

# A reappraisal of the mechanism of pion exchange and its implications for the teaching of particle physics

**Peter Dunne**

Preston College, Fulwood Campus, Preston PR2 8UR, UK

## Abstract

The origins of the pion exchange model of nuclear forces are described and the exchange process is reinterpreted in the light of current views on the quark–gluon structure of nucleons. It is suggested that the reinterpretation might provide a picture of cohesive nuclear forces that is more intellectually satisfying than that produced by the traditional approach. It is argued that it might be time to review the way we present the exchange particle concept at pre-university level.

## Introduction

The exchange particle concept is a central element of modern particle physics. Electromagnetic interactions between particles are described in terms of the exchange of photons between electric charges, weak interactions are described in terms of the exchange of W or Z particles and the strong interactions between quarks are described in terms of the exchange of gluons. The mathematics that particle physicists use to describe the exchange processes is sophisticated, thorough and is very successful in accounting for what is observed. But representations of the exchange process at pre-university level are not particularly intellectually satisfying. Introductory textbooks make the link between exchange processes and interparticle forces by using an analogy that describes a basketball being thrown from one person to another. In this analogy the thrower transfers momentum and energy to a ball, which then passes to the receiver who absorbs the energy and momentum from the ball. To a student who is approaching the subject with a Newtonian conceptual framework, this exchange process might adequately justify the communication of

a repulsive force but it offers no adequate explanation of attractive forces. Whilst it is recognized in some texts that the basketball analogy can present students with conceptual difficulties (see, e.g., [1, 2]), the use of the analogy persists and is encouraged by some exam syllabuses.

Particle physics textbooks that use the basketball analogy often refer, correctly, to the suggestion made by Hideki Yukawa, in 1934, that the strong binding force between protons and neutrons in a nucleus is associated with the transfer between nucleons of a particle having rest mass. This approach is supported by the fact that the use of Yukawa's exchange particle still turns out to offer a good quantitative description of the internucleon force at ordinary nucleon separations. But whilst it is reasonable to use Yukawa's approach to justify the analogy, it might not be reasonable to continue using the analogy itself to describe what goes on when particles interact.

The aim of this article is to look to see if we can offer to students an alternative description of Yukawa's exchange process without resorting to the basketball analogy. It draws upon current

views of what is going on inside a nucleon and offers a speculative, but plausible exchange process that suggests internucleon attraction. The first half of the article traces the development of the pion exchange view of the internucleon force and leads up to the eventual recognition that the strong nuclear force is better described in terms of the exchange of colour charge between quarks. The second half of the article reinforces the view that the transfer of colour charge is a cohesive process and extends the idea to suggest a plausible picture of internucleon pion exchange. It concludes by questioning the way fundamental forces and particle exchanges are represented at the introductory level.

### Heisenberg and Yukawa

The origin of the exchange particle model of nuclear forces can be traced to the work of Heisenberg in 1932. Chadwick's announcement of the discovery of the neutron in February of that year led to a flurry of speculation about the nature of the new particle. Heisenberg published three related academic papers in the second half of the year. He welcomed the neutron as a possible missing piece in the puzzle about the nature of the forces that held protons together in nuclei. He saw the neutron as a closely bound state of a proton and an electron in spite of his own quantum theory telling him that an electron confined to a space of nuclear dimensions would have kinetic energy sufficient for it to escape. He was prepared to accept that the law of conservation of energy might break down in such situations or that new physics would emerge to overcome the difficulties.

In accounting for the attraction between the proton and the neutron Heisenberg drew an analogy with the ionized hydrogen molecule  $H_2^+$ . In this molecule, the binding forces are associated with the continuous migration of the single electron from one atom to the other. The behaviour is well accounted for by standard quantum theory. He considered that a similar physical exchange process might take place between charged and uncharged nucleons. If the neutron is viewed as a closely bound state of a proton and an electron then the regular exchange of the electron between two nucleons would simply result in the proton and the neutron continually changing identity whilst both being bound by their common interest in the exchanged particle. Similarly, a pair of neutrons

could be viewed as a two protons bound by a continual exchange of a pair of electrons.

There was no ready analogy, however, to account for attractive forces between pairs of protons. Two protons, being bare positive charges, would have nothing to transfer between them; the positron had not emerged at the time. But this difficulty did not prevent other exchange speculations: physicists looked at various combinations of charge exchange and spin exchange between nucleons with varying degrees of success, but none could produce complete and satisfactory quantitative explanations of observed nuclear phenomena. The way out of the difficulties was provided by Yukawa.

