

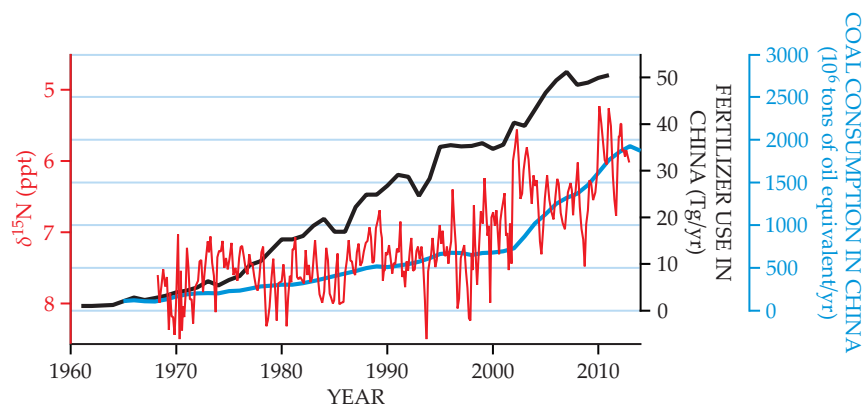


FIGURE 2. AS NITROGEN EMISSIONS from China have increased, so has their influence on Dongsha Atoll. The coral-derived record of the relative ^{15}N abundance $\delta^{15}\text{N}$ (red), normalized to air exhibits a change in slope around the year 2000, as does the annual coal consumption (blue) but not the annual fertilizer use (black). (Adapted from ref. 1.)

A decades-long coral record therefore offers a comparison between the N conditions in the present day and a time when nearly all the available N was natural.

To ensure a sufficiently long record, Ren's team collected 20 coral cores from colonies around the atoll. As coauthor Thomas DeCarlo explains, sampling is conducted with an eye toward the coral's long-term health. "After removing a core, we plug the hole with cement and seal it with epoxy so the corals can grow back," he says, "and we keep tabs on their recovery. We've never seen a colony die as a result of drilling."

Though one of their cores dated back 60 years, Ren and colleagues chose for

their analysis a core that covered a somewhat shorter time span. That coral grew faster, says Ren, "and the high growing rate allowed us to analyze it with better time resolution."

The results of the isotopic measurements, performed in Sigman's lab, are plotted in red in figure 2. Sure enough, over the course of the record, the ^{15}N abundance declined—note that the numbers on the red axis decrease going upward—by more than a part per thousand. From the magnitude of the change, the researchers deduced that some 20% of today's N comes from anthropogenic sources. That's consistent with the range that models estimate, though it's on the low end.

Also curious is the timing of the change: beginning around the year 2000. Fertilizer and coal use in China have both grown in recent decades, as figure 2 shows, but they've followed distinctly different trajectories. The coral N record seems to more closely track the latter.

The results hint that switching from coal to cleaner fuels that emit less NO_x could mitigate the impact on the open ocean, but it's hard to draw definitive conclusions from measurements at a single location. Ren and her colleagues are working toward extending their measurements to other coral reefs around the world, which are numerous in tropical and subtropical waters. "Dongsha is special because it's a hot spot for recent growth in anthropogenic atmospheric nitrogen," Ren explains. "Now that we've proved that we can detect this signal, the next obvious thing to do is to look for it in other places."

Johanna Miller

References

1. H. Ren et al., *Science* **356**, 749 (2017).
2. L. Muscatine et al., *Proc. Natl. Acad. Sci. USA* **102**, 1525 (2005); G. Marion et al., *Mar. Pollut. Bull.* **50**, 931 (2005).
3. X. T. Wang et al., *Geochim. Cosmochim. Acta* **148**, 179 (2015).
4. D. M. Sigman et al., *Anal. Chem.* **73**, 4145 (2001).

Proton–proton collisions prove stranger than expected

Enhanced production of strange particles joins a growing body of evidence that has physicists reevaluating their assumptions about quark–gluon plasmas.

By the time the universe was picoseconds old, the four fundamental interactions—strong, weak, electromagnetic, and gravitational—had become distinct from one another. Yet, for another few microseconds, the universe remained too hot to bind quarks into protons, neutrons, and other hadrons. Instead, quarks and gluons, the bosons carrying the strong force, existed as a hot, dense soup called quark–gluon plasma.

More recently, quark–gluon plasma

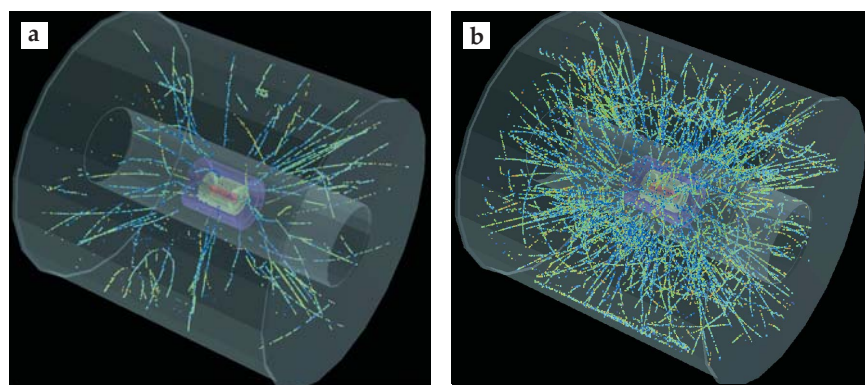


FIGURE 1. WHEN TWO PROTONS COLLIDE inelastically inside the ALICE detector, (a) the typical outcome is a few handfulls of particles. (b) Less than 1% of the time, a collision might produce hundreds of particles. In those rare collisions, the ALICE collaboration found signs that quark–gluon plasma may be forming. (Courtesy of CERN.)

