Making up matter

Protons, quarks, and the strong force

- Quarks make up much of the matter around us and are bound together by the strong force.
- Probing the mechanical properties of quarks and the strong force is hard as the gravitational force needed is comparatively much weaker.
- Using Deeply Virtual Compton Scattering (DVCS) allows scientists to probe the pressures and stresses within the proton, which is made up of quarks, and helps us to understand the building blocks of matter.
- Dr Volker Burkert, Dr Latifa Elouadrhiri, Dr Francois-Xavier Girod, and their colleagues at Jefferson Lab, USA have used gravity to probe the proton through DVCS, allowing them to discover the immense pressures exerted by the strong force.
- Their pioneering work establishes a new trajectory of research in the domains of nuclear and particle physics.

From the everyday objects around us to the planets and stars in our galaxy, everything is made up of tiny particles, called 'quarks'. Quarks are the building blocks of matter, and they are held together by gluons which carry the strong force, a fundamental force of nature. Using quarks, we can construct protons and neutrons, which make up the nucleus of atoms. Understanding more about protons can help us learn about the strong force and how it groups quarks together to form everything that we see around us.

Dr Volker Burkert, Dr Latifa Elouadrhiri, Dr Francois-Xavier Girod, and their colleagues at the Jefferson Lab, USA are working to uncover more about the proton through its mechanical properties. To probe protons, scientists have used other fundamental forces, such as the electromagnetic force and the weak force, while gravity has never been used as a probe.

Gravity (and its carrier, known as the hypothetical graviton) is the most challenging fundamental force to use as a probe, as it is the weakest of all forces. However, using gravity to investigate the proton allows us to discover more about its spin, its intrinsic distribution of angular momentum, its mass, and the D-term. The D-term is the last key property of the proton to be established – it encodes the pressure and forces within the proton.

Describing the proton's properties

The key information about the proton's properties form the elements of the energy-momentum tensor. Tensors are mathematical frameworks that describe physical properties.

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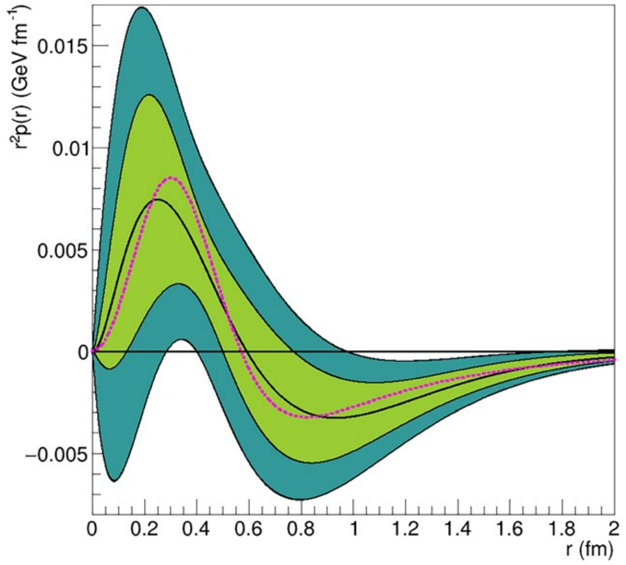
The tensor encapsulates how energy and momentum vary in spacetime, the mathematical model that combines the three-dimensional space that we typically imagine with time into a four-dimensional model which forms the basis of theories like relativity.

The energy-momentum tensor can be written as a matrix, or rows and columns of different numbers and expressions, where the various elements or parts of the matrix relate to different properties of the proton. From the energy-momentum tensor, these matrix elements can be broken down, and five Lorentz-invariant functions emerge – these are expressions that describe quantities that do not vary with the reference frame of an observer. These five functions are called the gravitational form factors of the proton. The gravitational form factors can only be measured directly using graviton–proton scattering.

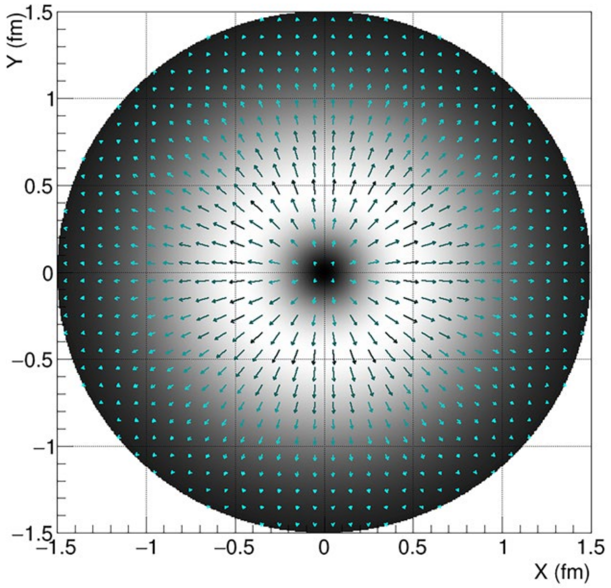
Graviton–proton scattering

Carrying out graviton–proton scattering, however, is a difficult process – the gravitational force is extremely weak, and there is no technique to create beams of gravitons. To overcome this problem, the research team has leveraged a process, called Deeply Virtual Compton Scattering (DVCS), that can provide indirect access to this information. Here, electrons are scattered off the constituent quarks of the proton. This occurs by exchanging a high-energy, virtual photon (an intermediate photon in the exchange of forces between particles) which emits a high-energy photon, or a discrete, quantised wave packet of light.

