1 From atoms to quarks, Rutherford redux

The kind of experiments we perform to probe the structure of matter belong to three categories: scattering, spectroscopy and break-up experiments. The results of such experiments brought us from the atom to the nucleus, to hadrons, to quarks.

Geiger and Marsden reported in 1906 the measurements of how $\alpha$ particles (the nuclei of He atoms) were deflected by thin metal foils. They wrote “it seems surprising that some of the $\alpha$ particles, as the experiment shows, can be turned within a layer of $6 \times 10^{-5}$ cm of gold through an angle of 90°, and even more”. Rutherford later said he was amazed as if he had seen a bullet bounce back from hitting a sheet of paper. It took two years to find the explanation. The atom was known to be neutral and to be containing negatively charged electrons of mass very much less than the mass of the atom. So how was the positively charged mass distributed within the atom? Thompson had concluded that the scattering of the $\alpha$ particles was a result of “a multitude of small scatterings by the atoms of the matter traversed”. This was called the soft model. However “a simple calculation based on probability shows that the chance of an $\alpha$ particle being deflected through 90° is vanishingly small”. Rutherford continued “It seems reasonable to assume that the deflection through a large angle is due to a single atomic encounter, for the chance of a second encounter of the type to produce a large deflection must be in most cases exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflection in a single encounter”. According to the soft model the distribution of scattered particles should fall off exponentially with the angle of deflection; the departure of the experimental distribution from this exponential form is the signal for hard scattering. The soft model was wrong. Geiger and Marsden found that 1 in 20,000 $\alpha$ particles was turned at 90° or more in passing through a thin foil of gold; The calculation of the soft model predicted one in $10^{3500}$. The nuclear atom was born with a hard constituent, the small massive positively charged nucleus. Rutherford calculated the
angular distribution expected from his nuclear model and he obtained the famous sin^4(\phi/2) law, where \phi is the scattering angle.

At almost the same time Bohr (1913) proposed the model for the dynamics of the nuclear atom, based on a blend of classical mechanics and the early quantum theory. This gave an excellent account of the spectroscopy of the hydrogen. Beginning with the experiments of Frank and Hertz the evidence for quantized energy levels was confirmed in the inelastic scattering of electrons from atoms.

The gross features of atomic structure were described well by the non-relativistic quantum mechanics of point-like electrons interacting with each other and with a point-like nucleus, via Coulomb forces.

As accelerator technology developed it became possible to get beams of much higher energy. From the de Broglie \( \lambda = h/p \) relationship it is clear that the resolving power of the beam becomes much finer and deviations from the Rutherford formula for charged particles scattering (which assumed point-like \( \alpha \)'s and point-like nucleus) could be observed. And they did! At SLAC in 1950 an electron beam of 126 MeV (instead of \( \alpha \)'s) was used on a target of gold and the angular distribution of the electrons scattered elastically fell below the point-nucleus prediction. (qualitatively this is due to wave mechanical diffraction effects over a finite volume on the nucleus). The observed distribution is a product of two factors: the scattering from a single point-like target (a la Rutherford with quantum mechanical corrections, spin, recoil etc.) and a “form factor” which is characteristic of the spatial extension of the target’s charge density.

From the charge density distribution it became clear that the nucleus has a charge radius of about 1-2 fm (1 fm=\(10^{-15}\) m); In heavier nuclei of mass number \( A \) the radius goes as \( A^{1/3} \) fm. If the nucleus has a finite spatial extension, it is not point-like. As with atoms, inelastic electron scattering from nuclei reveals that the nucleus can be excited into a sequence of quantized energy states (confirmed by spectroscopy).

Nuclei therefore must contain constituents distributed over a size of a few fermis, whose internal quantized motion lead to the observed nuclear spectra involving energy differences of order a few MeV.

Chadwick discovered the neutron in 1932 establishing to a good approximation that nuclei are neutrons and protons (generically called nucleons). Since the neutron was neutral, a new force with range of nuclear dimensions was necessary to bind the nucleons in the nuclei. And it must be very much
stronger than the electromagnetic force since it has to counterbalance the “uncertainty” energy (≈20 MeV; the repulsive electromagnetic potential energy between two protons at 1 fm distance is ten times smaller, well below the nucleon rest energy).

Why all this? The typical scale of size and energy are quite different for atoms and nuclei. The excitation energies in atoms are in general insufficiently large to excite the nucleus: hence the nucleus appears as a small inert point-like core. Only when excited by appropriately higher energy beams it reveals that it has a structure. Or in other words the nuclear degrees of freedom are frozen at the atomic scale.

