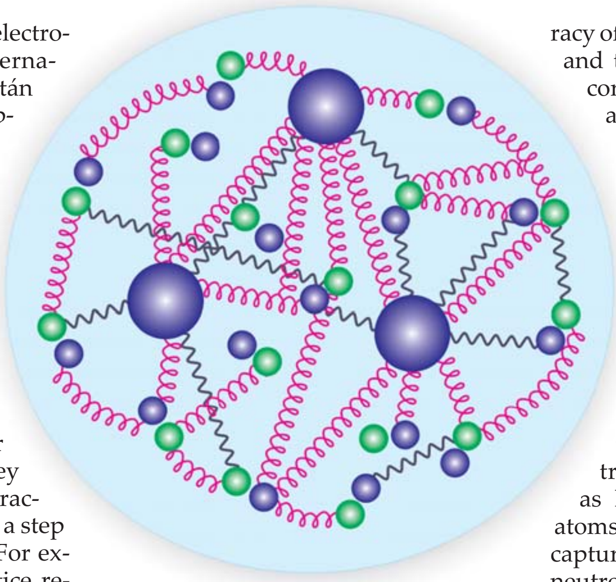
and down quarks, or ignoring electromagnetic effects. Now an international collaboration led by Zoltán Fodor at the University of Wuppertal in Germany has calculated the neutron and proton masses with a precision of 0.03%, and thus has made the most accurate theoretical determination of their difference to date.[1]

In simulations that produced a combined 60 terabytes of data, the researchers used four types of quarks: up, down, strange, and charm, each with a different mass. Crucially, after a series of QCD-only runs, they turned on electromagnetic interactions in the quark–antiquark sea, a step that was easier said than done. For example, the finite-sized QCD lattice requires imposing boundary conditions on the long-range electromagnetic interactions. The team had to figure out how to control the large artifacts that can crop up when applying those boundary conditions. "The theoretical approach, the algorithmic steps, which were developed for the strong interaction, had to be reworked," says Fodor. In all, the group combined 41 independent simulations to reach the final result.

The new calculation wasn't just a computational feat. The results revealed in detail a competition between electromagnetic effects and the mass difference between the up and down quarks. That the up quark is lighter than the down quark increases the neutron's mass relative to the proton's, whereas the QED contribution does the opposite.



The neutron and proton, in addition to having three valence quarks (larger balls), are filled with a virtual sea of gluons (red springs) and quark (purple)–antiquark (green) pairs. The quarks and antiquarks also interact electromagnetically by exchanging photons (gray wavy lines).

"For the first time, all effects have been included and controlled to the first nonvanishing order in the fine structure constant," says Thomas Blum of the University of Connecticut. Important next steps, he says, are to improve the accuracy of the calculated light quark masses and to apply similar electromagnetic corrections to other phenomena such as the decay of kaons, which pair strange quarks or antiquarks with up or down antiquarks or quarks. Observations of kaon decay in 1964 led particle physicists to discover a fundamental symmetry-breaking process called charge–parity violation.

Fodor and his collaborators think their findings also have important implications for cosmology. "Imagine that the electromagnetic coupling was twice as large," he explains. "Hydrogen atoms would collapse through electron capture." In the other direction, if the neutron–proton mass difference were much larger than it is, faster neutron beta decay would have left the universe with far fewer neutrons at the end of Big Bang nucleosynthesis. Stellar fusion of hydrogen and the production of heavy elements would be more difficult.

Robert Jaffe of MIT agrees. "How finely tuned do the parameters of the standard model have to be for complex structures like human observers to form?" he asks. "Only lattice quantum field theory can explore questions like this."

Sung Chang

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Remarkable gravitational lensing by the galaxy cluster Abell 3827

The distorted image of a background galaxy may be a record of frictional dark-matter interactions.