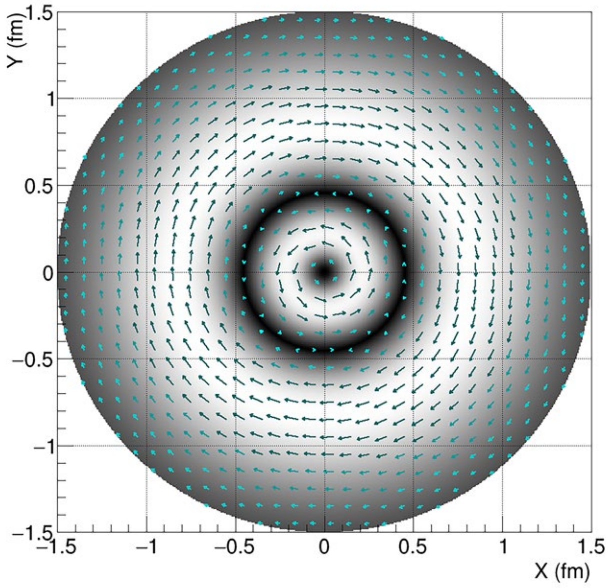
The DVCS process involves two photons – one in the initial electron-quark



Pressure experienced by quarks as a function of radius from the centre, scaled by the square of the radius. Note that the integral of this quantity vanishes, a constraint known as the 'stability condition'. The colour bands show the uncertainties from the world data before and after the JLab CLAS data. The dotted curve shows a model expectation.



Normal component of the force experienced by the quarks as a function of the distance from the centre. This component is always pointing radially outwards.



Tangential component of the force experienced by the quarks as a function of the distance from the centre. This component changes direction and vanishes around r = 0.4 fm.

scattering, and the second one emitted from the quark, as the quark remains bound in the proton. The direction, energy, and momentum, or the measure of the particle's mass and speed in a given direction, of the electron, proton, and emitted photon are used to probe proton's internal structure. If the two high-energy photons are recombined properly, they have the same properties as one graviton interacting with the proton, except the strength of the interaction is much larger – a duodecillion (10^{39}).

Measuring a gravitational form factor

The mechanical force that holds the quarks in the proton together is encoded in the D–term form factor and it depends on how much energy–momentum is transferred to the quark struck by the virtual photon that is exchanged between the electron and proton.

Knowing the general dependence of the D-term on the energy–momentum transfer to the proton allows the team to derive a mathematical function whose parameters are found by fitting this function to the DVCS data. A significant part of the uncertainty with which these parameters are determined results from instances where DVCS data is not currently available, namely in the kinematic space that is not reached due to limited energy of the electron beam available in the DVCS experiment.

Relating the D-term to the stress and pressure

The dependence of the D-term on momentum and energy-transfer to the quarks is theoretically related through complex transformations to the spatial dependence of pressure and forces in an appropriate reference frame. Knowing the D-term allowed the team to determine both the tangential forces and the pressure distribution in the proton. The values they determined are within the uncertainties that arise from the experimental DVCS data and extrapolation, meaning that they used the existing trends for the inference of values to cover the unmeasured kinematic space.

The team found that the powerful force near the proton centre exerts extraordinary pressure, about 10 times greater than the pressure in the core of a neutron star, or the very dense, high-pressure core that remains when a massive star collapses. The strong interaction also causes several tons of shear stress, which are forces that act tangentially on the quarks.

From the spatial distribution of pressure and forces, the team created maps of two-dimensional images in Euclidean space. This allows viewing of regions of stronger forces and weaker forces emerging as we move away from the proton centre and visualise how the direction of the normal force radiates out from the centre, whereas the tangential force direction instead forms concentric circles, with some travelling clockwise and others, anticlockwise.

Overall, by using DVCS, Burkert, Elouadrhiri, and Girod's team have been able to probe the pressure distribution inside the proton. The researchers aim to investigate high energies in future experiments with an aim to determine the D-term with increasing accuracy and completeness by considering even more of the space where momentum can be transferred to the quarks that make up the proton. By probing the proton in this way, the team hopes for a deeper understanding of the strong force, and a scope for further discovery about the fundamental constituents of the matter around us.

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Personal response

What were the primary factors leading to this research?

The research of our team was motivated and driven by our passion and the quest to unravel the intrinsic mechanisms binding quarks within the intricate structure of the proton. Guided by groundbreaking developments in the theory of strong interaction and by innovative experimental methodologies, our journey began with the experimental observation of the process of deeply virtual Compton scattering (DVCS) in 2000. Building upon this pioneering result, we began a programme to enhance the particle detection capabilities of the CLAS detector and double its operating luminosity to what was needed to conduct a dedicated exploration of DVCS, yielding unparalleled precision in the measured DVCS process both in the beam spin asymmetries and in cross sections.

