Proton spin puzzle: Research reveals gluons make a significant contribution to spin

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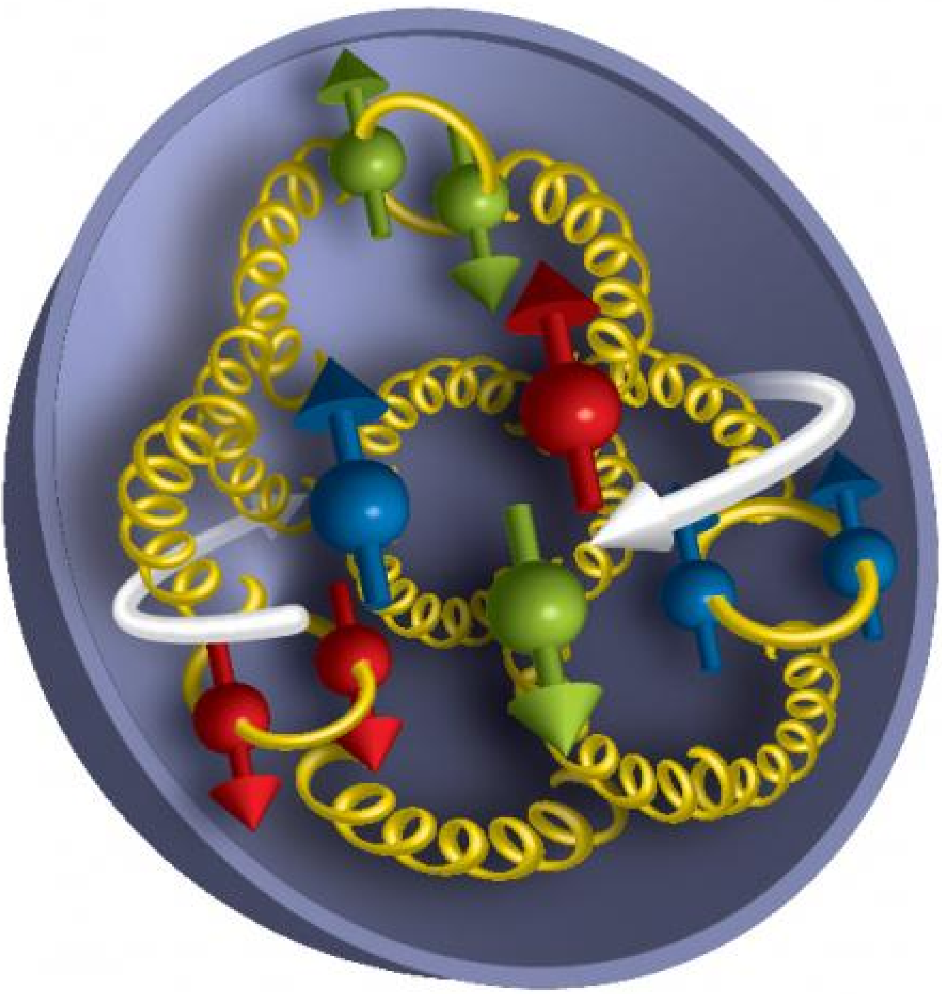


How the spins of the building blocks of matter add up: Measurements from RHIC's STAR and PHENIX experiments reveal that gluons (yellow corkscrews) contribute about as much as quarks (red, green, and blue) to the overall spin of a proton. But there is still a mystery to explain what accounts for the rest of the "missing" spin.

Results from experiments at the Relativistic Heavy Ion Collider (RHIC), a particle collider located at the U.S. Department of Energy's Brookhaven National Laboratory, reveal new insights about how quarks and gluons, the subatomic building blocks of protons, contribute to the proton's intrinsic angular momentum, a property more commonly known as "spin." Specifically, the findings show for the first time that gluons make a significant contribution to proton spin, and that transient "sea quarks"—which form primarily when gluons split—also play a role.

