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Structure of the Proton

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Protons are not fundamental particles but seem to be made of simpler elements called quarks. The evidence for this is given. But separated quarks have never been seen. A struggle to explain this seeming paradox may be leading us to a clearer view of the precise laws of the proton's structure and other phenomena of high energy physics.

Introduction to the Hadrons

We have often made great advances in physics by recognizing that the complexity of things at one level is the result of the fact that these things are composed of simpler elements at another level. For example, the enormous variety of behavior and character of matter could be understood by supposing it made of simpler elements, atoms. Deeper study of the atoms showed that they came in a hundred varieties and themselves had complex properties (like their spectra, for example). Atoms were then in turn understood as made of two elements, electrons and nuclei (held together by a third, the electromagnetic interaction, represented today as an exchange of photons). Further study suggested that nuclei were themselves complicated but their complexity can be better comprehended if they are imagined to be made of two elements—protons and neutrons. What held them together remained a question, hinting, as Yukawa pointed out, at the existence of still more particles. During the last quarter-century experiments have been performed to study the question of the structure of these particles. These experiments consisted in large part of hitting protons and nuclei together at high energy to see what came out. And what came out was an enormous variety of new particles—pi mesons (pions) whose mass was equivalent to an electron accelerated to 140 million electron volts (140 Mev). They come in three varieties: one electrically charged plus, one minus, and one neutral. Then there are K mesons (kaons) at 494 Mev in four varieties, sigmas at 1190 Mev (three varieties), lambdas, chis, deltas, rhos, omegas, etas—and soon we run out of names so we say another group of sigmas at 1386 Mev, other nucleons (like the proton and neutron whose mass is 938 Mev, but of higher mass), and so on, until today we have cataloged over 300 species of ever-increasing masses and expect the true number is unlimited. These particles (other than the proton) are all unstable and disintegrate, some exceedingly rapidly—most so rapidly, in fact, that they do not last for a long enough time that their energy (or mass) can be very well defined because of the quantum mechanical uncertainty principle. Such appear so transiently in reactions that they appear as bumps or "resonances" in the graph of a collision cross section as a function of energy of the bombarding particle. The proton, then, no longer appears particularly fundamental, but is just one particle of a vast number, the one that happens to be most stable. To understand it is, without doubt, to understand the entire array of what we call "the strongly interacting particles," or "hadrons."

What I intend to do here is describe our progress in understanding this array of strongly interacting particles, these hadrons. In particular I will describe one theory which seems to me the most promising—the theory that the strongly interacting particles can be thought of as made of other particles called quarks. I will show you the evidence that we have. Our understanding is still only rough and qualitative. I shall at the end explain some of the problems in finding the precise mathematical theory that would permit qauntitative calculation and prediction of the properties of protons, neutrons, and the other hadrons.

Kinds of Interactions in Physics Today

To discuss this I must review our picture of physical laws today. At present we divide all "forces" or interactions into four kinds. First there is gravitational interaction, but that is far too weak at an atomic level to concern us here.

The second interaction is the electromagnetic interaction, which is the force that principally governs the motion of atoms and matter outside the nucleus of atoms. It is described as mediated by photons and is responsible for all ordinary phenomena with the exception of gravitation, radioactivity, and nuclear forces. The laws this electromagnetic interaction obeys are very well understood by us; we have as yet found no discrepancy with experiment here. We deal with the electron as a structureless point. For example, if a hydrogen atom were magnified to 200 meters in diameter, the proton would be about ½ centimeter across, but the electron would look like a point as nearly as you could see. And your limit of visual acuity in this model would correspond to the present limits of the acuity of our instruments. We understand what is going on in the entire volume of this 200-m sphere, with the exception of the inside of that ½-cm proton. That we will talk about next.

