Deep inelastic scattering

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Feynman diagrams can be used to explain deep inelastic scattering, but it must be remembered that the emssion and absorption of a photon are not independent events—the underlying field is important.

In a recent article on the nature of force in particle physics (Allday 1997) I confessed to being uneasy about using the uncertainty principle to explain the nature of virtual particles (the exchange particles that mediate the fundamental forces). In this article I would like to explore a related unease to do with the way in which the use of particles as a 'probe' into the structure of matter is explained at A-level. I am thinking especially of the Deep Inelastic Scattering experiment performed at SLAC in the 1960s. This is an important experiment both in the history of physics and in the structure of many particle physics syllabuses at A-level. Deep inelastic scattering gives the most direct evidence for the existence of quarks within protons. It has important links back to Geiger and

Marsden’s experiments with gold foils, giving an appealing historical continuity to our search for the fundamental constituents of matter.

Deep inelastic scattering (DIS)

The experiment was performed during the 1960s at the Stanford Linear Accelerator Centre (SLAC) and the team leaders, Jerome Friedman and Henry Kendall, were awarded the Nobel Prize in 1990. Just as Geiger and Marsden used alpha particles to probe the charge structure of gold atoms in a foil, the DIS experiment used electrons accelerated by a 30 km linear accelerator to probe the charge structure of the proton. The accelerated electrons were fired into a liquid hydrogen target and the scattered electrons measured by a detector that could be moved both horizontally and vertically through a range of angles at the target. The substance of the results is that a dramatic increase in the number of electrons scattered to large angles (hard scattering) was observed as the energy of the electrons was increased.

This has an obvious analogy with Geiger and Marsden’s discovery of hard scattering of alpha particles. Rutherford subsequently explained this in terms of a small localization of positive charge within the atom (the nucleus) because only the strong electromagnetic field associated with such a charge localization could give the alpha particles an impulse great enough to reverse their path. Similarly the DIS results are interpreted as evidence for small charge localizations within the proton—the quarks. However, this begs the question as to why the hard scattering events are observed only at high energy.

Low energy electrons simply scatter off at small angles (soft scattering). Hard scatters are also accompanied by a shower of particles from the target. These particles are found to be hadronic in nature (all particles that contain quarks are called hadrons) and are the result of one of the quarks in the target proton being ejected from the proton. The interpretation of these results is that the incoming electrons interact with the quarks within the proton if the energy is high enough, but only with the proton as a whole if the energy is low. The mechanism of DIS needs to explain these features.

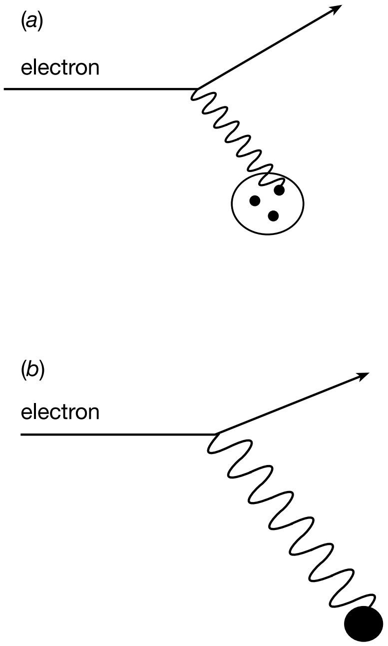

Figure 1. An incoming electron encounters a photon. (*a*) It emits a short wavelength photon which sees the quarks inside the proton. (*b*) It emits a long wavelength photon which sees the proton as a solid volume of charge.

The mechanism for DIS

Figure 1 shows an incoming electron emitting a photon which interacts with a proton in the target.

The conventional explanation of the features of DIS (i.e. the one most often found in popular books and therefore the one that I am assuming most teachers will be using) is that the fate of the photon depends on its energy. A high energy photon will have a short wavelength and is therefore more likely to ‘resolve’ the individual quarks within the proton (just as a microscope cannot resolve any objects smaller than the wavelength of the light that it uses), as shown in figure 1(*a*). As a result of emitting a high energy photon (which carries a great deal of momentum) the electron recoils at a sharp angle. This is the signal for finding quarks within the proton. The high energy photon will also blast the quark that it strikes out of the proton. This quark will then ‘dress’ itself into a stream of hadrons. The process of dressing comes about from the nature of the strong force; although not understood in detail it can be well modelled with computer programs.

A long wavelength photon (figure 1(*b*)) will be unable to interact with the individual quarks within the proton and will only ‘see’ the proton as a charged sphere. Furthermore, such a photon does not carry much momentum and so the electron will only recoil at a small angle. Clearly a low energy electron can emit only long wavelength photons and so the quarks can only be observed by using high energy electrons as the probe particles.

However conventional this explanation may be, it still suffers from the same problem that I alluded to in the previous article. In this context the problem is displayed by raising the following points:

1. Why should we assume that a high energy electron will emit **only** high energy photons?
2. If the high energy electron emits a high energy photon, then it will recoil at a sharp angle **irrespective of what the photon then goes on to strike**. Why should it matter what exists inside the proton? The photon only reaches the proton after it has been emitted and the electron recoiled.

These two points again indicate the problem of concentrating on the photon in diagrams such as figure 1 and ignoring the underlying field. The problems evaporate once it is understood that the emission and absorption of photons *are not independent events*. In the previous article I commented that when we draw a single Feynman diagram we are simplifying the process of interaction tremendously. The wavy line that we draw (in the case of a photon) represents a disturbance in a field that extends invisibly across the whole diagram. The photon in an electromagnetic field is like the ruck in a carpet. We can make the ruck move by whipping one end of the carpet, but the tension in the carpet and the distribution of furniture round the room all influence the motion because they are setting up the background conditions in which the motion is taking place. The photon is a disturbance in the field connecting the two particles and its creation is as much to do with the motion of the absorber as it is of the emitter.

With these ideas in mind, there is an alternative way of explaining the interaction of DIS based on the physical ideas that Feynman used in his theoretical study of the experiment.

Feynman on DIS

A high speed electron passes the proton in a very short period of time. The quarks within the proton are moving with very high velocities, but in the short period of time that the electron is in their vicinity they do not move very far. Time dilation also helps to slow down the motion of the quarks from the electron’s point of view. The electron observes three concentrations of charge (blurred slightly by the motion) and so three strong, interacting electromagnetic fields. Its own field interacts with the field of these charge concentrations and the result is an exchange of energy and momentum between them. A high energy photon is formed between the electron and one of the quarks. As a result of this exchange of energy and momentum the quark and the electron recoil, leading to the observed effects.

On the other hand, a low energy electron takes longer to pass the proton. The time dilation effect is also less noticeable. As a result, the quarks move a great deal while the electron is passing. This is rather like the effect observed with helicopter blades—filmed in slow motion the individual blades can be resolved, at normal speed they appear to form a solid disc. The low energy electron does not see individual quarks and point-like charge distributions. It sees a smeared out charge filling the volume of the proton. There is no strong electromagnetic field for it to interact with (the result of averaging the fields of the fast quarks) and so only a low energy photon is formed, leading to a soft scatter.

I have found this to be a much more appealing explanation of DIS. The energy of the electron is directly linked to the interaction process, and the reason for the photon having high energy if there are quarks within the proton is much more obvious.

Received 25 September 1997
PII: S0031-9120(98)87918-5

Reference

Allday J 1997 The nature of force in particle physics *Phys. Educ.* **32** 327–32