Nucleon Mass and Quark Spin

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When you step on your bathroom scale, what does the number you read off really tell you (other than cutting back on cookies would be a good idea)? What does it mean to say that somebody (or something) weighs so-and-so many pounds? Most scales measure simply the force of attraction between you and the planet Earth – and, yes, you are pulling on Earth with just the same amount of force as she is pulling on you. But we have learned (since Newton first discovered his laws of gravitation) that this force of attraction is simply proportional to our mass, so the pounds we read off the bathroom scale tell us how massive we are (what our inertia is). Now humans are made of atoms of (mostly) the elements hydrogen, oxygen, nitrogen and carbon, with a smattering of some heavier elements. Each atom in turn is made of a nucleus, which contains nearly all of its mass (99.95%), and electrons, which are rather lightweight. All nuclei are built from a number of positively charged protons and nearly equally massive but neutral neutrons. So ultimately, when you measure your "weight", you are really counting (in a sense) how many protons and neutrons (collectively called "nucleons") your body contains. In fact, each pound of weight is due to about 270 trillion trillion nucleons. So instead of saying "I should shed a few pounds", you could also say "I should lose a few gazillion nucleons".

But what determines the mass of each nucleon? One could guess that maybe the game just continues – the nucleons themselves are made of even tinier particles, called "quarks" that are bound together by "gluons", so maybe their mass is just the sum of all the masses of these "constituents". This could go on forever, but it turns out that this is not the correct answer. We know we need at least three quarks (of the lightest kind) to make a nucleon, but surprisingly these quarks (called "Up" and "Down") turn out to weigh nearly nothing – together, they make up little more than 1% of the nucleon mass. And the gluons that bind them together even have exactly zero mass. So instead of, say, 150 lbs, we humans should really weigh no more than maybe 2 lbs altogether if we just count the mass of all quarks (and electrons) in our body. Where do the remaining 148 lbs come from?

Blame Albert Einstein and his $E=mc^2$! He was the first to realize that mass (inertia) and energy (potential for work) are really two sides of the same coin – they can be converted one into the other, and if you calculate the mass of a composite object, you always have to add the contribution from all its internal energy.

There are actually two kinds of energy at work here. One is called "kinetic energy" and is due to the (very rapid) motion of the quarks inside the nucleons. This motion is due to one of the weird rules of quantum mechanics (called "Heisenberg's Uncertainty Principle"): if you confine a particle to a really tiny space, it has to be moving around with high (but uncertain) velocity. The resulting kinetic energy is always positive and adds to the inertia of the protons and neutrons. A series of experiments since the 60's and 70's of last century have shown that about 1/2 of the nucleon's (and therefore, our) mass is due to this rapid movement of the quarks inside. The other half comes from the interaction (potential) energy of these quarks with each other through the gluons that bind them together. This is at first glance counterintuitive – in most familiar cases, the potential energy due to some binding force is always **negative**, i.e., it should **reduce** the mass of the bound object (otherwise, it could just blow up into its pieces!). Indeed, this is how it works in nuclei: The mass of most nuclei is about 0.8% **smaller** than the masses of its protons and neutrons combined, due to the strong attractive force (and the resulting negative potential energy) that binds them together. That's why the sun can generate net energy by fusing protons and neutrons into helium nuclei.

But in the case of the quarks inside each proton and neutron, the total interaction energy is positive. So why do they not fly apart? The reason has to do with a quite perplexing feature (named "confinement") of the so-called "color force" that binds the quarks and gluons – and it is still at the center of much active experimental research and theoretical investigations. Premier among other laboratories worldwide, the Jefferson Lab in Newport News (VA) is dedicated to explore all aspects of this strong binding of quarks and gluons, which apparently is so strong that no single quark can escape its grip. In some sense, this force resembles a rubber band (made of gluons), which is stretched between the quarks inside the nucleon (yielding positive energy) but prevents them to simply fly apart. (The technical term for this band is "flux tube" or "string".) When you put more and more energy into this band (by moving the quarks at its end further and further apart), it will eventually break – but the excess energy gets converted into **new** quarks (and their antiparticles), so that each end of the string still has a quark (or antiquark) attached to it. These new bits and pieces simply rearrange themselves into new "hadronic" particles like nucleons or mesons (which are made of quark—antiquark pairs). So even in this case, we never get separate quarks – only the subatomic particles we already know.