The new precision measurements will help solve a mystery that has puzzled physicists since the 1980s, when findings from early spin experiments in Europe and elsewhere simply didn't add up. Those experiments showed that the spins of quarks—including the three valence quarks that determine most of the basic properties of the proton—plus antiquarks could account for, at most, a third of the proton's total spin.

"Those results made it apparent that it was naïve to assume that the spin of the proton was carried by its three valence quarks, and this triggered a search for the source of the 'missing' spin," said Brookhaven physicist Elke Aschenauer, a leader in the spin program at RHIC, a DOE Office of Science User Facility for nuclear physics research that was built in part to address this question. "RHIC is the only facility in the world capable of colliding spin-polarized protons," Aschenauer said, explaining how colliding beams of protons with their spins aligned in a particular direction, and the ability to flip the polarization, gives physicists an elegant way to directly probe the spin contributions of gluons as well as quarks.

Solving the proton spin puzzle is more than a matter of accounting. Tracking down the sources of proton spin is offering new insight into these particles' internal structure—including quarks and the gluons that bind them, which are numerous and often split to form transient sea quarks. Spin can also have influence on a wide range of more familiar physical characteristics, including optical, electrical, and magnetic properties—some of which are used in everyday applications such as magnetic resonance imaging (MRI). Pinpointing where spin comes from could yield new information about the mechanisms of the complex subatomic particle interactions within protons, the effects of spin on other properties, and perhaps even ways to control those properties for future, unforeseen applications.

Narrowing the focus

The latest results on possible sources of spin, some published and some undergoing final analysis, come from the STAR and PHENIX collaborations, two groups each with 500+ scientists poring over data from millions of proton collisions at RHIC.

"After the early spin experiments found such a small contribution to spin from a proton's quarks, people started making big predictions for gluons, the particles that hold quarks together within protons," said Kieran Boyle, a fellow of the Riken-BNL Research Collaboration (RBRC) who conducts research at PHENIX.

To gauge the gluon contribution, STAR measures jets of particles coming out of the proton-proton collisions when the spins of the protons in one beam align directly with the spins in the other beam, and repeating the experiment with the spins in one beam flipped, or antialigned relative to the other. PHENIX does the same thing, but measures the number of pions, the most abundant particles produced in jets. Any difference observed in jet or pion production rates when one proton beam's polarization is flipped is an indication of how much the gluons' spins are aligned with, and therefore contribute to, the spin of the proton.

Early spin results from RHIC appeared to deepen the spin mystery, showing gluons didn't make the huge contribution to spin that everyone had expected. In fact, the measurements came out close to zero, but with a lot of uncertainty.

"The problem is that these measurements need a lot of data," said Renee Fatemi, a University of Kentucky physicist who is a deputy spokesperson for the STAR experiment. "All we had was the ability to say the contribution [of gluons] wasn't very huge. But with very little data we had very large error bars. All we could tell was the difference between huge and not huge."

More data reveal significant role of gluons

RHIC has since collided many more polarized protons thanks to additional running time and accelerator advances that have vastly increased collision rates within each run and improved the degree of polarization in RHIC's colliding proton beams. In addition, the detectors, particularly STAR, have new capabilities that allow them to capture more collision events. With these expanded data sets, the error bars have shrunk and both STAR and PHENIX now have definitive results.

"RHIC has conclusively, for the first time ever in the world, taken measurements to tell us that the gluon contribution to spin is about equal to the contribution of the quarks," about 20-30 percent of the total proton spin, Fatemi said.

Specialized accelerator magnets known as Siberian snakes have a corkscrew design that helps maintain the polarization of proton beams for RHIC experiments. Keeping all the proton spins aligned in a given direction within at least one of RHIC's colliding beams helps scientists tease out the spin contributions of the proton's internal components.

The fact that STAR and PHENIX got similar results gives the scientists great confidence in their findings.