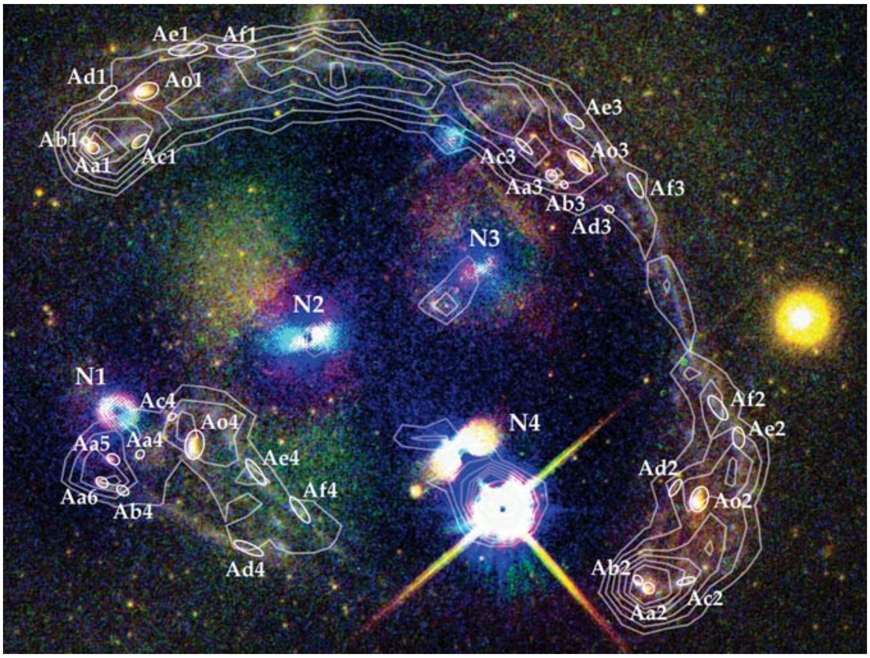
Most of the matter in the universe, according to the standard cosmological model, is invisible stuff whose nature is unknown. Dark matter interacts gravitationally but as far as we know is not subject to the electromagnetic or any other interaction. Gravity is enough, however, to ensure that a spherical halo of dark matter surrounds a galaxy's shining stars. Evidence for dark matter has accumulated from several sources; they include the anisotropy of the cosmic microwave background, galaxy-rotation data, and the gravitational lensing of light from galaxies by unseen masses.

In 2006 a pair of colliding galaxy clusters, together called the bullet cluster, provided a spectacular confirmation of dark matter. The two clusters had passed through each other 100 million years ago, and an analysis of how the bullet cluster distorted the images of background galaxies established that its intergalactic gas lagged behind its dark-matter halos. The proffered explanation was that gas–gas interactions dragged the conventional material while the halos traveled unimpeded. Indeed, observations of the bullet cluster enabled researchers to set an upper limit on how strongly dark matter can interact with itself (see PHYSICS TODAY, November 2006, page 21).

Now a team of astrophysicists led by Durham University's Richard Massey has spotted a galaxy in the Abell 3827 cluster that appears to be *leading* its halo as both are attracted toward the cluster center.[1] Massey and colleagues suggest that the offset may result from frictional interactions between the halo and the dark matter of the cluster core.

Finding halo

The four galaxies in Abell 3827 shown in the figure lie within a few kiloparsecs of each other (a parsec is a bit more than 3 light-years). Partially surrounding them is an arc that manifests the severe distortion of a background galaxy by the gravity of Abell 3827; additional lensing can be seen in the area of the galaxy labeled N1. With the help of spectroscopic measurements obtained by the Very Large Telescope in Chile, Massey and colleagues associated each



The core of the galaxy cluster Abell 3827 includes four galaxies, here labeled N1–N4. This *Hubble Space Telescope* image also shows a distorted, gravitationally lensed distant galaxy. Spectral contours guide the eye to the 30 lensed-galaxy structures labeled here. An analysis of the lensing detail indicates that the dark matter associated with N1 is farther from the cluster center than the luminous material. (Adapted from ref. 1.)

of the 30 lensed images labeled in the figure to the core of the lensed galaxy (denoted by Ao) or to one of the galaxy's six bright, star-forming regions (labeled Aa–Af). Armed with those identifications, the research team turned to a pair of independent computer models to map the locations of the lensing dark-matter halos in the core of Abell 3827 (not shown). They found N1 to be significantly offset from its halo, by 1.6 ± 0.5 kpc in the cluster-image plane, with the luminous matter closer to the cluster center.

