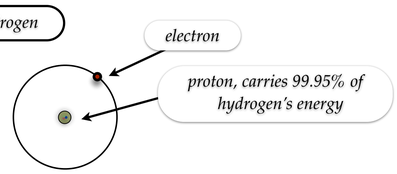
Simulating nature

by Raúl Briceño

Atoms and what is inside!

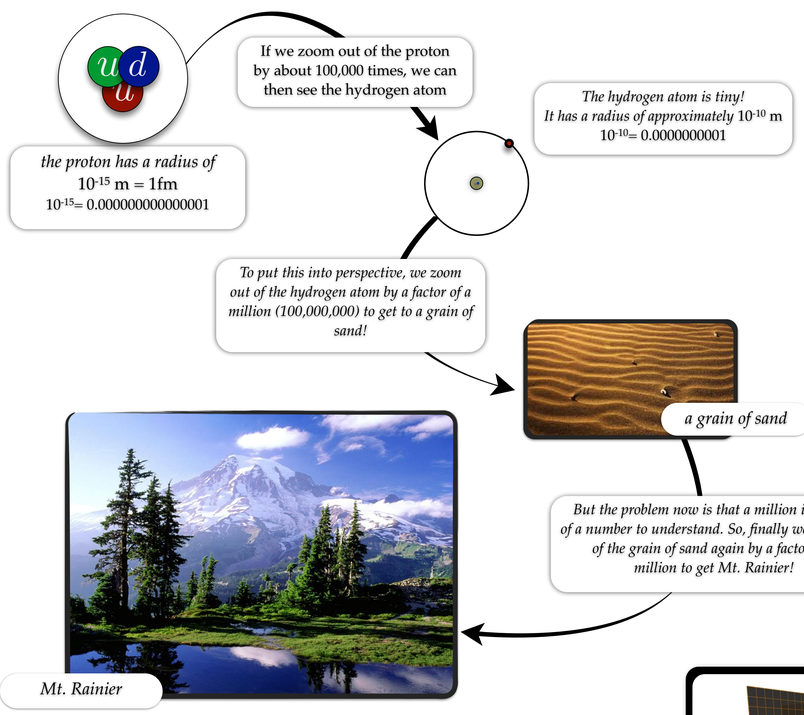
Atoms are the basic building blocks of every day matter! YOU are made out of atoms, and so is everything else you see! The lightest of all atoms is the ***hydrogen atom.*** The hydrogen atoms is made of a single electron ***orbiting*** a single ***proton***, similarly to how planets orbit the sun. The ***electron*** is an extremely light particle (approximately ***10^{-30} kg = 0.0000000000000000000000000000001 kg***) but it is responsible for the electric currents that power your TV as well as the source of lightning in hot summer days. The proton is the ***nucleus*** of the hydrogen atom, and it is about ***2,000 times*** heavier than the electron. The electron has a ***negative charge***, while the proton has a ***positive charge***, so they have opposite charge. This is why they are attracted and why they can come together to form electrically neutral matter!



The neutron, as its name suggest, is the electrically neutral partner of the proton. It has approximately the same mass and behaves in very similar ways as the proton, except it has zero charge! So electrons never see it!

How "*big*" is the proton?

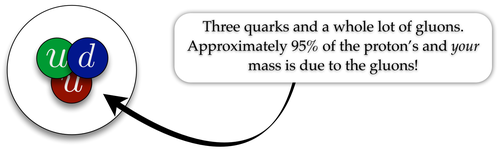
Atoms are tiny, so it is hard to imagine anything smaller than them, but sure enough, the proton and the ***neutron*** are much smaller than atoms. The proton has a ***radius*** of approximately ***0.000000000000001 meters (one femtometer)***! This is an astonishingly small number, that does not make sense in our everyday world, but we can try to put it in perspective:



So we conclude that a hydrogen atom is to a grain of sand as a grain of sand is to Mt. Rainier! But...remember that the proton is 100,000 times smaller than the hydrogen atom! And here at Jefferson Lab we are able to see inside of the proton to see what it is made out of!

Peering inside the proton?

For over half a century now it has been known that the proton is itself composed of other particles, known as ***quarks and gluons***. One can in fact think of the proton as three-quarks (two ***up quarks*** and one ***down quark)*** that are tied together by tons of gluons!

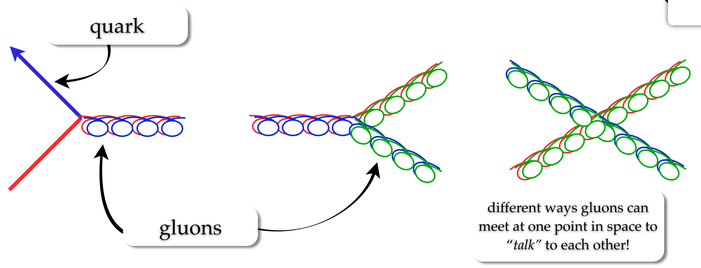


The mathematical theory that describes the interactions between quark and gluons is known as ***"quantum chromodynamics"*** (referred to as "*QCD*"), and it can be written down in a very simple way:

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_{\mathrm{f}}\left(\mathrm{i}\,\not{D} - \mathrm{m_f}\right)\psi_{\mathrm{f}} - \frac{1}{4}\mathrm{tr}\left(\mathrm{GG}\right)$$