Sometimes pumping energy into a nucleon does not lead immediately to its breakup into other hadrons, but instead to a heavier, internally excited state (called a resonance). This leads to the next question: what determines the mass of these excited nucleon states, most prominent among them the "Delta resonance"? After all, a Delta resonance is nearly 1/3 heavier than our more familiar nucleons, and if we were all made of Deltas instead of protons and neutrons, our weight would increase from 150 to 200 pounds, for example. One could guess that the quarks inside a Delta are just moving faster (kinetic energy = additional mass). However, that doesn't seem to be the case (as far as nuclear and particle physicists can tell). Or maybe the rubber band is stretched even tighter within a Delta – but what would be responsible for that? In fact, all indications are that a Delta and a nucleon are very much the same thing – until, that is, we include another quirky property of subatomic particles, called "spin".

Spin is another one of these "quantum" phenomena that our brain is really not quite equipped to fully understand (just like the incessant "zero-point" motion of particles in a confined space). The best way to visualize spin is some kind of rotation of an elementary particle around its own axis – just like Earth is spinning around once every 24 hours, giving us night and day. It turns out that all quarks have exactly the same amount of spin – 1/2 in the units of the subatomic world ($\hbar$). The nucleon as a whole also has that same spin of 1/2. This raises the question of how the quark spins arrange themselves inside the nucleon so that the total sum comes out right – obviously, they can't all be spinning in the same direction because then their spins would simply add to 3 times 1/2, more than the nucleon spin. The Delta resonance, on the other hand, has spin 3/2 and therefore can have all quark spins aligned. Maybe that's what makes it heavier!

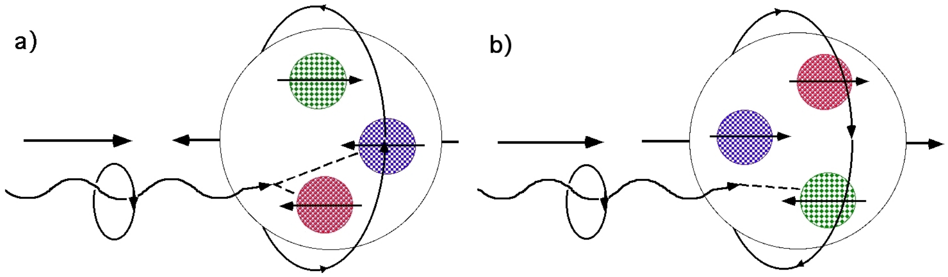

Figure 1: Simplified picture of a spinning nucleon (indicated by the large spheres). On the left (a), the nucleon is spinning around a horizontal axis so that its top moves away from the observer (we say the spin points to the left – indicated by the arrow) and on the right (b) its top is moving towards you (the spin points to the right). The quarks (indicated by the colored spheres) inside the nucleon can spin either in the same direction (blue, red) or opposite (green) to the overall nucleon spin. We can probe these spins using circularly polarized (virtual) photons (arrows at left).

It took a massive experimental effort over 35 years (and still ongoing today) to unravel the intricate ballet of spins and orbital motion executed by the quarks inside the nucleon and its resonances. These experiments require "atom smashers" with enormous beam energies (from the – now defunct – Stanford Linear Accelerator Center in California and the HERA electron-proton collider in Hamburg, Germany, to the still-operating experiments at CERN in Switzerland, RHIC in Brookhaven/NY and Jefferson Lab in Newport News/VA). These accelerators produce multi-billion-volt beams made up of electrons (or muons), all spinning in the same direction – a major technical accomplishment in itself – to probe the spinning nucleons within a "polarized target" – another technological tour de force which has already led to new medical applications.

When the spinning electrons interact with a nucleon, they emit a short-lived form of light called a "virtual photon", which carries some of that spin. Depending on the direction of this rotation, the virtual photon can only interact with quarks that are either spinning in the same direction of the nucleon, or opposite to it. By counting the number of electrons that get scattered out of the beam due to these interactions, we can in a sense count the number of quarks with each spin direction.

For this purpose, large detectors have been built at Jefferson Lab and elsewhere. For instance, in Jefferson Lab's experimental Hall B, a collaboration of universities (including ODU) and research labs from all over the world have used the "CLAS" (CEBAF Large Acceptance Spectrometer) for a series of four experiments over the last decade to probe the nucleon spin. CLAS is a detector which nearly surrounds the target where the interaction takes place. This detector is well suited for spin measurements, because it catches most scattered electrons (above a minimum angle) and therefore allows us to get a rather complete picture of the reaction.