The third kind of force is the strong

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interaction, about which very little is known. It is responsible for the forces operating in collisions between protons, and the other vast array of particles, hadrons, that I mentioned earlier. Of course, between two protons there is also an electrical force, but at the short distances (½ cm in our model or 10^{-13} cm in reality) at which strong interactions operate, they only amount to a few percent. Furthermore, this few percent can in some cases be estimated and allowed for, so the character of the "purely strong force" is easily extracted from experiment. When that is done, by the way, it is found that proton and neutron are true sisters—the forces between a proton and a proton and between a proton and a neutron are exactly equal. In like manner the three pions—plus, minus, and neutral—have exactly equal mass and are dealt with equally by the strong interactions. (In fact, they don't have equal masses; a charged pion is 3.4 percent heavier than a neutral one, an effect which, however, is accounted for by the extra energy in its electric field.) The strong forces have no direct effect on electrons. Thus electrons are not hadrons (we call them leptons).

The fourth kind of interaction we need to understand nature is called the weak interaction. It is, for example, responsible for nuclear beta-decay, in which nuclei emit electrons and neutrinos. Neutrinos interact only through weak interactions. They are not hadrons. The effects of the weak interactions are very small and, although only partially understood, are understood well enough to be separated from strong interaction effects in our experiments. We shall not discuss them further, except we cannot refrain from mentioning the curious fact that there are two other leptons, a kind of heavy electron called muon and a neutrino which goes with it. They are not involved in strong interactions but, as we shall see, can serve as tools to study hadrons.

There are a few very delicate experiments that show that nature does not quite fit into the above classification. Possibly a fifth interaction is required—the superweak interaction—or perhaps it is an unanticipated effect of our still only partially understood weak interaction.

With this knowledge we can carefully isolate in our experiments the effects of the strong interactions alone. What framework have we found adequate to describe them?

Principles Guiding the Analysis of Experiments

First, all the principles of the theory of relativity work exactly. For example, the energy E of a particle of rest mass m moving with momentum p is $E=(p^2+M^2)^{1/2}$ in units in which the speed of light is one unit. With this formula the laws of conservation of energy and of momentum hold. The total energy of the particles entering a reaction always accounts for the total energy of the particles leaving the reaction.

The general principles and descriptive concepts of quantum mechanics also work exactly. They go under the name of the principles of superposition of probability amplitudes. Anything that can be deduced from these principles alone always works perfectly in all our experiments. For example, it is a consequence of these principles that an isolated object, such as an atom or a new particle, can be characterized by a number called its spin, j. This j is an integer or half an integer. Thus, for a proton or neutron $j=1/2$, for a pion $j=0$, for a delta $j=3/2$. For such a particle of spin j its angular momentum around some axis is restricted to be one of the set of integrally separated numbers from $-j$ to $+j$ (the unit is Planck's constant divided by 2π). For example, a delta particle with $j=3/2$ might be found with its angular momentum about the vertical axis equal to $+3/2$, or possibly $+1/2$, or $-1/2$, or $-3/2$, but with no other value. We can use this spin number j to help classify states. We may mention also that the states can be classified in a bit more detail by another quantity, parity, which is either plus or minus, which we will not explain further here (it tells whether the wave function is even or odd upon reflection).

The combination of relativity and quantum mechanics also implies other things. For example, for every kind of particle that exists, one should find another kind of the same mass called the antiparticle. It must have the same spin, but opposite electric charge. The antiparticle to the electron of negative charge is the positron, of positive charge but of the same mass. With protons go antiprotons; with neutrons, antineutrons; and so forth. The spinning neutron acts as a small magnet; the antineutron has the same magnetic strength as the neutron but the poles are reversed. For some sufficiently neutral objects, such as the photon, the antiparticle is not distinguished from the particle—they are the same thing. The positive and negative pion are antiparticles of each other, but the neutral pion is its own antiparticle.

Particles and antiparticles can annihilate each other in pairs, and interactions can produce new pairs of particles and antiparticles.

All these things, and many more, which are deducible from the principles of relativity and quantum mechanics, seem to work in complete detail in all our experiments. When these new ideas of relativity and quantum physics were developed early in this century they appeared so strange that many conservative people hoped they would ultimately be proved wrong, but the last half-century of experiment of ever greater energy, scope, and accuracy have only continued to confirm them.