The fundamental equation of the strong nuclear force (the so-called ***Lagrangian*** of QCD)

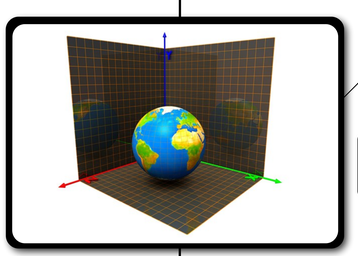
Inside this equation we see the basic interactions between quarks and gluons:



Simulating Nature

Not only does this *simple* equation describe the interactions between quarks and gluons, but it encodes how all nuclei are formed, how they interact with each other; it explains how nuclear fusion can happen in the sun, and how fission happens in nuclear reactors. This connection has been historically obscured because it falls in a class of theories that cannot be solved with the *"pen and paper"* mathematical tools we have developed through the ages. However, we can solve it by programming it into a computer and letting the computer do the work!

In go the fundamental equations of the universe!

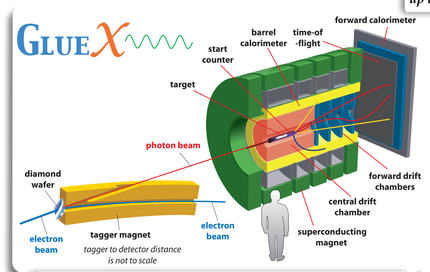


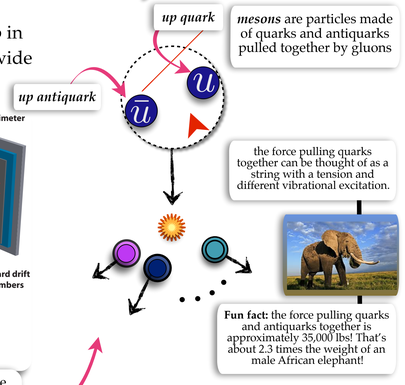
The fastest supercomputer in Virginia is right here at *JLab*!

Out comes the emerges of natural phenomena

What is being studied at *JLab*?

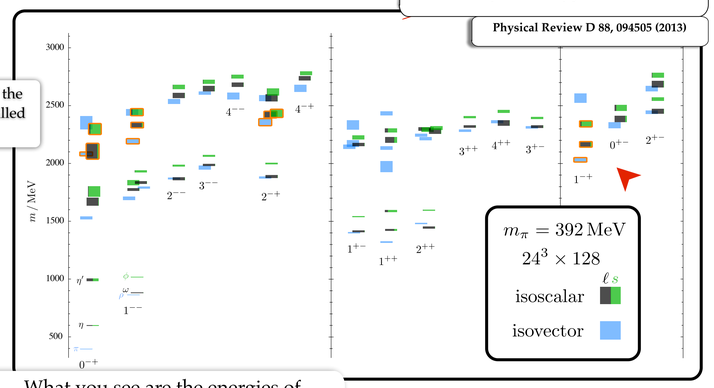
With the upcoming ***GlueX*** experiment at JLab in mind, the theory group has been leading worldwide efforts to calculate the masses of exotic ***mesons***.





GlueX will be able to see inside rare mesons and learn more about the forces between quarks. It does this by reconstructing the initial meson from its decays. This is like reconstructing a car accident from the debris...

The results of a calculation by the Hadron Spectroscopy Collaboration

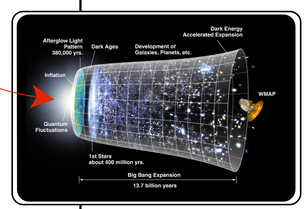


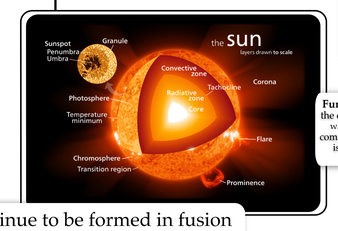
What you see are the energies of particle predicted from QCD that will wide experimental efforts at GlueX

Exotics!

With the goal to see the emergence of nuclei from the fundamental equations of quarks and gluon, the theory group has been at the cutting edge of studies of light nuclei. Most recently the group (along with collaborators at other institutions) have been able to determine the energies of nuclei such as deuterium, helium-3 and helium-4.

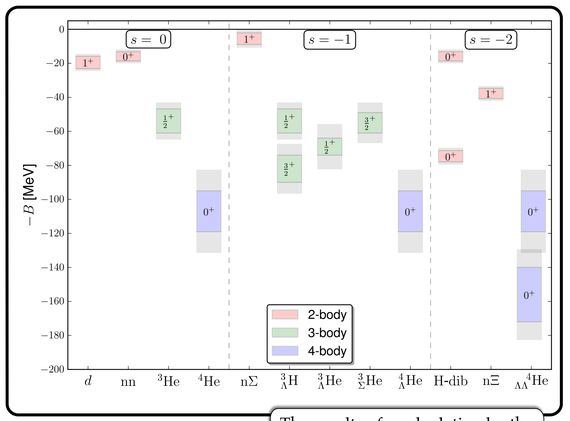
Light nuclei were first formed in the first 3 minutes of the evolution of the universe...





...and continue to be formed in fusion reactions inside the sun!

Fun fact: The power density density of the core of the sun is approximately 276.5 watts/m³. This is about the same as a compost heap! This slow burning process is essential for the formation of life!



The results of a calculation by the NPLQCD Collaboration

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