Yukawa started his academic career at the beginning of that revolutionary year; he emerged onto the stage along with the neutron. He took the step of considering that the nuclear force might be a new fundamental one to sit alongside gravity and electromagnetism rather than being a secondary effect explained in terms of established physics. Heisenberg had seen the electron as being the primary carrier of exchanged information in nuclear binding and had sought to derive the forces and potentials arising from familiar electromagnetic and quantum mechanical processes. Yukawa, in contrast, decided to start with the requirements of the forces and potentials and sought to derive the necessary properties of the exchanged entities. His fundamental field equations had a similar structure to those that describe electromagnetic processes and predict that the photon must have zero rest mass. By incorporating new terms in the equations, to ensure that the potential of the new field fell to zero within a range comparable to a nucleon diameter, Yukawa showed that the binding process had to be linked to the exchange of a new particle having a rest mass about 200 to 300 times that of an electron. He provided the mathematical insight that the mass of an exchanged particle was inversely linked to the range of the force. Yukawa's particle was called the 'meson' and the new field was referred to as the meson field. There was no immediate experimental evidence to suggest the material existence of such a particle but Yukawa proposed that the highly energetic processes linked to the newly discovered cosmic ray showers might result in the release of the new nuclear component and provide experimental confirmation.

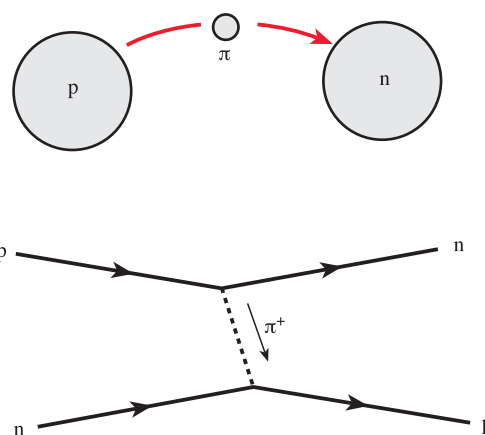
Yukawa's ground-breaking paper was published in November 1934 and sat alongside other speculative approaches to the nuclear force problem for three quiet years. Then, in 1937, Carl Anderson announced the discovery of a new particle observed in cosmic ray showers. The new particle had roughly the correct mass for it to be Yukawa's particle and was quickly presented as a promising candidate. It became known as the mesotron, and the meson exchange approach to nuclear forces took centre ground.

### The discovery of the pion

The suggested identification of a new fundamental force led to a rapid growth in the study of cosmic rays in the late 1930s and the following decade. In spite of the war, sophisticated new experimental techniques continued to be developed and detailed measurements of the properties of the mesotron were carried out. But close investigation showed that it did not interact strongly enough with atomic nuclei for it to be Yukawa's particle. A candidate with the right characteristics was eventually found in the late 1940s. Nuclear emulsion studies of high altitude cosmic radiation produced evidence of a strongly interacting short-lived particle with a rest mass about 300 times that of the electron. It was labelled the 'pion' and confirmed as the likely candidate to be Yukawa's meson. The earlier unpromising cosmic ray particle was relabelled as the muon. Yukawa's meson exchange mechanism for describing the strong nuclear force enjoyed a revival in the form of the pion exchange model.

In order to account for the various modes of interaction that could occur between the nucleons, three types of pion had to exist. One had to be positively charged, one had to be negatively charged and one had to be neutral. Typical textbook diagrams representing the exchange process are shown in figure 1.

During the 1950s, extensive controlled accelerator studies allowed physicists to create pions and study their properties in some detail. Those studies confirmed the properties of the three types of pion but also revealed the existence and properties of a large number of other related subnuclear particles. The discipline of particle physics developed rapidly with much creativity invested in the need to comprehend the growing list of particle types and interactions.



**Figure 1.** Typical textbook representations of pion exchange.

### Quarks and leptons

By the end of the century, physicists had managed to make sense of much that had been revealed by the extensive experimental work. It was recognized that the nucleons and all the newly discovered particles could be understood in terms of more fundamental particles called quarks and leptons. The nucleons were recognized as groupings of three quarks, and particles like the pion were recognized as quark–antiquark pairings. Particles constructed from quarks were called hadrons. The leptons were seen to be a class of particles that can interact with the groupings but do not form groupings or pairings amongst themselves. The electron, the muon and their neutrinos are leptons.

The proton, neutron and the pions could be constructed from two types, or flavours, of quark called 'up' and 'down'. The up-quark carried an electric charge of  $+2e/3$  and the down-quark carried an electric charge of  $-1e/3$ , where  $e$  is the magnitude of the proton charge. The proton consisted of two up-quarks and a down-quark (uud), the neutron consisted of two downs and an up (ddu). The positive pion consisted of an up-quark with an antidown ( $u\bar{d}$ ), the negative pion was a down-quark with an antiup ( $d\bar{u}$ ), and the neutral pion was recognized as a combination of an up–antiup and a down–antidown pairing.

Whilst Yukawa's work had shown that the strong force between nucleons could be linked to the exchange of pions, it eventually became clear that the forces between quarks were more fundamental. The strong force came to be

described in terms of the exchange of particles called gluons between quarks rather than pions between nucleons. The original Yukawa force is often presented as a residual effect of these strong quark–quark forces comparable to the way that the van der Waals force is a residual effect of the electrical forces between the electrons and the nuclear positive charges in the atom. Estimations of the relative contribution of a formal van der Waals type mechanism show, however, that it does not adequately describe the internucleon forces [3]; new mechanisms and new interpretations of pion exchange turn out to be more productive.