Classification of Hadron Characteristics

The strongly interacting particles can also be classified in accordance with certain numbers—just integers that each may be said to have—so that in a reaction the total of these integers entering is the same as the total leaving. The idea is simple—the particle carries "something" and the total "something" is never lost or gained. It is merely a matter of elementary counting. One of these numbers is the electric charge. Each particle carries a charge which comes in some unit, and the total charge of the reactants equals that of the products. Thus the positive pion, π^+, and proton, p, have charge $+1$; the neutral pion, π^0, charge O; the "delta double plus," Δ^{++}, charge $+2$, and so on. Then a reaction such as a plus pion hitting a proton and making a delta double plus and a neutral pion ($\pi^+ + \text{p} \rightarrow \Delta^{++} + \pi^0$) is possible because the total charge entering $(+1+1)$ and leaving $(+2+0)$ is the same.

Now the electric charge is physical, we can measure it directly. But even if we could not, we might, by noticing which reactions can occur and which cannot, have discovered this rule. In exactly this way we have discovered another number, the "strangeness," which, in the strong interactions at least, never changes. We can assign to each hadron a number S—for example, $S=0$ for protons, neutrons, and pions; $S=-1$ for sigmas; $S=+1$ for positive kaons, and so on—so that the total strangeness does not change in a strong interaction. For example, $\pi^+ + p \rightarrow \Sigma^+ + K^+$ is possible, but the decay $\Sigma^+ \rightarrow p + \pi^0$ is impossible via strong interactions. Actually the latter does occur slowly, but it is through the weak interactions. We cannot measure, or "see," the strangeness directly.

A third number of this kind has been found, the so-called baryon number. It is $+1$ for protons and neutrons, 0 for mesons, -1 for antiprotons. All our hadrons are of one of two classes; either they are mesons (which is the name given to those of baryon number 0) or else they are baryons (baryon number $+1$) or their antiparticles (of baryon number -1). (Particles of larger baryon number exist, but they are just nuclei, or related objects most easily understood as loose groupings of the more fundamental baryons. Thus, the lowest state of baryon number $+4$ is the helium nucleus, consisting of two protons and two neutrons.)

Now we can use these numbers—spin (and, if you wish, parity), charge, strangeness, and baryon number—to separate and characterize our hadrons to some extent, and to look for regularities. Extensive regularities have been found. It is in the attempt to explain these regularities that the model of a proton made of quark constituents was evolved.

Regularities Observed in Hadron Characteristics: A Decimet

By some examples, we shall discuss these regularities and how they are explained by the model. It is very successful qualitatively—what at first appear as several hundred particles fall nicely into place in a pattern. It is not so successful quantitatively—attempts to calculate the exact numerical values for, say, magnetic moments or decay rates only show that we are on the right track but lack a completely precise dynamic theory.

Let us start then with a certain selection from the hadrons. Choose first baryons (baryon number $+1$) of spin $j = 3/2$, and lay out the particles of various charges and strangeness in a chart. There are many such particles, but we just choose those which are lowest in mass in each case. (This is about one-third of the known ones of $j = 3/2$. If we use parity to help us in further selection, choosing just parity plus, the mass separation to the next higher one is much clearer so that there can be no ambiguity.) We then obtain the chart of Fig. 1. We give the charge horizontally, so particles in the same column have the same charge. Where we have found a particle we write in the letter we have given it as its name. We separate them vertically by strangeness number—or, if you wish, by mass. For we already notice a regularity: those with more (negative) strangeness are heavier. The masses of the particles are given far on the left. For a particular strangeness, charge does not affect the mass—all the four deltas are within a few percent of the same mass, and that few percent is presumably due to electromagnetic energy we are abstracting away.

Mass	Strangeness number				Decimet (10)
1696	-3	Ω^-			
1535	-2	Ξ^-	Ξ^0		
1386	-1	Σ^-	Σ^0	Σ^+	
1236	0	Δ^-	Δ^0	Δ^+	Δ^{++}
	Charge →	-1	0	$+1$	$+2$

Fig. 1. Selecting baryon states of spin $j = 3/2$. (We choose the lowest mass of each strangeness category. They have parity +.)

