To answer that question, Bialek and Setayeshgar applied the fluctuation–dissipation theorem, as they did for their 2005 analysis. According to the theorem, a system in thermodynamic equilibrium will respond in the same way both to a small driving force and to a random thermal fluctuation. From that intuitive proposition, Albert Einstein famously related the dissipative, Brownian motion of a particle to the random, fluctuating knocks the particle receives from the molecules that surround it.

In Bialek and Setayeshgar's analysis, the fluctuations come from the local concentration of target molecules as they bind and unbind, knocking the cooperative molecule dissipatively in and out of its various states.

Their analysis is somewhat involved, but, to Bialek and Setayeshgar's surprise, it yielded a compact formula for $\Delta c/c$. As in their earlier 2005 analysis, including cooperativity adds a second, always positive term. Moreover, the formula is general: It applies to cooperative and noncooperative sensors alike. Whereas cooperativity increases the gain, it doesn't lower the noise floor.

Experiments that determine $\Delta c/c$ have been done only recently. According to Bialek and Setayeshgar's formula, the 10% accuracy with which *Escherichia coli* transcribes genes is reached within one minute. That sampling time is consistent with the time, three minutes, that messenger RNA survives in the cell.

Bialek and Setayeshgar's formula also predicts, within a factor of three, how often *E. coli* changes direction in response to concentration gradients (see figure). The agreement is historically apt. Purcell first became interested in biochemical sensing when he saw Berg's movies of zigzagging bacteria.

Charles Day

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Electron-scattering experiments resolve short-range correlations among nucleons

Researchers at Jefferson Lab confirm that high-momentum neutron–proton pairs in a carbon nucleus are 20 times more prevalent than proton–proton pairs.

According to the shell model, the protons and neutrons—collectively known as nucleons—that make up nuclei move independently in discrete quantum orbits and are bound by an average potential created by their mutual attractive interactions. But that picture is too naive. In the 1980s, electron-scattering experiments that knocked protons from both valence and deeply bound nuclear orbitals found only 60–70% of the number predicted by the mean-field approximation.

At the time, some theorists attributed the difference to correlations between nucleons. A rich variety of low-energy nuclear phenomena, including collective rotations and vibrations, shape mixing, and superfluidity, are known to originate in correlations between nucleons separated by several femtometers. But those long-range correlations make up less than half the difference. Short-range correlations (SRCs), on the scale of a femtometer or less, can close the gap, but direct evidence for them has proven elusive. Still, physicists have surmised their presence for decades, not least because short-range repulsion between nucleons prevents the collapse of a nucleus.

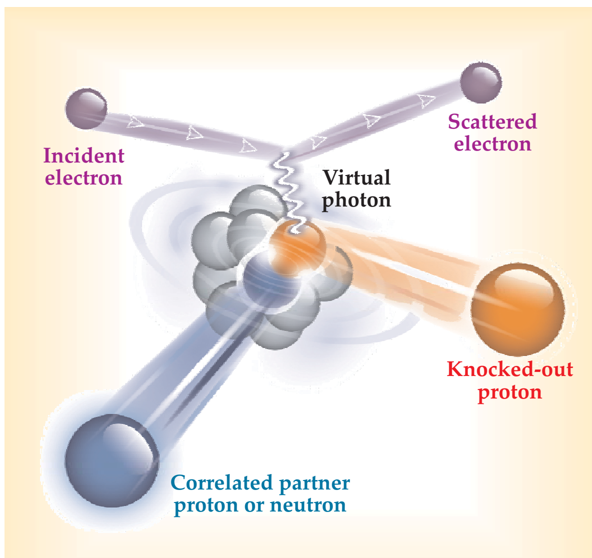


Figure 1. An energetic electron scatters off a carbon nucleus and transfers a fraction of its momentum to a proton through the exchange of a virtual photon. The momentum knocks the proton out of the nucleus. At the same time, another nucleon, although untouched in the exchange, is ejected with a signature that the initial state was in a short-range correlation. (Courtesy of Anna Shneor.)