### The discovery of colour charge

The quark model was very successful in accounting for all the known hadrons but it did present some early theoretical difficulties. There was no real fundamental reason for the particles to adopt groupings of three quarks or quark–antiquark pairs. In addition, experiment had revealed the existence of short-lived particles that would carry the combinations  $uuu$  and  $ddd$ . These were the  $\Delta^{++}$  and the  $\Delta^{-}$  particles. The combinations appeared to violate the Pauli exclusion principle, a fundamental rule in quantum physics which says that no two identical spin-half particles coexisting in the same system can have the same set of quantum numbers. The quarks are spin-half particles and would have the same set of quantum numbers in the  $uuu$  and  $ddd$  combinations. The way out of the difficulty was presented in 1965 by Moo-Young Han of Duke University, Yoichiro Nambu of the University of Chicago and Oscar Greenberg of the University of Maryland at College Park. Their proposal was to suggest that the quarks each carried an additional different quantum number so that they were no longer identical. The new quantum number would have to have three values and the values would have to combine such that the sum of the numbers would be zero for the quark groupings.

The name ‘colour’ was adopted for the new property. This choice was driven by the fact that three primary optical colours, i.e. red, green and blue, combine to give the neutral white. Each quark type could exist in three colour states, e.g.  $u_r$ ,  $u_g$  and  $u_b$ , so that the  $uuu$ -type combination no longer violated the Pauli principle. A requirement that only colour-neutral objects can exist as free particles explained the occurrence of quark

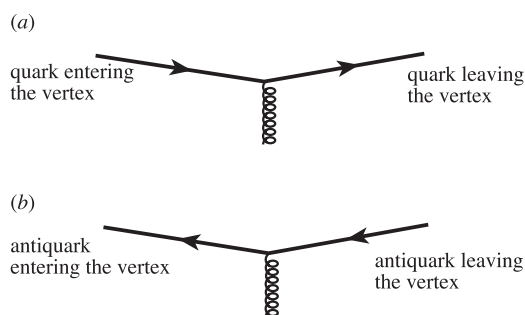
trios and quark–antiquark pairs. Antiparticles would carry anticolour so that the quark–antiquark meson combinations could also be colour-neutral. Antiquark pairs and trio mixtures of quarks and antiquarks and could not produce colour neutrality, hence particles with those combinations would never be seen.

Colour came to be recognized as the fundamental ‘charge’ of the strong interaction between quarks. The gluons were the agents that exchanged colour between quarks and the binding of stable quark groupings involved a continual interchange of colour as gluons passed between them. Heisenberg had originally attempted to explain nucleon binding in terms of the interchange of electric charge; today’s physics looks for an explanation involving the complex interchange of a new type of charge. Just as atomic chemistry is driven by the need for electrical neutrality, particle ‘chemistry’ is driven by the need for chromatic neutrality.

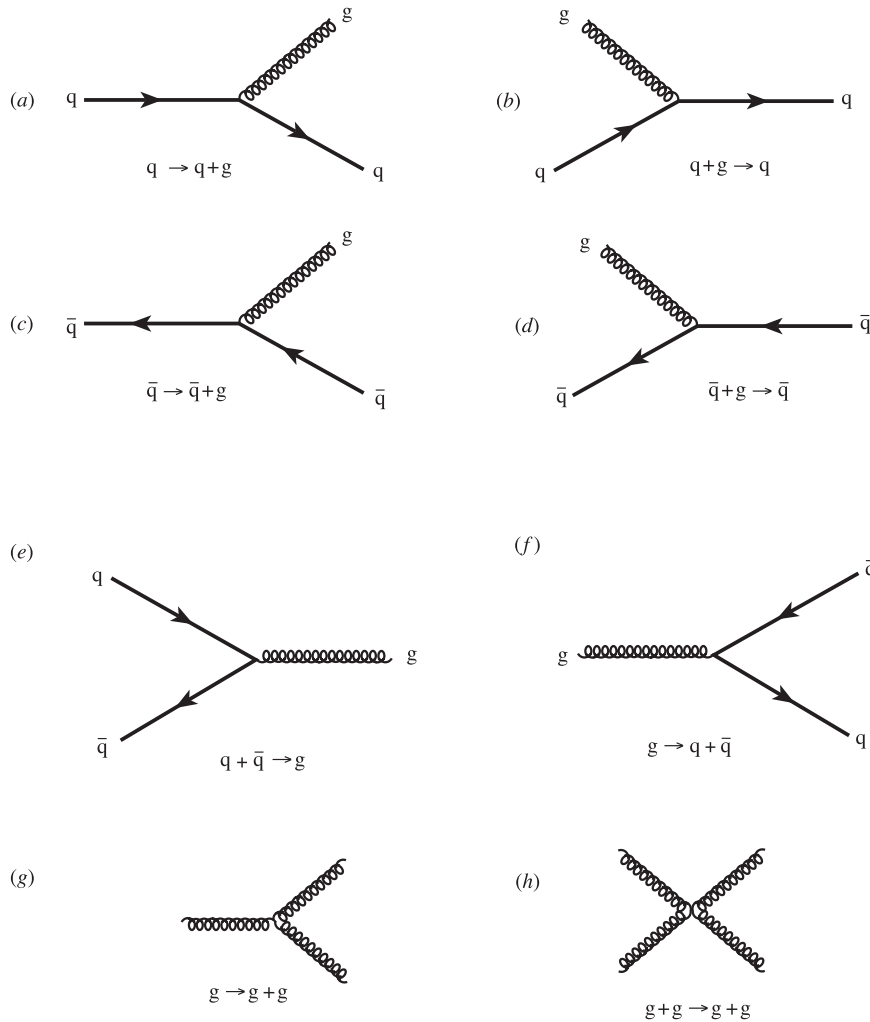
### Feynman quark–gluon vertices and colour flow