For example, at strangeness -1 we find a family of three, one plus, one minus, and one zero, all at the same mass, 1386 Mev. A member of a family of three with these charges and strangeness we call a sigma, and since there are many such families at different masses, and not many letters, we append the mass in million electron volts. Thus, we show here the particles named $\Sigma(1386)$.

One cannot help seeing the pretty triangular pattern—in fact the $\Omega^-(1696)$ was predicted before it was found experimentally. A set of states obviously related to one another is called a multiplet and this group of ten a decimet or (10).

Strangeness			
-1	s		← Contributes extra mass
0	d	u	← Equal "mass"
Charge →	$-1/3$	$+2/3$	

Fig. 2. Properties of quarks. There are three kinds, u, d, and s; they have spin $j = 1/2$ and baryon number $1/3$. Baryons consist of three quarks, $q\bar{q}q$, and mesons consist of one quark and one antiquark, $q\bar{q}$.

The Quark Model

Now we shall describe the model, invented independently by George Zweig and by Murray Gell-Mann, that we use to understand the patterns. We suppose hadrons are made of a number of smaller elements called quarks. A quark can come in one of three varieties called u, d, and s. Their properties are given in Fig. 2. The spin of a quark is $1/2$ so its vertical component of angular momentum can be only $+1/2$ or $-1/2$. They have baryon number $1/3$, and all baryons consist simply of three quarks. The mesons, of baryon number 0, consist of one quark and one antiquark. We discuss them later.

The charge of the u quark is $+2/3$ and the d and s carry charge $-1/3$. Only the s carries strangeness, -1; and u and d have zero strangeness. The u and d are equivalent in affecting the mass: replacing a u quark by a d quark or vice versa does not affect the mass of a state, but replacing either by an s quark increases the mass.

We first consider the three quarks of a baryon bound together and in the lowest state of relative motion. Then all the angular momentum that the baryon has is due to the spin of the quarks on their axes. In general, there could be an additional angular momentum because they also revolve about each other, but in their lowest state we expect that this "orbital angular momentum" averages to zero.

Suppose the quarks are spinning with $+1/2$ about the vertical axis, so the total angular momentum about this axis (which simply adds) is $+3/2$, and can be no higher. Thus we are talking about a baryon of spin $j = 3/2$ and, in fact, how it looks when its vertical angular momentum is $+3/2$.

The various baryons have different kinds of quarks inside. For example, all three quarks could be of type u, each contributing charge $+2/3$ and no strangeness; and so we understand the Δ^{++} (1236), a baryon of charge $+2$, strangeness 0, spin $3/2$ (see Fig. 3). Or one quark might be of type d, and the other two of type u—indicated as duu in Fig. 3. We shall suppose all quarks identical, and since they are moving the same way and spinning the same way we have just one state here, uud is not distinct. The strangeness is unchanged, as well as the mass, but the charge is one less, $\Delta^+(1236)$. The rest of the pattern is obvious: changing this d now for s to form suu does not change the charge, but the strangeness is now -1

Strangeness				
−3	sss			
−2	ssd	ssu		
−1	sdd	sdu	suu	
0	ddd	ddu	duu	uuu
Charge →	−1	0	+1	+2

Fig. 3. Possible states of three quarks, qqq.

and we have the $\Sigma^+(1386)$ of somewhat higher mass. Strangeness is simply the number of s quarks in a baryon (with sign reversed), so the greatest (negative) strangeness is -3 when all three of the quarks are s quarks, $\Omega^-(1696)$. A complete success in understanding the decimet.