One can think of SRCs as transient fluctuations in the local nuclear density when the wavefunctions of two energetic nucleons strongly overlap. For less than a trillionth of a femtosecond, the nucleons approach each other closely enough to form correlated pairs, with local densities close to what's expected in the core of a neutron star. While short in time, those correlations are ever present, with a percentage of nucleons paired up at any given time. The development of high-energy accelerators has made observing such pairs possible, primarily because a probe's wavelength can be made smaller than the nucleon–nucleon distance.

To resolve SRCs, an experiment must transfer to the nucleus momenta near 1 GeV/c, an amount larger than the characteristic Fermi momenta of nuclei. According to Mark Strikman, a theorist at the Pennsylvania State University, momentum-transfer reactions can test two fundamental features of SRCs: First, the shape of the high-momentum component of the nucleon wavefunction is independent of the nuclear environment; in effect, the bare interaction in a pair is unmediated by the presence of other nucleons. And second, the ejection of one nucleon is accompanied by the ejection of its correlated partner with equal and opposite momentum, leaving the rest of the system nearly unaffected.

Two years ago Strikman, along with Eliezer Piasetzky (Tel Aviv University), Misak Sargsian (Florida International University), Leonid Frankfurt (Tel Aviv University), and John Watson (Kent State University), analyzed the data from a 2003 Brookhaven National Laboratory experiment using the AGS accelerator in which GeV protons were incident on a thin carbon foil. The team found the telltale signs of correlated

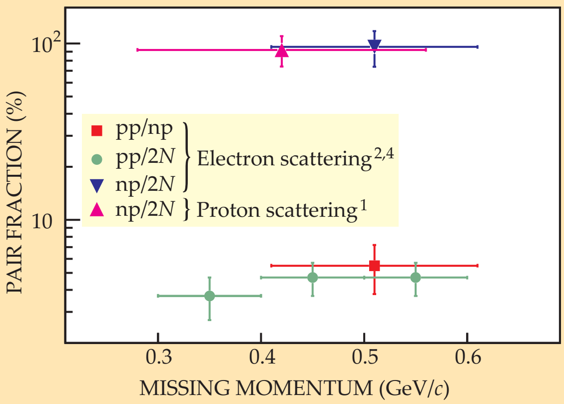


Figure 2. The fractions of correlated-pair combinations, as measured from electron- and proton-scattering experiments. At momenta above 275 MeV/c nearly all of the nucleons N ejected from carbon-12 are correlated. The data reveal a roughly 20-to-1 predominance of neutron–proton (np) pairs over proton–proton (pp) ones. The red square plots the inverse, pp/np, and other data points plot the number of pp or np pairs over the total number of nucleon pairs. Missing momentum refers to the difference between the virtual photon's momentum and that of the knocked-out proton. Horizontal bars signify the range of momentum averaged over, not uncertainties. (Adapted from ref. 2.)

pairing and a striking asymmetry in the data: Of the SRCs analyzed, the vast majority were neutron–proton pairs.[1]

Now a collaboration of 64 scientists, Piasetzky and Watson among them, from 31 institutions around the world has published what may be the most direct observation yet of those asymmetric correlations.[2] Instead of firing protons at carbon-12, the new experiment fired electrons, which interact with nuclei not via the strong force but through an electromagnetic interaction. The much different probe captured the same SRC physics.

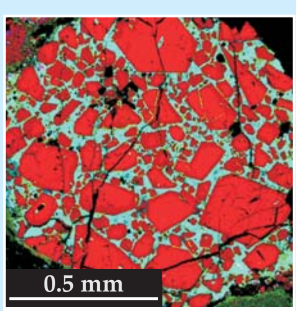
In concept the experiment is simple. An incident electron transfers a portion of its momentum through a virtual photon to a single proton in the ^{12}C nucleus, as sketched in figure 1. In execution, it's daunting. Preparation for the experiment, performed at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, spawned three PhD theses. Ramesh Subedi (Kent State), Ran Shneor (Tel Aviv), and Peter Monaghan (MIT) custom-built detector components, ran simulations to optimize the kinematics, and modified existing spectrometers to ensure they would actually work when sprayed with a 4.6-GeV electron beam of high luminosity (10^{38} cm^{-2} s^{-1}). The experiment took years to build and three months to run, with scientists continually monitoring the accumulating data.

