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Abstract:	Some experiments in the US and Germany challenges current thinking on the shape of the proton. Far from being tidy spherical balls, the experiments suggest protons are squashed out along at least one of their axes. Until recently, to question the spherical shape of the proton was taboo. The composition of the proton was confirmed in 1969 by experiments at the SLAC Laboratory in Stanford, California. Researchers used beams of high-energy electrons to split protons in hydrogen and deuterium targets in just the way Gell-Mann predicted. By measuring the energy and angle of the deflected electron, physicists can work out the distribution of quarks inside the proton. According to the law of conservation of momentum, the gamma ray will be deflected with the same transverse momentum as the quark, but in the opposite direction. High-resolution images of the proton could also help theorists struggling with the notoriously difficult equations of the strong force, which holds nuclear matter together.
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Atomic buffet

We used to think of protons as billiard balls, but now there's a smorgasbord of possible shapes to choose between, from peanuts to sausages and chicken drumsticks. Charles Choi explains

EAVESDROP on a chat between particle physicists today and you could be forgiven for thinking you were in a grocery store. “It looks like a peanut at this resolution,” says theorist Gerald Miller of the University of Washington in Seattle, “or a sausage.” But zoom in closer, says Xiangdong Ji of the University of Maryland in College Park, and perhaps it looks more like a doughnut, or a spinning cigar.

Such discussions are the result of experiments in the US and Germany that challenge current thinking on the shape of the proton. Far from being tidy spherical balls, the experiments suggest protons are squashed out along at least one of their axes. This idea, of an oblate or peanut-shaped proton, has theorists rethinking their approach to the “strong force” that holds nuclei together. “It is as surprising as thinking the Earth was round and finding it is flat,” says John Ralston of the University of Kansas in Lawrence.

Until recently, to question the spherical shape of the proton was taboo. According to the "standard model" — which describes the elementary particles of matter and the forces between them — the proton is made of three quarks: two "up" quarks and one "down". The spins and charges of these three quarks add up to give the proton as a whole a spin of ½ and a charge of +1. In the simplest interpretation of this picture, which was published in 1964 by Murray Gell-Mann, then at the University of Chicago in Illinois, each quark moves in the smallest possible circular orbit. This makes the proton spherical.

The composition of the proton was confirmed in 1969 by experiments at the SLAC Laboratory in Stanford, California. Researchers used beams of high-energy electrons to split protons in hydrogen and deuterium targets in just the way Gell-Mann predicted. So theorists accepted the idea of a spherical proton, too.

Until, that is, Ji began to make more detailed calculations of how electrons scatter off quarks when they are fired at the nucleus. The SLAC experiment had shown that when an electron scatters off a proton, it interacts with one of the quarks inside. By measuring the energy and angle of the deflected electron, physicists can work out the distribution of quarks inside the proton. Previous experiments told only part of the story, though, because they measured only one component of quarks' momentum: the part in the same direction as the incoming electron beam. This only tells you about the length of the proton, not its shape.

Ji realised that you could work out its width as well, by measuring the component of momentum at right angles to the beam. The trick is to look for rare cases where the struck quark emits a high-energy gamma ray — a process called "deeply virtual Compton scattering" (DVCS).

According to the law of conservation of momentum, the gamma ray will be deflected with the same transverse momentum as the quark, but in the opposite direction. So the way gamma rays are emitted during a proton-electron interaction should tell us about the motion of quarks in the proton.

Just as an ordinary camera photographs objects by capturing the light rays scattered off them, gamma rays with wavelengths more than a billion times smaller could image the locations of quarks within the proton. "You could make a photograph and actually see the size and shape of the proton," says Ralston.

In 2001, researchers used the HERMES detector at the DESY laboratory near Hamburg, Germany, to scatter a beam of positrons — the antimatter counterparts of electrons — off the protons in gaseous hydrogen. They wanted to confirm that the gamma rays were really being emitted by quarks and not by electrons, which is much more usual when an atom is bombarded. The results, published in Physical Review Letters (vol 87, p 182001), showed that the rays had indeed been emitted by quarks.

Since then the group have looked at the distribution of gamma rays when both electrons and positrons scatter off quarks. Because electrons and positrons have opposite charges, comparing the two distributions reveals how the quarks, which also carry different charges, are moving relative to each other. The team were looking for random quark motion, but instead they found a pattern in the combined distributions that shows the quarks moving in a regular way, as if they were influencing each other. This effect could be due to them carrying angular momentum in specific orbits, making the proton bulge.

So far, the team only has a hint of this new picture of a bulging proton; finding out exactly how the quarks are moving will require more detailed measurements. The intensity of the beam at DESY is so low that it's like trying to take a photograph in the dark, says team member Gerard van der Steenhoven. He reckons an intensity roughly a hundred times that currently available would be needed. Fortunately, both DESY and two facilities in the US have plans to build electron beams as intense as this over the next few years.

Meanwhile, further evidence for a bulging proton has come from the Jefferson Lab in Newport News, Virginia. In 2001, researchers looked at the motion of protons in a liquid hydrogen target hit by high-energy electrons. The electrons were more likely to flip the protons' spin — a magnetic interaction — than to deflect their motion — interacting with their electric charge. This came as a surprise, because the two effects were expected to have similar magnitude. According to research by Miller, it is easier to flip the proton's spin if the quarks inside the particle are in rapidly tumbling orbits. In other words, the Jefferson results make sense if the quarks in a proton have a lot of orbital angular momentum and the proton is not spherical.

As the evidence comes in, theorists are tumbling over themselves to develop models of a bulging proton. We will only know which of the many options is right when more detail becomes visible. If the quarks have enough angular momentum, the sausage-shape could itself bulge or bend in various ways, like a jelly bean or chicken drumstick, for example. So far, the new models have made some progress towards resolving a long-standing mystery in particle physics known as the "spin crisis". In the simplest quark model, the quarks should move so that their spins add up to give the spin of the proton. But many experiments have found a shortfall. Orbital angular momentum could make up the difference.

High-resolution images of the proton could also help theorists struggling with the notoriously difficult equations of the strong force, which holds nuclear matter together. Knowing the internal structure of the proton could provide clues as to how to reformulate the theory so it can be solved not only for the case of the proton, but for all nuclear matter, says Gell-Mann, now at the Santa Fe Institute in New Mexico. "It could suggest what the answer is," he says.

In the meantime, though, theorists are not sitting idle. Now is the time to stake a claim on a drumstick or a jelly bean, says Miller. "It's really important to put things in a way that takes a risk," he says. "That way you can move the foundations and still get somewhere."

"High-resolution images of the proton could help with the notoriously difficult equations describing the strong force. They could be solved for all nuclear matter"

DIAGRAM: PICTURING THE PROTON

PHOTO (COLOR):

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explained by Charles Choi, Charles Choi is a writer in New York City

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