Massey's group was not the first to see a halo–galaxy offset in Abell 3827, nor the first to suggest that it might be a manifestation of dark-matter self-interactions. Those honors go to Liliya Williams (University of Minnesota) and Prasenjit Saha (University of Zürich),[2] who have joined Massey in the more recent work. Assuming that the offset was entirely due to dark-matter self-interactions, Williams and Saha obtained a lower bound for the interaction strength σ per unit mass m. Massey and company used the same assumptions and with their offset obtained an estimate of $\sigma/m = (1.7 \pm 0.7) \times 10^{-4}$ cm^2/g. The deduced interaction strength depends on the duration of the galaxies' movement to the cluster center; the team's value of σ/m used a ballpark estimate of 10^9 years. The interaction strength is expressed in particle physicists' conventional cross-section units; by way of comparison, the cross section for hydrogen gas is roughly $\sigma/m = 10^8$ cm^2/g.

An assertion that dark-matter self-interactions have been unambiguously observed would require extraordinary evidence, and Massey and company do not claim to have made an ironclad case. The challenge of determining experimental uncertainties and the modeling required to obtain the halo locations are formidable, and even given those locations, the researchers note that "interpreting an offset between mass and stars is difficult."[1] The combined effects of matter along the line of sight to Abell 3827 and conventional physics in the complex environment of the cluster could somehow be responsible for the inferred misalignment of dark and luminous matter. Detailed simulations in the future should help clarify whether frictional dark-matter interactions exist.

Furthermore, the dark-matter interaction model used to obtain σ/m is greatly simplified. Indeed, within a couple of weeks of the publication of the Massey work, a team led by Felix Kahlhoefer (German Electron Synchrotron) considered a more sophisticated model of dark-matter self-interaction.[3] The theorists concluded that if the displacement observed by Massey and company is totally due to unconventional dark-matter physics, then $\sigma/m = 1.5$–3 cm^2/g, a value high enough to strain the upper bounds determined from the bullet cluster and other observations.

Steven K. Blau

References

1. R. Massey et al., *Mon. Not. R. Astron. Soc.* **449**, 3393 (2015).
2. L. L. R. Williams, P. Saha, *Mon. Not. R. Astron. Soc.* **415**, 448 (2011). See also I. Mohammed et al., *Mon. Not. R. Astron. Soc.* **439**, 2651 (2014).
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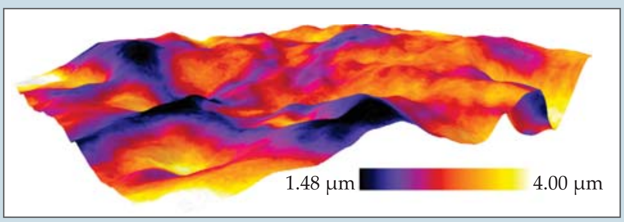
physics update

These items, with supplementary material, first appeared at http://www.physicstoday.org.

The topography of ink on paper. Dribble some ink or toner into water and it will diffuse uncontrollably. More sophisticated substrates are needed for controlled printing, and the interaction of ink with paper is of great importance to the ultimate quality and durability of the product. Coating paper with minerals or polymers is a common way to influence that interaction. Yet the microscopic three-dimensional structural characteristics of the ink–paper interface still remain mysterious. A group of researchers in Finland, led by Jussi Timonen (University of Jyväskylä), is working to clear that up. The team



brought old techniques together in new ways for their analysis of 1-mm^2 samples of lightly coated paper—very heterogeneous substrates with almost no coating in some patches—covered with cyan toner. First, they used x-ray tomography on the printed paper to get a sample's underlying topography at 0.8-μm resolution in all three dimensions. That resolution was