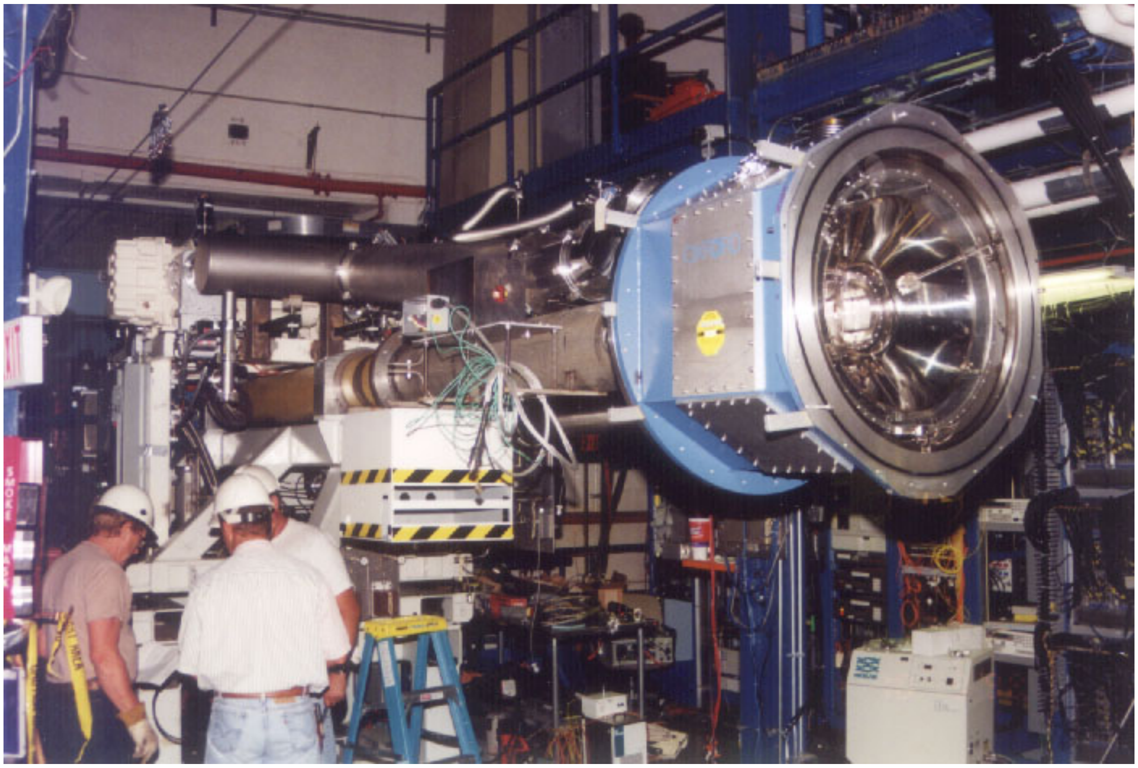

Figure 2: The polarized hydrogen target used for some of the experiments at Jefferson Lab. The blue vacuum vessel to the right contains a superconducting magnet (50000 Gauss field – about a hundred thousand times the magnetic field of Earth) and a Helium refrigerator (-272 degrees Celsius, just one degree above absolute zero). The hydrogen nuclei (protons or deuterons) contained in molecules of ammonia (NH_3) can be polarized under these conditions, using microwave frequency irradiation. The electron beam enters through the large pipe to the left, and the scattered particles are detected in the CLAS spectrometer (outside the picture, to the right).

