing the nuclei.

The GSI-LBL group has now tried three pairs of nuclei. Calcium-calcium collisions showed no strong "side-splash." Niobium-niobium collisions demonstrate a distinct effect. "Side-splash" should be even more pronounced in the heavier gold-gold system. Experiments with gold beams up to 1 GeV per nucleon have now been completed, but the analysis of the results is still under way.

Meanwhile, Greiner, Gerd Buchwald, Joachim Maruhn, and their co-workers at Frankfurt and Stöcker have explicitly modeled the niobium-niobium system and found the same strong sideward peaks in the distribution of events as the experimentalists saw. At this point, the agreement is mainly qualitative.

Establishment of nuclear compression opens the way to a wide-ranging exploration of the properties of nuclear matter under conditions of varying temperature and density. By using the heaviest possible nuclei and carefully choosing the beam energy, physicists should be able to "adjust" the compression to create the temperature and density of interest. Moreover, during the expansion process, the density will "overshoot" and decrease to less than that of ordinary nuclear matter, so that low densities can be explored as well.

What will physicists find, if they carry out this program? Theorists promise them a rich variety of new states of nuclear matter. One of the most intriguing is the quark-gluon plasma. According to models of the evolution of the universe after the Big Bang, during the first microsecond of existence there were no protons, neutrons, mesons, or other heavy particles. Instead, quarks, which are the entities out of which elementary particles are constructed, and gluons, which cement the quarks together, roamed freely everywhere.

After the first microsecond, the universe had "cooled" enough that the liquid-like quark soup "froze," creating the elementary particles in the process. With a sufficiently powerful accelerator, theorists say, it is possible to reverse this process in nuclear collisions. The nucleons momentarily "melt" and generate a quark-gluon plasma. In effect, scientists would be able to study in the laboratory the kind of matter that only existed just after the Big Bang.

Although it is somewhat conjectural how high a collision energy is necessary, the Nuclear Science Advisory Committee, which counsels the Department of Energy and the National Science Foundation on facilities for nuclear physics, last fall recommended as the highest priority in the field the construction of an accelerator that would allow counter-circulating 30-GeV-per-nucleon beams of heavy nuclei to collide head on. A rough guess on the price was $250 million. The latest results from the GSI-LBL collaboration will not hurt the process of building political support for such a machine.—**Arthur L. Robinson**

An Impact but No Volcano

It had looked as if the arguing would go on for years. Did a huge volcanic eruption or the impact of an asteroid or comet lay down the clay layer associated with the extinction of so many species 65 million years ago? In this issue of *Science* (p. 867), Bruce Bohor and his colleagues at the U.S. Geological Survey (USGS) in Denver present "compelling evidence" that an impact did it. Experts familiar with their discovery believe that, if anything, the USGS researchers are being too modest in their claim. The quartz grains that they found in the clay layer now marking the 65-million-year-old Cretaceous-Tertiary extinctions are engraved by the apparent traces of a highly energetic impact. "It has to be an impact," says Jay Melosh of the University of Arizona. "Nothing else could do that."

For the USGS group, the search for evidence of an impact began with their studies in the Branch of Coal Resources. The mineralogy of the boundary, whether the clay began as volcanic ash or dust from an impact, should be as informative as that of the volcanic ash layers called tonsteins that they had studied in coal beds, they reasoned. Once they found their own exposure of the boundary clay near Brownie Butte in east-central Montana, the USGS workers removed the 99.99 percent of the sample that was clay, leaving mostly quartz grains about 80 micrometers in diameter. Hydrofluoric acid treatment, the last step in the removal of the clay, serendipitously left many of the grains etched by a distinctive pattern of intersecting, parallel grooves precisely oriented with respect to the crystal structure. There was the proof.

The only way known to produce such features in quartz grains is by a high-velocity impact. The shock of the impact—producing in this case pressures of over 150,000 atmospheres—disorganizes the crystalline quartz and produces amorphous glass, but only on planes having particular orientations with respect to the crystal structure. High-velocity shock experiments in the laboratory have produced these planar features and their grooves, as have nuclear explosions. Such features are also found in the debris from known impact craters on Earth, but they have never been found in volcanic ash. As Richard Grieve of Brown University explains, crustal rocks are too weak to contain pressures greater than 1000 atmospheres and, even if trapped gases could generate higher pressure during explosive release, the easily compressed gases cannot transmit that pressure to the relatively incompressible rock. "It just doesn't work," he says.

The USGS group has other evidence. X-ray diffraction analysis of the quartz grains revealed streaking of the normally sharp diffraction spots, which is typical of shocked quartz. It also detected stishovite, a form of quartz formed at pressures above 100,000 atmospheres. "We're sure it's there," says Bohor, but its low abundance has prevented the production of an x-ray diffraction pattern that is strong enough to be reproduced in a journal. They have also seen the planar shock features in quartz from Cretaceous-Tertiary boundary clays at three other sites in east-central Montana and at the now-classic European locales—two sites in Denmark, two in Italy, and one in Spain. Charles Pillmore of the USGS in Denver and his colleagues subsequently discovered similarly shocked quartz at the boundary in the Raton Basin of Colorado and New Mexico.

The unequivocal evidence of highly shocked quartz follows less compelling finds in the boundary clay. These included spherules that presumably condensed from vaporized rock and are too large to have been flung around the globe by a volcano, and osmium isotope compositions that allowed an extraterrestrial or volcanic source but not a continental source (*Science*, 11 November 1983, p. 603). Recently, Jan Smit, Frank Kyte, and John Wasson of the University of California at Los Angeles reported that they have found spheres containing geochemical markers of an extraterrestrial object and magnetite that must have crystallized from a very high-temperature liquid.

Once the shocked quartz grains settle the impact-volcano question, they may be put to further use. Since continents contain abundant quartz and ocean basins very little, these quartz grains may shed light on the question of where the impact occurred.—**Richard A. Kerr**