In the "triple-coincidence" experiment, three separate detectors were positioned to measure the momenta of the scattered particles with subnanosecond time resolution over a range of kinematic settings above the nucleons' Fermi momenta. Two high-resolution spectrome-

physics update

Supplementary material related to these items can be found at www.physicstoday.org.

New chemical clues to Earth-like planet formation. Sodium is volatile. It easily burns and boils and diffuses. Meteorites are hardy, and the type known as chondrites are also primitive, dating back to the very early solar system. Chondrites contain a high density of so-called chondrules—roughly millimeter-sized spheres like the one shown here in polarized light—that were flash-melted at temperatures around 2000 K and subsequently cooled and incorporated into a meteorite's parent object, typically an asteroid. The heating mechanism is unknown but could involve shocks or lightning. Mostly made of silicate minerals such as olivine and pyroxene and of the metals iron and nickel, chondrules are expected to be deficient in volatile elements like sodium. But researchers at the Carnegie Institution of Washington, the US Geological Survey, and the American Museum of Natural History say it isn't so. Using electron microprobe spectroscopy, they studied 26 chondrules from the Semarkona meteorite that fell in India in 1940 and found significant sodium throughout. The only way that could happen, they say, is if the chondrules formed as closed systems at densities in the solar nebula (the disk of gas and dust from which the planets formed) that were far higher than previously thought. That way, the cooling droplets would be crowded together in an area of saturated sodium vapor. The required ambient densities range from 10 to hundreds of grams per cubic meter, far exceeding the standard assumption of 0.1 g/m^3 or less. At the much higher densities, astronomically tiny regions just a few thousand kilometers across can collapse under their own gravity. Thus chondrule formation seems to be intimately linked to planetesimal formation, the first step in making planets like Earth. (C. M. O'D. Alexander et al., *Science* **320**, 1617, 2008.) —SGB



Photoluminescence in nanoneedles. Silicon is the workhorse among semiconductors in electronics. In optoelectronics, where light signals are processed along with electronic signals, gallium arsenide is the workhorse light emitter—for example in LEDs and lasers—but getting GaAs to cooperate with Si remains challenging. Scientists at the University of California, Berkeley, have now grown GaAs needles that poke out of a Si substrate, and the needles emit bright photoluminescence at room temperature. About 3–4 μm long and tapering at a gentle 6- to 9-degree angle down to tips about 2–5 nm across, needles like the one shown here were grown to match the crystal structure of the Si despite a 4% lattice mismatch where they meet the substrate. Working in Connie Chang-Hasnain's lab, graduate student Michael Moewe says that he expects the needles to be valuable in several applications including atomic force microscopy; the sharp tips can be grown in arrays without additional etching or processing steps. Delivering light from a sharp tip

ters defined distinct proton knock-out events, while a third, affectionately called BigBite, caught correlated protons that recoiled over a wide cone of solid angles. Behind BigBite sat yet another detector comprising an array of scintillators to catch recoiling neutrons.

That unique arrangement of detectors allowed the Jefferson Lab team to present its data in the form of pair fractions (see figure 2). About 20% of nucleons in ^{12}C form SRC pairs, a percentage consistent with 1980s-era spectroscopic results. And, of those, roughly 96% appear in the form of neutron–proton pairs, a confirmation of the BNL analysis.

Tensor force

The interaction between two nucleons has two preeminent features: a strong repulsion at short distances, and a strong coupling between the nucleons' spins and their spatial separation at distances greater than a femtometer. That tensor character is important for binding the proton and neutron in the deuteron and for making its ground state spherically asymmetric, in marked contrast to systems like the hydrogen atom, where the radial Coulomb attraction results in a spherical ground state.

The tensor force is also responsible for the prevalence of neutron–proton pairs over proton–proton and, by inference, neutron–neutron ones when the relative momentum between the nucleons in the pair is large. To obey the Pauli principle at such short range, two like nucleons must be antisymmetric under exchange of spins, while a neutron and proton pair can be symmetric in spin. The unlike nucleons can, like a compact deuteron, thus experience an attraction, while those of like nucleons cannot.[3] "It's no surprise that tensor forces are behind the asymmetry we measure," says Jefferson Lab physicist Douglas Higinbotham, "though the amount [of that asymmetry] is sure to constrain future nuclear-structure models."