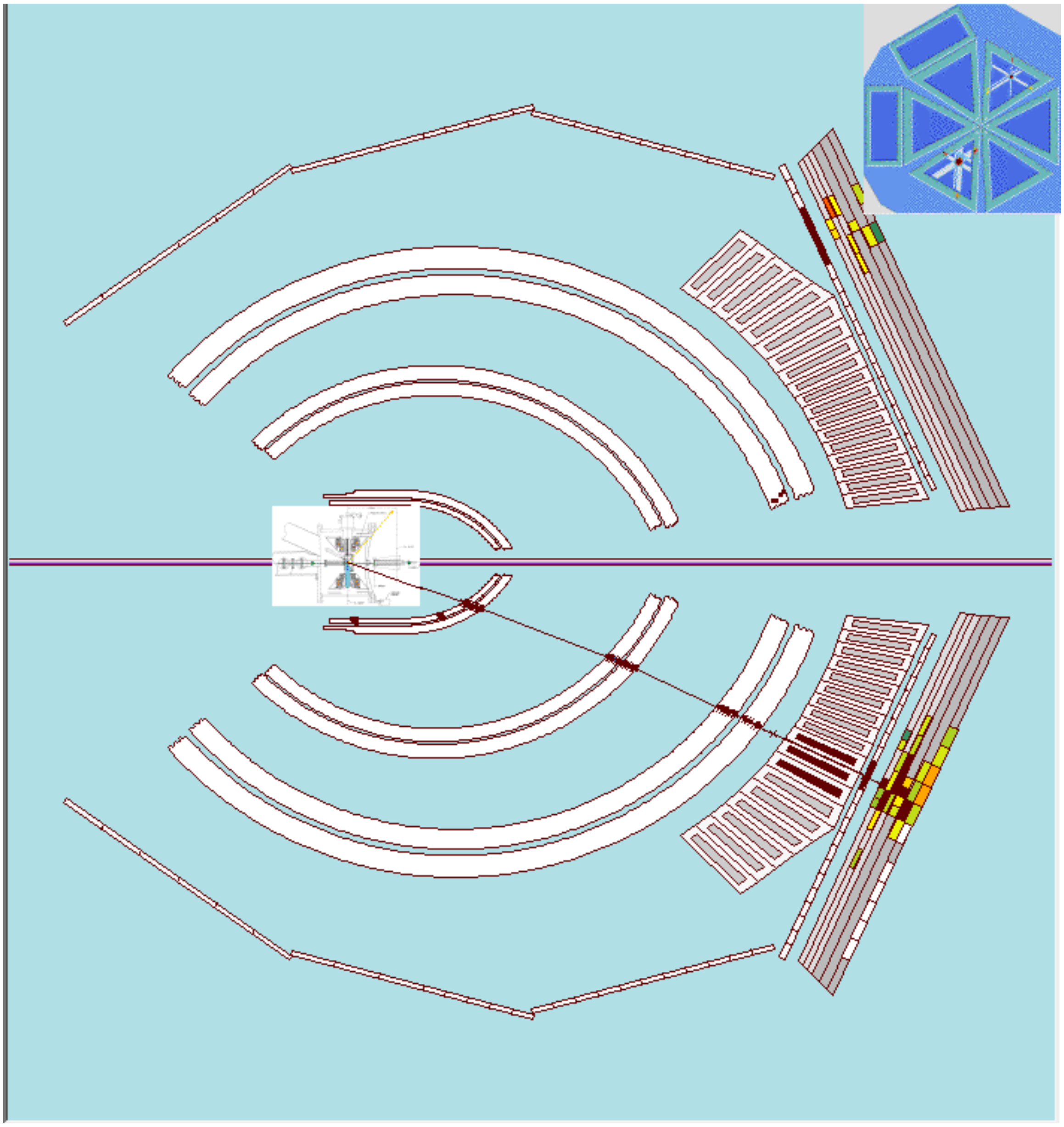

Figure 3: An electron scattered in the polarized target is detected by the many detector layers of the CLAS in Jefferson Lab's Hall B. The first three layers are so-called "drift chambers'' which can very accurately reconstruct the path of a particle through space. (The middle set of these, the "Region 2 Drift chambers", were built by Old Dominion University with help from Jefferson Lab). The remaining detector layers (Cherenkov counter, time-of-flight scintillator and electromagnetic calorimeter) help distinguish electrons from other particle types.

What this and similar experiments have found is that quarks don't like to spin in the same direction – they tend to pair up with opposite spins so that their net contribution to the nucleon spin is actually quite small! This can be compared to the interaction of two magnets held side-by-side – again, the two magnets tend to align in the opposite direction. (The technical term for quarks is "color-magnetism" since their main interaction is not electromagnetic but through the “color force”). This explains why the lightest hadronic particles (mesons) have zero net spin – they are made of one quark and one anti-quark, spinning in opposite directions. However, the nucleons we are all made of contain at least three quarks, so at least some of them have to be spinning in the same direction – and that boosts the energy (and therefore the mass) of these nucleons. The Delta resonance can have all three quarks spinning in the same direction – that’s the main reason why it is so much more energetic (heavier) than the ordinary nucleons. Since the quark spins overall don’t contribute much at all to the nucleon spin, most of it must come from the orbital motion of the quarks and from the gluons that bind them.