To figure out whether the nucleons are point-like the picture we already developed is repeated once again. First elastic scattering results of electrons from nucleons (Hofstadter) revealed that the proton has a well defined form factor, indicating approximately exponential distribution of charge with an rms radius of about 0.8 fermi. Also the magnetic moments of the nucleons have a similar exponential spatial distribution. Inelastic scattering results, as expected, showed signs of nucleon spectroscopy which could be interpreted as internal motions of constituents. For example in the scattering of energetic electrons from protons there is one large elastic peak (at the energy of the electron beam) and other peaks that correspond to excitations of the recoiling system. The interpretation of the data is a hairy story: several excited recoil states contribute to the same peak and even the apparently featureless regions conceal structure. In one of the first experiments that used close to 5 GeV electrons, only the first of the two peaks beyond the elastic had a somewhat simple interpretation: It corresponded exactly to a long established resonant state observed in pion-nucleon scattering and denoted by Δ. Four charge combinations correspond to the accessible pion-nucleon channels: $\pi^+p$, $\pi^+n(\pi^0p)$, $\pi^-p(\pi^0n)$, $\pi^-n$. The results of such “baryon spectroscopy” experiments revealed an elaborate and parallel scheme as the atomic and nuclear previously. One series of levels comes in two charged combinations (charged and neutral) and is built on the proton and neutron as ground states; the other comes in four charge combinations (−,0,+,++) with the Δs as ground state.

Yukawa predicted the pion as the quantum of the short-range nuclear forces. In the 60s the pion turned out to be the ground state of excited states forming charge triplets. Let’s note again that we are looking at the excitations of the constituents of composite systems. Gell-Mann and Zweig
proposed that the nucleon-like states (baryons), are made of three 1/2 spin constituents: the quarks. The mesons are quark-antiquark bound states. Baryons and mesons are called collectively hadrons. As in the nuclear case the simple interpretation of the hadronic charge multiplets is that the states are built out of two types of constituents differing by one unit is charge - hence its constituents appeared fractionally charged. The assignment was that the two constituents were the up (u) and down (d) with 2/3 and -1/3 charge. The series of proton would then be uud and the neutron udd while the Δ++ would be uuu. The forces between the quarks must be charge independent to have this kind of excited states. Let's point here that the typical energy level differences in nuclei are measured in MeV. For the majority of nuclear phenomena the neutrons and protons remain in their ground unexcited states and the hadronic excitations are being typically of order MeV; the quark-ian, hadronic degrees of freedom are largely frozen in nuclear physics. People did not like the quarks; They really thought it was nonsense. Nevertheless a very simple “shell model” approach of the nucleon was able to give an excellent description of the hadronic spectra in terms of three quarks states and bound states of quark-antiquark. So now, how would we try to see those quarks directly? We need to think Rutherford scattering again and extend the inelastic electron scattering measurements to larger angles. The elastic peak will fall off rapidly due to the exponential fall off of the form factor. The same is true for the other distinct peaks; this indicates that the excited nucleon states have some finite spatial extension. The bizarre thing is that for large energy transfer the curve does not fall as the angle increases. In other words for large enough energy transfer the electrons bounce backwards just as the αs did in the Geiger-Marsden experiment. This suggests hard constituents! This basic idea was applied in 1968 in so-called deep inelastic scattering experiments by Friedman, Kendall and Taylor in which very energetic electrons were scattered off of protons. The energy was sufficient to probe distances shorter than the radius of the proton, and it was discovered that all the mass and charge of the proton was concentrated in smaller components, spin 1/2 hadronic constituents called “partons” which were later identified with quarks. A lot of spectroscopy and scattering data became available in the ’70s and still people used the quarks as mathematical elements that help systematize a bunch of complicated data. In fact the following quote is attributed to Gell-Mann: “A search for stable quarks of charge -1/3 or +2/3 and/or stable di-quarks of charge -2/3 or +1/3 at the highest energy accelerators
would help reassure us of the non-existence of real quarks”. Indeed quarks have not been seen as single isolated particles. When you smash hadrons at high energies, where you expect a quark what you observe downstream is a lot more hadrons - not fractionally charged quarks. The explanation of this quarky behavior – that they don’t exist as single isolated particles but only as groups “confined” to hadronic volumes – lies in the nature of the interquark force. November 1974 was a revolution of quarks: A new series of mesonic (quark-antiquark) spectra, the \(J/\psi\) particles, were discovered, with quantum number characteristics of fermion-antifermion states. The \(J/\psi\) spectrum is very well described in terms of \(c\bar{c}\) states where \(c\) is a new quark: the charm. The \(c\bar{c}\) is called charmonium after the \(e^+e^-\) positronium. There is a funny resemblance between the energy states of the charmonium with those of the positronium given that the positronium is bound via electromagnetic forces while the charmonium via strong forces.