The Octet

Now, however, suppose one of the three quarks is spinning with vertical component $-\frac{1}{2}$ while the other two have $+\frac{1}{2}$, a total of $+\frac{1}{2}$ about the vertical axis. Suppose first the three quarks are the same, say u. Then this can be done in only one way, and we have a Δ^{++} but with vertical angular momentum $+\frac{1}{2}$. But this is not unexpected; we know any object of total spin $j = \frac{3}{2}$ can be found with vertical spin $+\frac{3}{2}$, $+\frac{1}{2}$, $-\frac{1}{2}$, or $-\frac{3}{2}$, and we now have $+\frac{1}{2}$, so nothing new is found. However, if one of the quarks is a d quark and two are u, there are *two* states possible, for the quark spinning $-\frac{1}{2}$ may either be a d or a u. One of these states we expect, the Δ^+ with vertical angular momentum $+\frac{1}{2}$. The other is new. Where do we expect new states? None at the extreme corners of the triangle of Fig. 3; one at every other place, except that at the center—sdu, with charge 0 and strangeness -1—we expect *two* extra [a total of three because the $-\frac{1}{2}$ quark can be either s, d, or u, but one is just our old $\Sigma^0(1386)$ with vertical angular momentum $+\frac{1}{2}$]. This makes eight new states. These new states have vertical spin $+\frac{1}{2}$ but not higher (all the $+\frac{3}{2}$ have been accounted for in the decimet) so they belong to a multiplet of total $j = \frac{1}{2}$. If we look at the lowest states of hadrons for $j = \frac{1}{2}$ (they also have parity plus) we find the states of Fig. 4: exactly eight with the charges and strangeness expected. This pattern we call an octet (8). It is here that we find our familiar proton (duu) and neutron (ddu) of strangeness 0; such a family of two is called a nucleon, here N(938). Here we also find for $S = -1$, in addition to the family of three $\Sigma(1190)$, an extra state of charge 0, a family of one, the $\Lambda(1115)$. According to our little model we could expect Λ and Σ to have the same mass. They do not, but they are close. Some interaction among quarks could account for that, but exactly how is a job for our future dynamic theory.

We do not get anything new by supposing two quarks or three have angular momentum component $-\frac{1}{2}$. We just get the foregoing states again but with their total angular momentum negative.

Relativistic quantum mechanics requires that there be antiquarks coming in three varieties with all their quantum numbers reversed, thus the $\bar{s}$, the antiquark to the s, has strangeness $+1$ and charge $+\frac{1}{3}$. The $\bar{u}$ and $\bar{d}$ have zero strangeness and charges $-\frac{2}{3}$ and $+\frac{1}{3}$, respectively. They all have baryon number $-\frac{1}{3}$, so each antibaryon is made of three of them in the same way as the corresponding baryon is made of quarks. This is such a perfectly symmetrical relation that nothing new is learned, of course.

Mesons

But we are going to try to understand the mesons, the hadrons of baryon number 0, as being made up of one quark and one antiquark. The principles are the same so I will be brief. For the lowest states, those of zero orbital motion, the vertical angular momentum will be $+1$ when both quark and antiquark are $+\frac{1}{2}$—so we expect at least a multiplet of mesons of total $j = 1$. But when one is $+\frac{1}{2}$ and the other $-\frac{1}{2}$ there are two states, depending on whether the $-\frac{1}{2}$ is on the quark or the antiquark; one is expected, but the other means we also expect a multiplet of mesons of $j = 0$ (and the parity is negative for an antiparticle of spin $\frac{1}{2}$ has opposite parity to a particle).

We make up each multiplet by making three different choices among u, d, and s for the quark and three among $\bar{u}$, $\bar{d}$, and $\bar{s}$ for the antiquark—nine possibilities in all, a nonet. You can work out the charge and strangeness values expected and you will find exactly those of the two lowest mass meson multiplets found in nature—a nonet of spin $j = 0$ and one of spin 1, shown in Fig. 5. (In these charts the

Mass	Strangeness			Octet (8)
1320	−2	Ξ^-	Ξ^0	
1190	−1	Σ^-	Σ^0	Σ^+
1115	−1		Λ	
938	0		N	P
	Charge →	−1	0	+1

Fig. 4. Baryon states of spin ½, parity +.

K^+ and K^0 have the same mass as $\bar{K}^0$ and K^- for they are antiparticles of each other, although I have had to draw them separately for clarity. K^0 of strangeness $+1$ is $\bar{s}d$ and its antiparticle $\bar{K}^0$ is $\bar{d}s$ of opposite strangeness. But the three other neutrals of zero strangeness made up of various combinations of $\bar{u}u$, $\bar{d}d$, and $\bar{s}s$ obviously do not have distinct antiparticles.