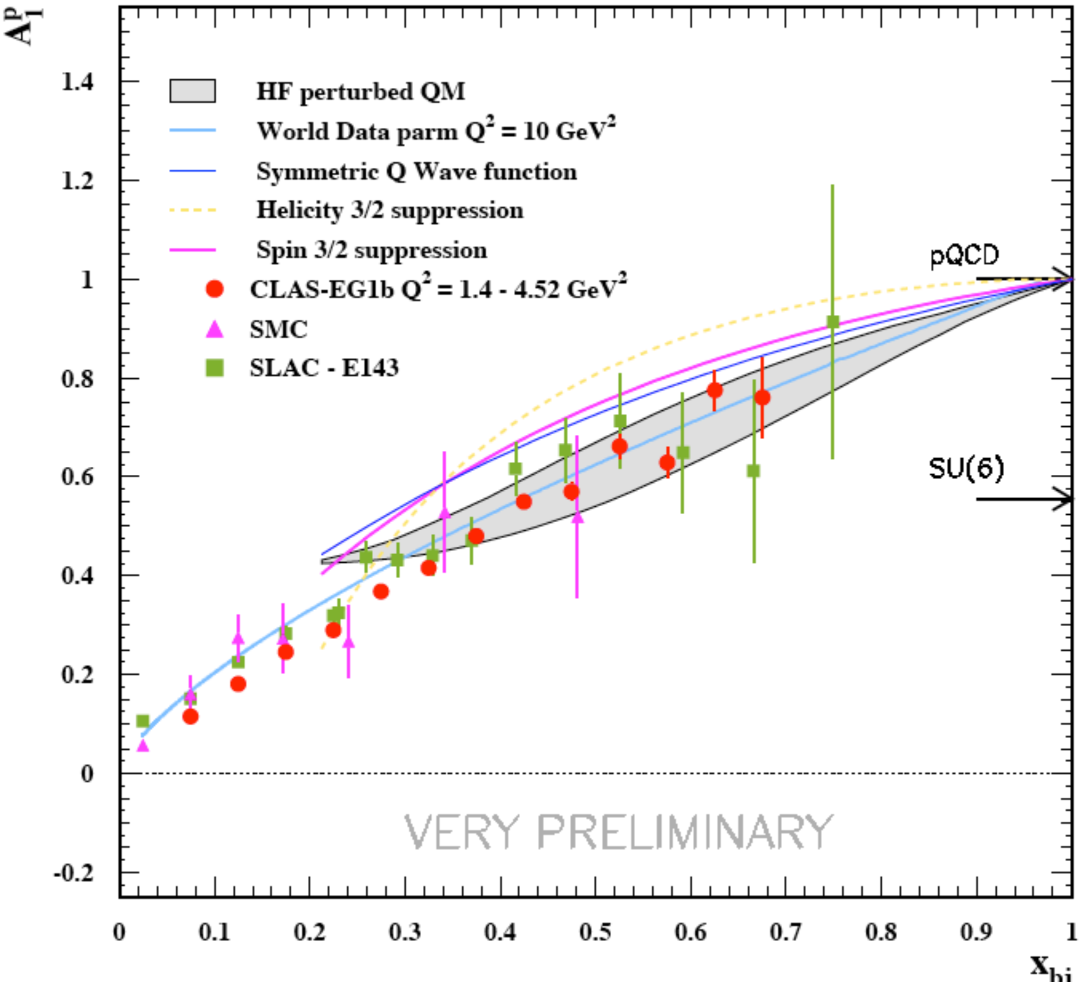

Figure 4: First results from the Jefferson lab spin experiment: The asymmetry A_1 indicates the fraction of the nucleon spin carried by the quarks. The more of the energy of the nucleon is carried by a single quark (right end of the graph), the more likely it is aligned with the nucleon spin. The results agree best with the “Hyperfine perturbed Quark Model” (grey band) which takes “color magnetism” into account. On the opposite end of the graph, we find that the average spin of quarks carrying only a small fraction of the nucleon energy nearly cancels out to zero. This is the due to a large “sea” of quark-antiquark pairs that pop in and out of existence inside the nucleon, with their spins aligned opposite to the overall nucleon spin.

Even the impressive work done so far cannot conclusively answer one key question: What happens when a single quark carries nearly all of the mass-energy of the nucleon (which would correspond to the right edge of Fig. 4, where the variable x tends to 1)? For this, one needs higher energies than even Jefferson Lab has been offering up to now, but at the same time one needs the superior beam qualities (high intensity and continuous operation) only Jefferson Lab can provide. The solution is an upgrade that has doubled the energy of the Jefferson Lab accelerator to 12 billion electron-Volts. The large community of researchers working at Jefferson Lab (over 1000 scientists) has made large contributions to this upgrade (the ODU group once again built a set of drift chambers, as well as led the development of a new polarized target). At this point (mid-2014), this energy upgrade has passed nearly all milestones and experiments with the higher energy beam are expected to begin within a few months. Ultimately, through continuing experiments of ever-increasing accuracy (and corresponding advances in theoretical models) we can hope to unravel the mechanism of confinement, and in turn the true origin of most of the visible mass in the universe – including our own weight.