Piasetzky likens SRC pairs to "a poor man's neutron star." Indeed, the transient fluctuations that briefly pair up nucleons push their local densities to some five times their typical value of 0.16 nucleon/fm^3. The Jefferson Lab collaboration argues that if neutron stars contain even the small 5–10% of protons that theorists think they do, the strong neutron–proton interactions will cause the momentum distributions of nucleons in the stars to differ from that of an ideal Fermi gas. The challenge is to understand the consequences.

Equally intriguing is how the structure of nucleons inside nuclei should change when densities are greater still and three-body or higher correlations emerge from the data. In a few years Jefferson Lab expects to upgrade its facility to one that can fire 12-GeV electrons at a nucleus. Eventually, comments Sargsian, experiments may reach a momentum-transfer regime in which nucleons lose their individual identities and dissolve into a sea of quarks. Currently, the short-range repulsion that preserves nucleon identity is a mystery. "Theorists now just draw it in by hand."

Mark Wilson

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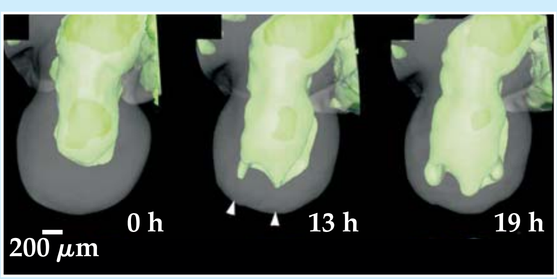
4. R. Shneor et al., *Phys. Rev. Lett.* **99**, 072501 (2007).

could allow a targeted examination of the sample and possibly even permit the spectroscopic study of single molecules. (M. Moewe et al., *Appl. Phys. Lett.*, in press.) —PFS

Quantifying tissue development. Biology, dauntingly complex as it is, nevertheless is slowly becoming more quantitative and thus more amenable to testable models and predictions. For example, an embryo's various organs and body parts develop at different times and at different rates. How can one come up



with a rigorous model for the process? James Sharpe (Centre for Genomic Regulation, Barcelona, Spain) and his colleagues are beginning to address that question with a new imaging technique: time-lapse optical projection tomography. Their setup involves taking live tissue from a mouse embryo and transferring it on tungsten pins to a nutrient- and oxygen-rich chamber. The pins are on a mount that is magnetically attached to a micromanipulator, which rotates the tissue through 360° in 100–200 steps. Labeling gene activity within the tissue with green fluorescent protein and using deep-penetrating 800-nm light, the researchers acquired a full set of images every 15 minutes. The images here of three-dimensional surface renderings show the dynamic activity of a gene involved in controlling development of the limb, as it buds out from abdominal tissue, at 0, 13, and 19 hours. The researchers quantified the global dynamics by measuring the surface expansion through tissue velocity vector fields. Surprisingly, the limb buds didn't simply expand radially but twisted and showed other spatial variations as they grew. In other experiments, Sharpe and company imaged dynamic changes in spatial gene-expression patterns in growing limbs and studied the early development of embryonic mouse eyes. (M. J. Boot et al., *Nat. Methods*, advance online publication, doi:10.1038/nmeth.1219, 30 May 2008.) —SGB

Heat goes ballistic. At the May Conference on Lasers and Electro-Optics in San Jose, California, University of Colorado graduate student Mark Siemens reported on studying how tiny parcels of heat, called phonons, spread in a crystal. He and his colleagues used a near-IR laser to heat a grating of nickel lines—each 20 nm high and 1 μm wide—grown on a sapphire substrate that acted as a heat sink. Then, by recording the transient diffraction of 10-fs pulses of coherent soft x rays from the sample, the researchers could monitor with picometer (10^{-12} m) precision the displacement of the heated nickel nanostructure. The transport of heat is considered "ballistic" if the characteristic distance over which a phonon moves—about a micron in this case—is smaller than its mean free path before scattering off another phonon. At room temperature a typical phonon's mean free path in sapphire is a mere 150 nm but grows to more than a micron when the sample is cooled below 130 K. At that temperature the data show a clear transition from thermally diffusive to ballistic behavior. One reason for trying to understand how heat moves away from a nanoscale interface, says Siemens, is to manage the thermal environment of future advanced high-speed transistors. —PFS ■