Hadrons of Higher Energy

We have explained many hadrons, 18 baryons, 18 antibaryons, and 18 mesons. But we have discovered many more hadrons than that: among others, for example, baryons of higher spins like $j = 5/2$ (even some up to $j = 11/2$). Will we represent that as four quarks and an antiquark all spinning $+\frac{1}{2}$? No, that does not work at all; it gives incorrect patterns and many combinations of charge and strangeness which do not appear at all. Instead we simply suppose that the baryon is just three quarks but that these quarks can move about each other in various orbits (analogous to planetary revolution), and it is the angular momentum of such revolution together with the proper spin ½ of each quark (analogous to planetary rotation) which gives these new possibilities the total spin j of the entire state.

For example, the new baryon states next higher in mass should have one unit of orbital angular momentum (and hence negative parity). This combines with the spin in various ways that are easy to analyze by the most elementary quantum mechanics. We get the old decimets (10) and octets (8) of various angular momentum, as well as one new kind of multiplet consisting of just one particle (a Λ type), a singlet (1). If we add further units of excitation of internal motion we get very many new possibilities of spin and parity but no new kinds of multiplets. All baryons should be found in decimets, octets, or singlets. I show the states expected in Fig. 6 for the lower excitations. The states that we find experimentally can be neatly fitted into this scheme. Where we have found one I put a number equal to the mass of the lowest state of that multiplet. You see, at the top, the octet containing the proton $N(938)$, and the decimet with its $\triangle(1236)$. Then all the lowest negative parity states that are expected are found. The little question mark on one state is because this still lacks the complete confirmation by all workers that the others have. When we get to higher states there are few known and many possible pigeonholes, so not much is proved, although things can be fitted very nicely. (For example, the highest state whose spin we know has $j = 11/2$. It is a Δ and probably corresponds to $N = 4$ with four units of orbital angular momentum and the three ½ quark spins all spinning the same way to make 11/2.)

For the higher mesons we imagine the quark and antiquark to revolve about each other, and things can be fitted well although the experimental situation is more confused there. I need not go into detail. The point is made that this quark model with internal motion adequately describes the patterns of the hadrons that we know.

Furthermore, you see immediately that there are many combinations of quantum numbers which would be impossible for hadrons if this model is correct. For example, we could not expect a meson of strangeness −2, or again a baryon of strangeness + 1. Of the hundreds of hadrons there is not one sure exception to these rules. (There is a possible exception of one strangeness +1 baryon resonance. There is an unusually rapid variation of cross section with energy of $K^+ + p$ scattering, but whether this is a true resonance or has some other cause has still not been determined.)

Attempts to Calculate Hadron Properties

All this cannot be a coincidence, yet one of the most obvious expectations is that these quarks should come apart in hard collisions between protons. Where are they? They have not been seen. They should be easy to see, carrying unusual charges like ⅔ or ⅓ as they do, for all our instruments for detecting particles are sensitive to the charge these particles carry, and non integrally charged particles have not been seen. We shall have to discuss this paradox again, but first we shall have to discuss some evidence that all this is not the result of some accident of rules of counting. In these states are there really particles going around each other, or is it all the result of some mathematical or group theoretical simplicity without the dynamic underpinning we have supposed?

The first attempts to find out consisted of making some naively simple model of these motions—in fact, that they were not of relativistic velocities—to see whether some understanding of the quantitative properties of these states could be obtained. The results were rough, but surprisingly good, and the consensus was that even the dynamic properties indicated the model was on the right track.

I should like to give you some idea of the nature of these calculations by going into one in a little detail. It is not my purpose to teach you how to do them yourselves. I shall borrow many simple results from quantum mechanics without explanation. The point is to emphasize that they are of the most simple nature and do not involve elaborate theory.

These hadron particles have not only spin about their axes, they act as little magnets. It is the strength of these magnets—technically their magnetic dipole moment—that we shall calculate. In the lowest decimet and octet there is no contribution from motion of the quarks, the magnetism is simply due to the fact that the quarks themselves are magnets. It is expected by relativistic quantum mechanics that a u quark with spin +½ about an axis is a magnet of strength +2 units, whereas the d quark contributes −1. The magnetism is proportional to the charge +⅔ and −⅓, respectively, and the unit is called the magneton for the final state, but we will not go further into this. Turning the u quark over, so its vertical spin component is −½, turns the magnet around and it contributes −2; the d quark in the same condition contributes +1.