Back to Rutherford again. We saw how the large angle large energy transfer electron scattering from nucleons provided evidence for “hard constituents”. What if we collide two nucleons? With a “soft” model of the nucleons we expect some sort of an exponential fall off of the observed “reaction products” as a function of their angle to the beam direction. On a “hard” model we should see prominent “events” at wide angles, corresponding to collisions between the constituents. The hard scattered quarks are converted into two roughly collimated ‘jets’ of hadrons. These jets and their angular distributions provide indirect evidence of quarks. At \(p\bar{p}\) collisions at CERN jets were observed in the 80s when CERN achieved with SPS the largest momentum transfers. Clear evidence of hadronic jets associated with primary quark processes were observed earlier in electron-positron collisions.

If quarks are not point-like we expect to see at higher energies, where the sub-quarkian degrees of freedom unfreeze perhaps at the Tevatron and the LHC, deviations from the theory similar to the deviations observed in the deep inelastic scattering experiments.

1.1 Technical handbook

The fragments of a high energy collision in matters of nanoseconds have decayed and/or left the detectors. In the early times of particle experiments an event was a picture in a bubble chamber for example, of the trail the particles left when ionizing a medium. Now an event is an electronic col-
lection of the trails many particles left in a multiple complex of detectors. We are taking a little detour here to define some jargon particle physicists use, to discuss briefly what is the modern process of particle detection and what is the data analysis after all. To start, there is a physics collision for which we have a theoretical model to describe the particle interaction (we draw a Feynman graph). The fragments of the collision decay and interact with the detector material (we have for example multiple scattering). The detector is responding (there is noise, cross-talk, resolution, response function, alignment, temperature, efficiency...) and the real-time data selection (trigger) together with the data acquisition system give out the raw data (in the form of bytes; we read out addresses, ADC and TDC values and bit patterns). The analysis consists of converting the raw data to physics quantities. We apply the detector response (e.g. calibration, alignment) and from the interaction with the detector material we perform pattern recognition and identification. From this we reconstruct the particles’ decays and get results based on the characterization of the physics collision. We compare the results with the expectations by means of a reverse path that simulates the physics process calculated theoretically and driven through a computational model of the detector, the trigger and data acquisition path (Monte Carlo). The challenge is to select the useful data and record them with minimum loss (deadtime) when the detector and accelerator is running properly; and of course to analyze them and acquire results that are statistically rather than systematically limited. When the statistical uncertainty becomes smaller than the systematic uncertainty, it is time to build a new experiment for this measurement.

To give an example, in a hadronic collision at CMS in 2007, the interaction rate should be 40 MHz (corresponding to data volume of 1000 TB/sec). The first level of data selection is hardware implemented and by using specific low level analysis reduces the data to 75 kHz rate (corresponding to data volume of 75 GB/sec). The second level of judging whether an event is going to be further retained is implemented with embedded processors that reduce the data rate to 5 Hz (5 GB/sec). The third level of the trigger is a farm of commodity CPUs that records data at 100 Hz (100 MB/sec). These data are being recorded for offline analysis. The final data volume depends on the physics selection trigger and for example we expect at the first phase of the Tevatron Run II to have between 1 and 8 petabytes per experiment. The improvement in high energy experiments is multifold. Better accelerator
design and controls give higher energies and collision rates. Better trigger architecture is making best use of the detector subsystems. Better storage, networks and analysis algorithms contribute to precise and statistically significant results. Large CPU and clever algorithms improve the simulations and theoretical calculations that in turn enable the discovery of new physics in the data.

To summarize the jargon: **trigger** is a fast, rigid and primitive, usually hardware implemented selection applied on raw data or even analog signals from the detectors. Triggers have *levels* that an event passes through or fails. The trigger system and algorithms are emulated so that the signals are driven through a computational model of the trigger path, and the results are compared with the acquired data for diagnostic purposes. The efficiency of a multilevel trigger path is measured in datasets coming from orthogonal trigger paths (e.g. you want to measure the efficiency of a multilevel missing energy trigger in a dataset of events that come from a trigger that has no missing energy in its requirements). The duration of time when the data acquisition system cannot accept new data (usually because it is busy with current data) is called **deadtime**. To go faster modern experiments are running parallel data acquisition on sub-detector systems that are ending in fanned out triggers (**data streams**); the combination of the fragments of data from the detector subsystems is the **event building**. A **filter** is a later selection after the trigger, which is usually software implemented and can be sophisticated. **Reconstruction** is the coding that converts the sparsified hardware bytes to physics objects (tracks, vertices, tags etc.) A computer **farm** is a dedicated set of processors and associated networks used to run filters, event reconstruction, simulation etc. **Efficiency** is the probability to pass an event (signal or background). **Enhancement** is the enrichment of the data sample after a selection is applied.