"These experiments were designed to be complementary," said PHENIX deputy spokesperson John Lajoie of Iowa State University. "Measuring the same physics with different experiments gives us a way to cross-check our findings and also increases the validity of the comparisons of experimental results with predictions derived from nuclear physics theory."

There's still a caveat to the claim, however, because RHIC is designed to measure particles streaming out of collisions in a particular "kinematic range"—tracking only the particles that emerge at particular angles. PHENIX mainly looks at particles streaming out perpendicular to the paths of the colliding protons. STAR captures that same range plus particles knocked a bit farther forward or backward from the collision zone—produced by more "lopsided" collisions between a high-momentum quark in one beam with a lower-momentum gluon in the other.

"Our measurement makes assumptions about places we can't even look yet," Fatemi said. She emphasized that the new results build on the experiments that came before, thus showcasing the importance of extending the range of measurements. They also set the stage for possible future explorations, such as those that could be done at an electron ion collider (EIC), a facility nuclear physicists hope to build to help solve the spin mystery and other scientific challenges.

"An EIC would allow us to make numerous, extremely precise measurements across a much wider range of momentum fractions," Aschenauer said. "It would be the only facility in the world that could measure the distribution of polarized gluons as a function of their momentum and also their spatial distribution in the proton—like a microscope that resolves even the smallest features very precisely. "

Splitting fractions, gluons, sea quarks and spin

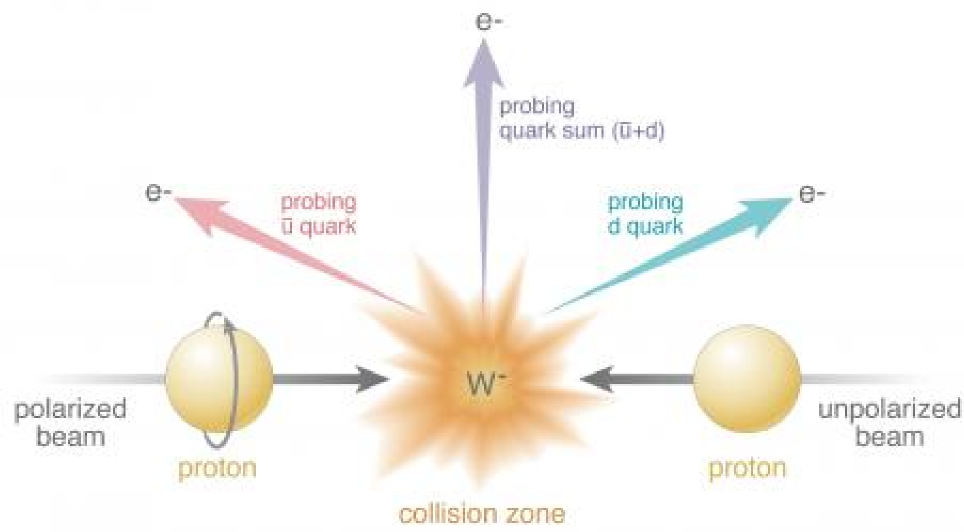
But that doesn't mean physicists have given up the quest to measure gluons' role in spin even more precisely and over a greater range of momentum fractions at RHIC.

For example, PHENIX is working on measuring the gluon contribution to the proton spin at more forward angles. These measurements will extend to a different kinematic region, giving results for the gluons carrying a smaller fraction of the overall momentum of the proton, which may offer further insight into the spin puzzle.

The physicists are also searching for other possible sources of spin. In 2011, they reported the first measurements at RHIC of so-called sea quarks, virtual quark-antiquark pairs that form when gluons achieving a certain energy—say, when protons are accelerated to near the speed of light at RHIC—split and then reform. Though these transient sea quarks flit in and out of existence, they may contribute to spin—and possibly in a way that depends on their flavor.