The physics of particle interactions is described in terms of sophisticated advanced mathematics. The processes themselves, however, can be described via a pictorial representation of the mathematics called the Feynman diagram. An understanding of the nature of pion exchange can be gained through the use of Feynman diagrams to describe quark interactions and to track the flow of colour.

The diagrams are assembled using elementary building blocks called vertices. A vertex represents the interaction of a particle with a mediator of one of the basic fields. There are fundamental vertices for quark and lepton interactions with electromagnetic photons, vertices for the quark and



**Figure 2.** (a) The basic quark–gluon–quark vertex. (b) The basic antiquark–gluon–antiquark vertex.



**Figure 3.** (a)–(f) The six interactions that can be derived from the two basic quark–gluon–quark vertices. (g), (h) Gluon–gluon interactions allowed by gluon theory.

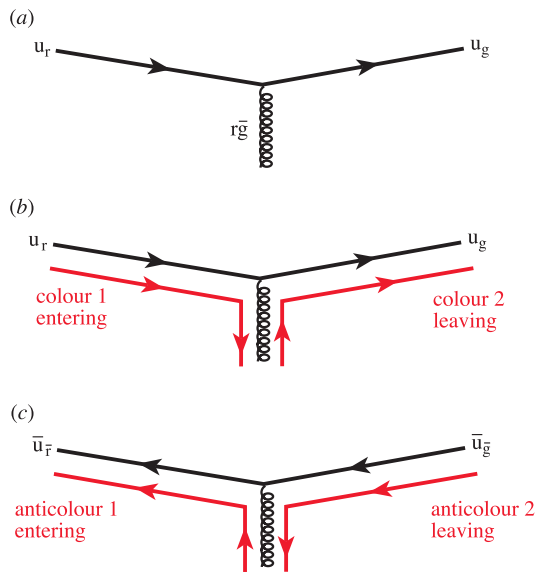
lepton interactions with the W and Z particles and vertices for the interactions between quarks and gluons. Clear descriptions of the different kinds of vertices can be found in the textbooks written by Martin and Shaw [4], Williams [5] and Griffiths [6]. The rules for the construction of Feynman diagrams have been described in an earlier article in *Physics Education* [7] and comprehensive software that allows the user to construct consistent diagrams is available on the Internet [8].

The two basic quark–gluon vertices are shown in figure 2. The diagrams are read from left to right and time is represented as flowing in that direction. Figure 2(a) shows a quark entering a vertex from the left, interacting with a gluon

and then leaving. Forward-facing arrows are used to represent particles and backward-facing arrows are used to represent antiparticles travelling forward in time. Figure 2(b) shows an antiparticle entering a vertex, interacting with a gluon and then leaving. By reorienting the arms of the diagrams a range of quark–gluon interactions can be represented. Figure 3 shows the six processes that can be generated from the basic quark–gluon vertices together with two additional vertices showing gluon–gluon interactions. The additional vertices illustrate that, as well as interacting directly with the quarks, gluons are capable of interacting with each other.

The quark–gluon interaction is an exchange

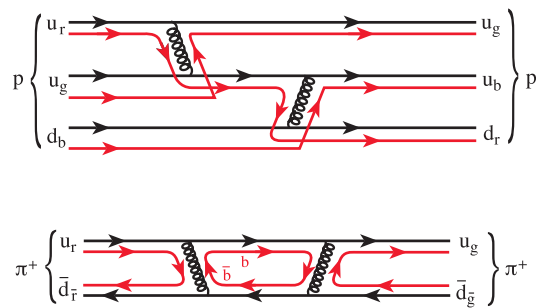




**Figure 4.** (a) Standard representation of a quark–gluon vertex. (b, c) Colour flow at the quark–gluon vertices. Note that the colour has to flow from quark to gluon or from gluon to quark. The colour does not flow directly from quark branch to quark branch. The colour on one side of the vertex is different to the colour on the other side. The vertex has the effect of being a colour-changing point.

of colour between the particles. The traditional representation of the exchange involves placing colour–anticolour notation beside the gluon symbol as shown in figure 4(a). It is suggested that it is easier to track colour exchanges if the ‘flow’ of colour is represented as in figures 4(b) and 4(c). The gluon can be regarded as a channel through which colour flows. The colour flow is from quark to gluon and from gluon to quark at the vertex. The arrow convention for the colour flow is the same as that for the quarks: a forward-facing arrow represents colour travelling forwards in time and a backwards-facing arrow represents an anticolour also travelling forwards in time. The colour arrows follow the quark arrows to ensure that particles are coupled with colour and antiparticles are coupled with anticolour.