The challenge then was how to exploit the precise experimental data in a bold next step involving the development of a creative technique to connect the recent theoretical insights and experimental data obtained from CLAS. This enabled us to elucidate, for the first time, the mechanical intricacies of the proton. In 2018, we were able to unveil the extreme mechanical pressure distribution hidden within the proton's core, followed by the revelation of the distribution of the internal forces in 2023.

Throughout our collective efforts spanning over two and a half decades, we have not only deepened our understanding of the fundamental forces governing subatomic particles but also illuminated a new pathway for future research and discovery. Even so, we intend to go beyond simple understanding as this work holds the promise of redefining the boundaries of scientific understanding between different areas of physics and paving the way for a new era of discovery.

Where could this work be applied, and what impacts might it have in different areas of physics?

Understanding gravitational structure allows us to explore the nature of the universe across diverse scales, spanning from the microscopic to the cosmic. Research on the gravitational structure of the proton is driven by both theoretical and experimental motivations, seeking to enhance our comprehension of the fundamental forces and particles that underpin the universe in its essence. The investigation of gravitational structure holds critical importance across multiple domains of physics, particularly in our field of nuclear and hadron physics, as well as in areas like quantum gravity and high-energy physics.

After publishing our first work in 2018, a significant number of new theoretical publications have emerged, expanding into investigations concerning baryons, mesons, and nuclei, and even beyond hadronic physics across diverse disciplines. This proliferation highlights the expansive research trajectory and the potential applications of this work.

What will the future look like for the gravitational structure of the nucleon?

In our comprehension, the future trajectory regarding the gravitational structure of protons and neutrons is shaped by continuous experimental research and theoretical advancements in nuclear and particle physics. We see several potential avenues for future investigations:

1. Precision Measurements: Evolving experimental techniques and new data will significantly refine our ability to probe the gravitational structure of protons, neutrons, and other particles facilitating more accurate measurements of gravitational properties for both quarks and gluons distributions inside the proton and neutron.
2. Theoretical Development: Theoretical models to describe the nucleon structure, including their gravitational attributes, may advance in sophistication. Integrating insights from quantum chromodynamics (QCD) and gravitational theories could deepen our understanding of how gravity interacts with nucleon constituents, quarks and gluons.
3. Lattice QCD Calculations: Utilising supercomputers for lattice QCD calculations could yield more precise predictions regarding the gravitational structure of nucleons and other baryons and mesons. The calculation could also allow improved precision, minimising systematic uncertainties.
4. New facilities: Future enhancements to experimental facilities, such as upgrades of CEBAF at Jefferson Lab to higher energies, and the construction of the US Electron Ion Collider will enable researchers to explore gravitational effects in particles with heightened precision and sensitivity.
5. Interdisciplinary Research: All matter and all energy are subject to interaction with gravity. As experiments can probe the short distance interaction of gravity with matter or energy, there could be applications that are out of reach of the normal long distance gravitational interaction in the universe. Collaborations of physicists across disciplines with gravitational physicists could find common interest in this subject that potentially yield novel insights into the gravitational interaction with matter and energy at subatomic scales.

In summary, advancing our understanding of the gravitational structure of nucleons is anticipated to involve a blend of experimental progress, theoretical refinements, and interdisciplinary collaborations. This ongoing research endeavour promises to deepen our comprehension of the fundamental forces and constituents governing subatomic matter.

Details

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w: en.wikipedia.org/wiki/Volker_Burkert
w: www.jlab.org/news/releases/quarks-feel-pressure-proton
w: www.jlab.org/news/releases/gravity-helps-show-strong-force-strength-proton

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Bio

Dr Volker Burkert is a Principal Staff Scientist at Jefferson Lab. He led the experimental program in Hall B for 17 years. He is the spokesperson for DVCS experiments on the proton. His research explores the proton's quark structure and its excited states, with current focus on the gravitational structure. He is recipient of the Governor of Virginia Outstanding Scientist award in 2019.

Dr Latifa Elouadrhiri is a Senior Staff Scientist at Jefferson Lab, the LDRD project manager and Acting Director of CNF. Her research is centred on understanding the fundamental quark substructure of the proton. Elouadrhiri is spokesperson for the DVCS experiments on the proton. She has been honoured with the APS Jesse B. Beams Award.

Dr Francois-Xavier Girod is a Staff Scientist at Jefferson Lab. His research focuses on the study of GPDs. Girod is spokesperson for the DVCS and deep φ-meson electroproduction experiments on the proton. He is currently expanding his work to encompass the science and the analysis techniques of the Electron Ion Collider at Brookhaven National Laboratory.

Further reading

- Burkert, VD, Elouadrhiri, L, Girod, FX, et al, (2023) Colloquium: Gravitational form factors of the proton. *Reviews of Modern Physics*, 95(4), 041002.
- Burkert, VD, Elouadrhiri, L, Girod, FX, (2018) The pressure distribution inside the proton. *Nature*, 557, 396–399.