is produced at particle colliders such as CERN's Large Hadron Collider (LHC) and Brookhaven National Laboratory's

Relativistic Heavy Ion Collider (RHIC) by smashing together the nuclei of heavy atoms. From those collisions, researchers

hope to learn about the conditions that were present in the early universe and to probe the nature of strong interactions at high energy densities. Thus far, they have pieced together that quark-gluon plasma behaves as a nearly perfect, viscosity-free fluid. That's in stark contrast to the electromagnetic plasma, which is best described as a weakly interacting gas of electrons, ions, and photons.

Physicists have thought that quark-gluon plasma could be produced in the lab only through collisions of heavy nu-

clei. Thus ALICE (A Large Ion Collider Experiment)—a detector built to study quark-gluon plasma—and other detectors at the LHC and at RHIC use proton-proton collisions to obtain a baseline for heavy-ion collisions. Simultaneously colliding many protons and neutrons in close proximity to each other produces quark-gluon plasma, but colliding one pair of protons does not. Or does it?

In the past few years, evidence has been mounting that the creation of quark-gluon plasma may not be the

exclusive domain of heavy-ion collisions. For instance, signatures of collective flow indicating a low-viscosity fluid have been detected in both proton-proton and proton-lead collisions at the LHC.

The latest evidence comes from the ALICE collaboration's analysis of proton-proton collisions measured during the LHC's first operational run in 2010–13. As shown in figure 1a, the collisions typically produce just a handful of charged particles, and no quark-gluon plasma is created. But, in rare, so-called high-multiplicity events such as the one in figure 1b, the collision creates a high number of particles. In those instances, reports the ALICE collaboration, the relative abundance of particles containing strange quarks grows, and even approaches that seen in lead-lead collisions.¹

Enhanced production of strange particles in heavy-ion collisions, identified in the 1980s, was one of the first proposed hallmarks of quark-gluon plasma.² If it turns out that proton-proton collisions can indeed create quark-gluon plasma, physicists will have found a simpler system than heavy-ion collisions to study the exotic phase of matter.

Squeezing out quarks

According to quantum chromodynamics, the strong interaction displays a property called quark confinement. Because of strong quark-gluon coupling, any attempt to pry loose a quark from a proton or a neutron ends up instead producing new quark-antiquark pairs that immediately bind to other hadrons and resist the quark's liberation. When hadronic matter is heated and squeezed to conditions resembling those of the early universe, however, the coupling between gluons and quarks starts to weaken. Eventually the hadrons melt into quark-gluon plasma.

Smashing two gold or lead nuclei together at ultrarelativistic speeds creates at the collision point just such conditions, explains particle physicist Wit Busza of MIT. "Then you go to theory and it says, that small blob, which has so much energy density, must be free quarks and gluons."

In 2000, CERN scientists announced that they had found compelling evidence for quark-gluon plasma in lead-lead col-

Kurt J. Lesker
Company

Enabling Technology for a BETTER WORLD



We help our customers compete and succeed on the leading edge of technology, utilizing our range of quality products and vast experience providing solutions to the vacuum community.

- Research & Development
- Aerospace
- UHV/Synchrotron
- Electronics
- Wear/Decorative Coatings
- Optics
- LED



Visit Us

Semicon West - Booth 6344

www.lesker.com

17-093

lisions. By 2005—after three years of colliding gold nuclei—researchers at RHIC had learned that the newly spotted phase of matter behaved like an inviscid liquid. (For an overview of the RHIC results, see the article by Barbara Jacak and Peter Steinberg, *PHYSICS TODAY*, May 2010, page 39.) No single measurement gave definitive proof for the existence of quark-gluon plasma, but the combined collection of signatures convinced particle physicists that they had succeeded in producing it.

Two of the signatures discovered at RHIC have come to take center stage in studies of quark-gluon plasma: so-called jet quenching and collective hydrodynamic flow. High-energy collisions tend to produce multiple particles that fly out in common directions as collimated jets. Jet quenching occurs because those particle jets lose much of their energy as they traverse quark-gluon plasma. The collective flow indicates a thermalized, zero-viscosity liquid-like state.