Nucleons and pions can be represented as dynamic groupings of colour-exchanging quark–gluon vertices as shown in figure 5. The nucleon consists of three quarks travelling forwards in time. Similarly, the pion is represented by a colour-neutral particle–antiparticle pair travelling forwards in time. Two gluons are shown in the diagrams in each case but it doesn’t matter how



**Figure 5.** The proton and the positive pion shown as a grouping of colour-exchanging quark–gluon vertices. Time flows from left to right across the diagram.

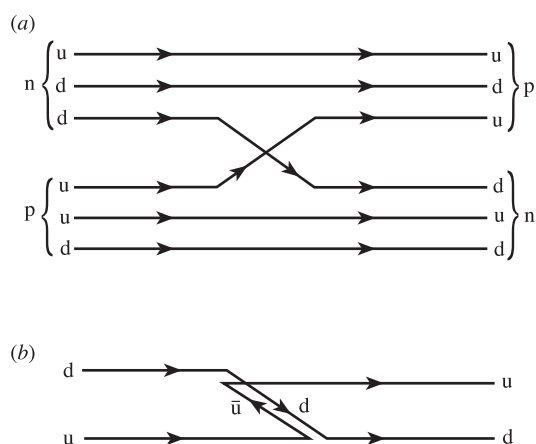
many are inserted: the colour flow and the rules for colour behaviour at the vertices will ensure that the groups of quarks will be colour-neutral at all times.

### Attempts to describe nucleon bonding in terms of quark exchange

Yukawa described his particle exchange process as being like a game of catch as a quantum of energy is transferred from one nucleon to another. As the picture of the nucleon as an assembly of quarks developed, particle physicists looked again to see if they could account for an attractive force by analogy with the familiar and successful atomic bonding processes. A good, short, qualitative discussion of the atomic–nuclear analogies is given in section 16.3 of the text written by Povh *et al* [9].

The atomic ionic bond arises when an electron is lost from one atom and captured by another. The exchange is driven by the fact that the final state of the two atoms has a lower energy than the initial one. The loosely analogous process of quark transfer between nucleons is not favoured since the need for colour neutrality makes the qq + qq configuration a higher energy state than the qq + qq configuration.

The van der Waals bond between molecules arises as charge density fluctuations within neutral atoms produce transient electric dipoles. The electrical attraction between the dipoles provides the intermolecular bonding. It turns out that fluctuations of colour charge within nucleons can produce similar effects but the way the colour forces vary with distance produces effects that are too weak to account for the bonding between nucleons.



**Figure 6.** (a) Simple quark exchange between two nucleons. The gluon exchanges have been omitted to make the diagram clearer. (b) Topological adjustment to the exchange section to show the equivalent  $\pi^-$  ( $\bar{u}d$ ) exchange.

This leaves covalent bonding as a possible analogue. Covalent bonding in atoms is driven by the preference for closed shells of electrons in systems where the two participating atoms have some electron shell deficiency. The dynamic sharing of electrons between atoms results in satisfaction of the closed shell requirement. It turns out that there are quasi-covalent quark transfer mechanisms that can offer a suggestion of internucleon cohesion. The assembly of nucleons in a nucleus can be taken to be a close packed arrangement in which groups of three quarks have a chance to overlap. Whilst colour neutrality encourages groups of three to remain together, there is always the possibility that same colour quarks can be exchanged between nucleons such that they continue to maintain their chromatic neutrality. The process is illustrated, leaving out the representations of gluon exchange for the sake of diagram clarity, in figure 6(a). If the quark colour charges are attractive in nature then this quark exchange mechanism is inherently cohesive.

The plausibility of the mechanism is increased when one looks at the Feynman diagram for the exchange. A simple topological adjustment to the diagram, as shown in figure 6(b), suggests that the process is equivalent to pion exchange, a mechanism that has continued to provide the best quantitative agreement with experiment despite the changes in our view of the nature of nucleons. But the simple quark exchange

mechanism is found to be inadequate in describing the internucleon bond. The strength of the interaction is only about one third of what it should be. This is explained by the fact that, for the exchange to take place, the migrant quark has to exchange with another of the same colour. As the quark has three neighbours to choose from, the probability finding the right quark is 1/3.

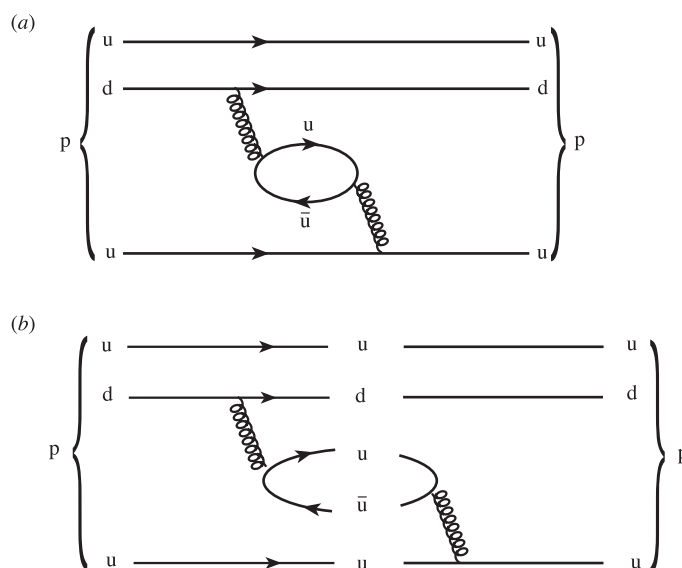
None of the direct atomic analogies turns out, it seems, to offer a fully satisfactory picture of internucleon bonding. One of them appears consistent with pion exchange but does not produce quantitative agreement with experiment. It remains to consider whether the limitations lie in the assumption of a simple three-quark nucleon structure. High energy scattering experiments suggest that the picture might be a little more complex.