To track the sea quarks' contributions to spin, physicists again compare what happens when the polarization of one of RHIC's beams is flipped, but this time colliding it with an unpolarized proton beam and tracking the production of particles called W bosons.

"W's are produced when a quark inside a proton in one beam collides with an antiquark in the other beam. So W's are more selective than jets, which can come from quark-quark, gluon-gluon, or quark-gluon interactions," said Ernst Sichtermann, a physicist at DOE's Lawrence Berkeley National Laboratory and another deputy spokesperson for STAR. "The Ws pick out the quark-antiquark signal."



Collisions of polarized protons (beam entering from left) and unpolarized protons (right) result in the production of W bosons (in this case, W-). RHIC's detectors identify the particles emitted as the W bosons decay (in this case, electrons, e-) and the angles at which they emerge. The colored arrows represent different possible directions, which probe how different quark flavors (e.g., "anti-up," u and "down," d) contribute to the proton spin.

Even better, the electric charge of the W can precisely identify the type, or flavor, of the antiquark involved in the collision. W- particles decay into electrons, giving information about "anti-up" quarks, while W+ particles decay into positrons, revealing information about "anti-down" quarks.

So far the results from PHENIX and STAR indicate these sea quarks make a fairly minor contribution to spin. More specifically, the measurements of W+ particles at RHIC indicate that the anti-down quarks' contribution to spin is in agreement with earlier experiments that looked at sea quark contributions in a less direct way.

"Our result is more precise and was done in a different way, which provides strong confirmation of what's been seen before," STAR's Fatemi said.

The results for W-, on the other hand, give the first glimpse that there is an unexpected difference in the polarizations of the anti-up and anti-down sea quarks.

"While our uncertainties are still significant, the RHIC data hint that the contribution from W-, or anti-up quarks, may be a bit larger than had been expected," Sichtermann said.

Aside from suggesting a difference in the spin contribution depending on the flavor of the antiquark, this result could offer interesting insight into the mechanism by which gluons split to form sea quarks in the first place, Sichtermann said.

"Gluons can split into up/anti-down or down/anti-up," he explained. "If that's the only mechanism, and gluons don't care about flavor, you should get equal numbers and equal polarization. So if there is a preference [for anti-up quarks to be more polarized than anti-down], there must be some other mechanism for generating these sea quarks."

STAR will continue to analyze data to increase precision. "With the 2013 data, we have every expectation that the uncertainties could be reduced and we may have evidence in the end," Sichtermann said.

Again, the measurement from STAR comes from the most central region of the collision, not a wide range of momentum fractions. "More forward measurements using similar methods to measure muons will be able to better tease out the antiquark contributions," PHENIX's Boyle said. Recent upgrades to enhance the detection of forward muons were in place for the 2013 run, the data has been fully reconstructed, and the PHENIX collaboration is currently finalizing the results for publication.

"Together, these results show that RHIC lays the ground work for starting to understand the complexity of the spin of the proton—one of the fundamental quantum numbers of every single particle in the universe," Aschenauer said. "But the ultimate answer to unravel its mystery would come from an EIC."

More information: "Inclusive double-helicity asymmetries in neutral-pion and eta-meson production in $\vec{p}+\vec{p}$ collisions at s√=200 GeV." *Phys. Rev. D* 90, 012007 – Published 17 July 2014, journals.aps.org/prd/abstract/ … 3/PhysRevD.90.012007

"Precision Measurement of the Longitudinal Double-spin Asymmetry for Inclusive Jet Production in Polarized Proton Collisions at s√=200 GeV." *arXiv*:1405.5134 [hep-ex]. arxiv.org/abs/1405.5134

"Measurement of Longitudinal Spin Asymmetries for Weak Boson Production in Polarized Proton-Proton Collisions at RHIC." *Phys. Rev. Lett.* 113, 072301 – Published 13 August 2014. journals.aps.org/prl/abstract/ … ysRevLett.113.072301

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