In 2010 the LHC began slamming protons into each other at an energy an order-of-magnitude higher than what's possible at RHIC. Just months into the first operational run, the CMS (Compact Muon Solenoid) collaboration found that the debris of high-multiplicity proton-proton collisions also displayed spatial correlations indicative of collective flow.³

"Before, we thought you could only make quark-gluon plasma in heavy-ion collisions," says Yale University's Helen Caines, a spokesperson for RHIC's STAR (Solenoidal Tracker at RHIC) collaboration and a member of the ALICE collaboration. That the assumption may not hold doesn't rock the foundations of quantum chromodynamics, but it does show that phenomenological models that apply the theory to particle collisions may need revamping.

By 2013 two other LHC experiments—ALICE and ATLAS (A Toroidal LHC Apparatus)—had measured similar signs of collective liquid-like behavior in proton-lead collisions.⁴ In addition, the ALICE collaboration reported last year that high multiplicity also enhances strangeness production in proton-lead collisions.⁵

The ALICE collaboration's finding of strangeness enhancement in proton-proton collisions is another indication that heavy-ion collisions may not be the

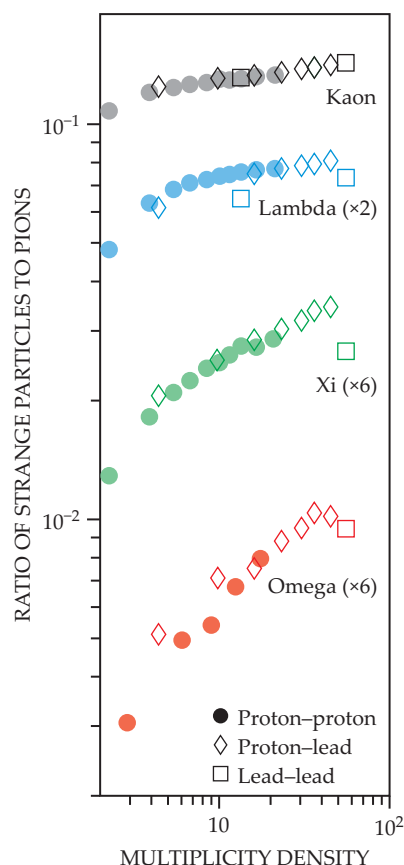


FIGURE 2. AS MORE AND MORE PARTICLES are produced in proton-proton collisions—given by a unitless quantity called multiplicity density—the ratio of strange particles to pions increases. The effect is stronger for particles with more strange quarks: A kaon contains two quarks, one of them strange; a lambda contains one strange quark out of three; a xi has two strange quarks out of three; and an omega contains three strange quarks. Numbers in parentheses are scaling factors. (Adapted from ref. 1.)

only way to make quark-gluon plasma. Figure 2 plots the ratio of strange particles to pions (up-down quark pairs) as a function of multiplicity density, the total number of particles produced per unit pseudorapidity. Pseudorapidity is a unitless quantity related to the polar angle away from the beam axis at which particles fly out. Pions, as the most abundantly produced collision particles, are good stand-ins for the nonstrange fraction of collision products. In going from kaons, which are strange-antistrange quark pairs, to omegas, which have three strange quarks, the enhancement with multiplicity becomes more pronounced. At the highest multiplicities, the ratios

even appear to approach the values seen in lead-lead collisions.

However, Busza warns against reading too much into that comparison. He notes that in lead-lead collisions, multiplicity density is mostly a measure of how many constituent protons and neutrons collide, whereas in proton-proton collisions, it is more a proxy of how violent each proton-proton collision is. As suggestive as the new finding is, he says, he would have been more convinced if the strangeness enhancement came to a plateau. Such a plateau would suggest a transition from hadronic matter to quark-gluon plasma.

"Quark-gluon plasma would provide a ready-made explanation for what we observe," explains ALICE spokesperson Federico Antinori, "but there are still many open points." For example, what happens at even higher multiplicities? With the LHC well into its second operational run, Antinori says, "Our plan is to really have a comprehensive measurement of the physics of high-multiplicity proton-proton collisions."

Those complete measurements also include looking for signs of jet quenching, which has yet to be conclusively detected in proton-proton or proton-lead collisions. "That would be our killer measurement," says Caines, but she adds that it's trickier than it sounds. Jet quenching in heavy-ion collisions is identified by comparing the energies of particles produced in them with the energies of particles produced in proton-proton collisions. At the moment, no such baseline exists for proton-proton collisions.

Caines also notes, "It's not like finding the Higgs where you say, oh look, there's the peak." As happened with heavy-ion collisions, it will be a collective body of evidence that solves the riddles of whether quark-gluon plasma can be created with proton-proton collisions.

Sung Chang

References

1. J. Adam et al. (ALICE collaboration), *Nat. Phys.* **13**, 535 (2017).
2. P. Koch, B. Müller, J. Rafelski, *Phys. Rep.* **142**, 167 (1986).
3. V. Khachatryan et al. (CMS collaboration), *J. High Energy Phys.* **2010**(9), 91 (2010).
4. G. Aad et al. (ATLAS collaboration), *Phys. Rev. Lett.* **110**, 182302 (2013); B. Abelev et al. (ALICE collaboration), *Phys. Lett. B* **719**, 29 (2013).
5. J. Adam et al. (ALICE collaboration), *Phys. Lett. B* **758**, 389 (2016).