### Deep inelastic scattering

Direct evidence for the material existence of quarks comes from the high energy scattering of electrons, muons and neutrinos by nucleons. Whilst elastic scattering of electrons gives information about the size of nucleons, the higher energy inelastic scattering reveals the existence of point-like scattering centres within neutrons and protons.

In electron or muon scattering, the collision processes result in the exchange of a virtual photon between the incoming lepton and one of the constituents of the nucleon. The inelastic nature of the interaction results in the creation of a number of new particles but the focus is not on those newly created entities; the experimenters concentrate on tracking the energies and angular distributions of the recoil electrons in order to determine the properties of the quarks from which they scatter. The analysis is carried out using a frame of reference that based on the 'centre of mass' of the virtual photon and the target nucleon. From this point of view, the nucleon is seen as a group of quarks and gluons with relatively slow internal motions but with the group approaching the photon with considerable momentum.

Inelastic neutrino scattering involves the mediation of a W or a Z particle between the incoming lepton and a quark. As the W or Z particles can also couple to antiquarks, the scattering is capable of revealing the presence of those components. The experimental findings turn



**Figure 7.** (a) A typical textbook representation of a materialization of a sea quark-antiquark pair. (b) The diagram cut in half to emphasize the five-particle intermediate state.

out to suggest the routine existence of antiquarks within nucleons.

Interpretation of the data from the complementary scattering experiments suggests a nucleon structure based upon trios of quarks responsible for the ordinary properties of protons and neutrons but they are accompanied by a dynamic population of transient quark-antiquark pairs. The ordinary trio of quarks responsible for the main properties of the nucleons are called 'valence' quarks whilst those belonging to the transient population are called 'sea' quarks.

In addition to revealing the existence of the sea quarks, the scattering experiments show that only half of the momentum attributable to the nucleon constituents can be accounted for by the valence and the sea quarks. The missing half of the momentum has to be carried by components that interact neither electromagnetically (in electron or muon scattering) nor weakly (in neutrino scattering). They are identified as the gluons.

### A plausible pathway to pion materialization?

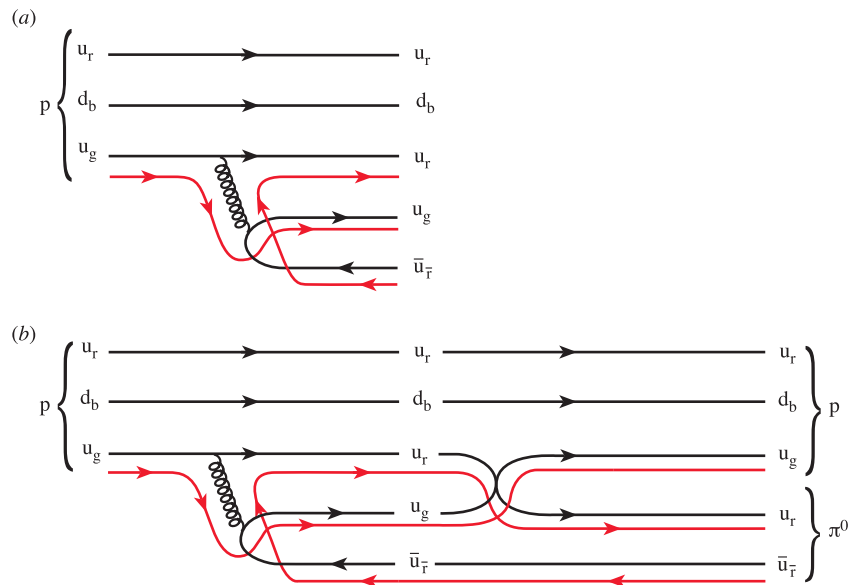
The nucleon is now seen as a group of valence quarks, sea quarks and gluons in a state of dynamic equilibrium. At its simplest level, the standard textbook picture of the materialization of a sea quark pair is represented as in figure 7(a). The

sea quark section of the diagram can be seen as a straightforward combination of Feynman vertices (*f*) and (*e*) from figure 3. Since the traditional basketball picture of pion exchange does not offer a satisfying approach to internucleon attraction it is of interest to see if we can construct a plausible exchange mechanism in terms of Feynman diagram vertices and the behaviour of colour charges.

With the diagram cut in half, as in figure 7(b), the process can be interpreted as a situation in which the three-quark assembly turns into a five-quark one; the five-quark assembly then falls back into a three-quark configuration. If one adds the colour flow to this picture then it becomes apparent that the original three quarks are no longer colour-neutral at the five-particle stage. Figure 8(a) shows colour flow added to a similar sea-quark materialization with the positions of the quarks redrawn to separate out the sea quarks from the originals. It is helpful to recognize that the green colour from the original up-quark must follow the gluon path at the first vertex and then find its way to the up-quark in the sea quark pair. The anticolour that materializes with the sea antiquark is chosen so that the original up-quark experiences a colour change at the gluon vertex.

If we recall that the cohesive agent driving the quarks to settle into trios or quark-antiquark pairs is the requirement of colour neutrality then





**Figure 8.** (a) The first step in the  $\pi^0$  production. In this example the green up-quark changes colour through the emission of a  $g\bar{r}$  gluon. The gluon materializes into a coloured sea quark–antiquark pair. (b) The quarks then reshuffle to get colour neutrality.

we can regard the original three-quark colour-neutral state as a low energy one and the five-quark colour excitation state as a higher energy one. The situation can de-excite back to a three-quark configuration, as in the previous figure 7(b), with the gluon path either returning to the original quark or to one of the other two. But, equally, the original quarks and the sea quarks could reshuffle, as in figure 8(b), driven by the need to find appropriate colour-neutralizing partners. This simple reshuffling produces a pion to accompany the nucleon. The process is

$$p \rightarrow p + \pi^0.$$

Figure 9 shows a similar situation with the materialization of a down–antidown sea quark pair resulting in the process

$$p \rightarrow n + \pi^+.$$

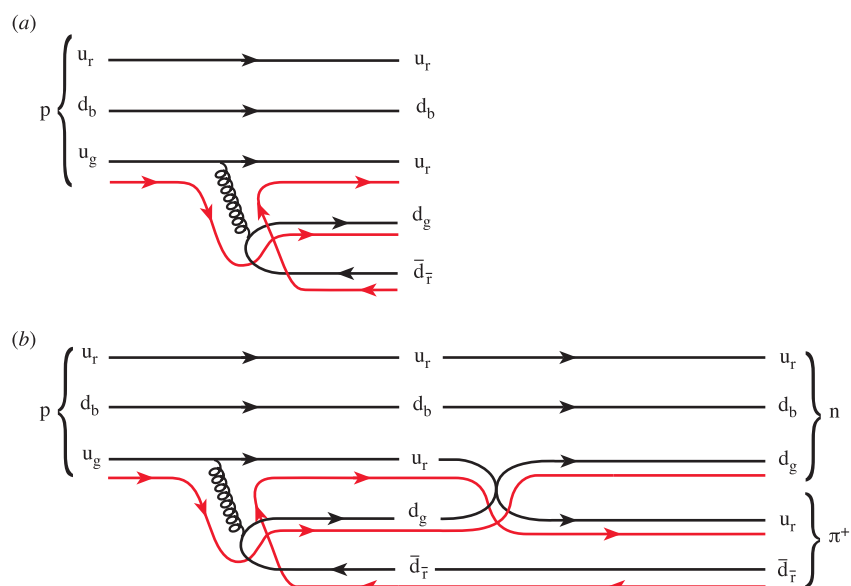
From this perspective, the emergence of pions within nucleons can be seen to be a natural consequence of ordinary energy fluctuations coupled with the requirements of colour neutrality. This suggested picture of processes within the nucleon gives us a plausible mechanism for communication between nucleons through pion exchange.

### Cohesive pion exchange

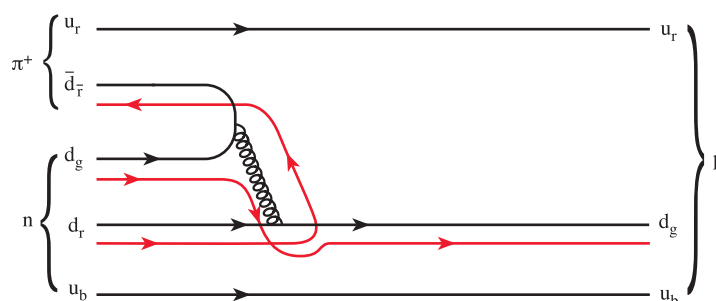
Each of the two processes described above is reversible. The existence of the nucleon plus the sea quark pair is a higher energy state than that of the nucleon alone. The reshuffling of the original quark trio and the sea quarks into a nucleon and a pion would represent some reduction in energy but not sufficient to take the system back to the energy associated with the single original nucleon. In order to get back to the lower energy state the pions would have to be reabsorbed.

The pions could fall back and be reabsorbed by the parent quark trios. This would require the antiquark in the sea quark pair to couple with a same flavour quark in the parent quark trio. The couplings would be represented by vertex (e) in figure 3. In essence, this would be like running figures 8(b) and 9(b) backwards with the additional option that the antiquark in the pion does not need to couple with the original quark that it materialized with.

A nucleus, however, is a close assembly of quark trios and the pions will have an equal chance of interacting with a colour-neutral neighbouring nucleon quark grouping. The antiquark in the pion might annihilate with a quark in the neighbouring nucleon as shown in figure 10. In this example, the anti-red antidown quark combines with the green



**Figure 9.** (a) The first step in the emission of a  $\pi^+$  from a proton. The up-quark emits a  $g\bar{r}$  gluon that materializes into a coloured  $d\bar{d}$  pair. (b) The quarks then reshuffle to regain colour neutrality.



**Figure 10.** The anti-red antidown quark in the pion annihilates with the green down-quark in the neighbouring neutron. The effect is to change the neutron into a proton.

down-quark with the emission of a gluon. This process is, in effect, vertex (e) in figure 3 followed by an example of vertex (b). The annihilation results in the transfer of green colour charge to the down-quark in the nucleon. The remaining up-quark from the pion, carrying its red colour charge, would now be attracted to the remaining blue and green charged quarks to form the proton. It is worth noting that this up-quark has found its way from the original proton to the new one via the pion; the intermediate state is a channel for quark exchange to occur. Figures 9 and 10 are complementary and illustrate proton–neutron coupling via the exchange of a positive pion.

The absorption of the neutral pion by a neighbouring nucleon is similar to the process

shown in figure 10. In this case, the antiup quark in the pion would combine with an up-quark in the nearby nucleon.

Each of the situations described above could be seen in terms of a two-nucleon assembly of six quarks being excited into an eight-particle state followed by a de-excitation back into a six-particle state. The overall particle reshuffling in a system of attractive charges produces a cohesive effect.

### Implications for particle exchange in general

The pion was originally taken to be the ‘carrier’ of the strong force and the model for the basketball exchange analogy. The exchange process might now be viewed as occurring because of the

materialization of sea quarks and the existence of attractive colour charges. In this view, the strong force is seen to be not 'caused' by pion exchange—the exchange itself is caused by the force. This new perspective on pion exchange, and the redundancy of the basketball approach in this context, leads us to question the general role of the exchange particle as presented in the teaching of particle physics at pre-university level.

David Griffiths, in chapter 1 of his *Introduction to Elementary Particles* [6, p 16], points out that when we say a force is mediated by the exchange of particles, we are 'not speaking of a merely kinematical phenomenon'. He suggests that we are simply referring to the fact that some kind of package of information has to be exchanged irrespective of whether the effects are attractive or repulsive. As we can identify distinct fundamental interactions it is reasonable to expect that there must be a characteristic mediation of information for each of them. The mediation must reveal its quantum nature at the scales used for particle processes. This quantum aspect is the mediator and carries the packet of information.

Whilst each interaction has its mediator, the mediators that we describe at the introductory level do not have a consistent role between the different fundamental interactions. We traditionally describe the attractions and repulsions between electrical charges in terms of the exchange of the mediator of the electromagnetic force, the photon. The photon passes between the charges and the exchange somehow causes the attraction or the repulsion. In the case of the weak interactions, where attractions and repulsions are not actually specified, the mediating W and the Z particles are not described as passing between fundamental charges of a weak field: they have the role of changing the nature of the interacting particles, i.e. quarks change their flavour, leptons change between neutrino and charged lepton states, or do not change in the case of the Z exchange. In the popularly presented view of the strong interaction, the gluon is the mediator that passes between quarks and involves attraction only. The emphasis on the colour-exchanging role of the gluon is only slowly finding its way into pre-university and popular texts. The picture presented in this article takes things a little further: it suggests that the colour exchange might have some aspects similar to the electric charge exchange in the hydrogen

molecular ion. The attractive nature of the colour charge, and the fact that the colour charge is carried by quarks, results in the cohesion of the quarks. The gluons do not pass between the charges of the strong interaction in the way that we require the photons of the electromagnetic interaction to pass between the electrical charges; they have a different role: the gluons are either charge changers or charge exchangers.

In each of the cases, the mediators are not communicating kinematical forces between particles in the 'push-pull' sense; they are doing something other than that and the 'something other' is different in each case. So it might not be appropriate to apply a single basketball exchange picture to illustrate the exchange processes. It is true that exchange processes are occurring, that the 'particle-like' mediators are fundamental to the mathematics of the interactions and the mathematics is highly successful; but it might be more appropriate, when we are teaching at the introductory level, to simply present the mediators as the theoretical devices that we use to describe the different quantized effects of the different fundamental interactions. It might also be more appropriate to play down the popular basketball exchange picture, emphasize that we are not dealing with 'throw and catch' type situations, and that 'throw and catch' is not the mechanism through which fundamental forces arise. In the example of the original massive particle exchange process, the pion interaction between nucleons, it has been shown that if Feynman diagrams are dealt with correctly at the introductory level then it might be possible to present a consistent and alternative picture based upon current established principles, findings and techniques.

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### Further reading

The historical aspects of the development of the pion and quark views are dealt with in detail in the following texts:



**Peter Dunne** graduated from the University of Durham in 1976 and gained an MSc from the University of York in 1989. He is a lecturer in physics at Preston College and his main interests are particle physics, electronics and computing. He runs extracurricular projects involving cosmic ray measurements.