Now, for example, what would the magnetism be for a Δ^{++} with angular momentum component + 3⁄2? It is three u quarks, each with angular momentum +½, each therefore contributing +2, making a total of +6. Unfortunately we have not measured this quantity, for the Δ^{++} lasts too short a time for its magnetism to be measured. But the proton does last, and its magnetism is measured very well. The calculation for the proton is out-

S	$j = 0^-$				$j = 1^-$			
0	960		η'		1020		ϕ	
0	526		η		785		ω	
−1	494	K^-	$\bar{K}^0$		890	K^{*-}	$\bar{K}^{*0}$	
+1			K^0	$K^+(u\bar{s})$			K^{*0}	$K^{*+}(u\bar{s})$
0	140	π^-	π^0	$\pi^+(u\bar{d})$	765	ρ^-	ρ^0	$\rho^+(u\bar{d})$

Fig. 5. Mesons, $q\bar{q}$; $j = 1$ or 0; parity −. There are nine kinds of each.

	$j \rightarrow 1/2$	3/2	5/2	7/2
$N = 0$	(8) 938			
Even parity		(10) 1236		
	(1) 1405	(1) 1520		
$N = 1$	(8) 1535	(1) 1520		
Odd parity	(8) 1700	(8) 1700?	(8) 1670	
	(10) 1650	(10) 1670		
	(8) 1470			
$N = 2$		(10)		
Even parity		(8)	(8) 1688	
etc.	(10) 1910	(10)	(10) 1890	(10) 1950
		(1)	(1)	
		etc.		

Fig. 6. Baryons, qqq: exciting internal motion to N steps.

		Δ^+	p	Magnetic moment
Probability of state	$\overset{+\,+\,-}{u\;u\;d}$:	1/3	2/3	$+2+2-(-1)=+5$
Probability of state	$\overset{+\,+\,-}{u\;d\;u}$:	2/3	1/3	$+2-1-(+2)=-1$
			From quantum mechanical counting	u: $+2$; d: -1

		Experiment
∴ Magnetic moment of Δ^+	$= 1/3\,(+5) + 2/3\,(-1) = +1$	
Magnetic moment of p	$= 2/3\,(+5) + 1/3\,(-1) = +3$	$+2.79$
Similarly, magnetic moment of n	$= 2/3\,(-4) + 1/3\,(+2) = -2$	-1.91

Some results:

		Theory	Experiment
Magnetic moment	p	$+3$	$+2.79$
	n	-2	-1.93
	Λ	-1	-0.80 ± 0.08
	Σ^+	$+3$	$+3.28 \pm 0.58$
	Ξ^-	-1	-2.7 ± 1.1
β-decay coupling constant	G_A	$5/3 = 1.67$	1.26

Fig. 7. Calculation of the magnetic moment for the proton and the Δ^+, made up of quarks uud; the vertical angular momentum is $+\frac{1}{2}$.

lined in Fig. 7. When the proton has vertical angular momentum $+\frac{1}{2}$, it (and the Δ^+ in the same condition) is made up of quarks uud, with one spinning with component $-\frac{1}{2}$ and the other two with $+\frac{1}{2}$. There are two cases. (a) The $-\frac{1}{2}$ may be on the d, in which case the moment is $+2+(+2)$ from the u quarks and $+1$ from the d (for it is upside down), or $+5$. Or (b) the $-\frac{1}{2}$ may be on one of the u quarks, so their effect cancels and only the $+\frac{1}{2}$ d, giving -1, remains. But which is the proton, (a) or (b)? It is characteristic of quantum mechanics that it is neither one nor the other, but a superposition with a certain probability of finding case (a) and another of finding case (b). In the case of the Δ^+ the $-\frac{1}{2}$ spin is found with equal likelihood on each quark, so it is on a u quark [case (b)] two-thirds of the time, and on a d quark [case (a)] one-third of the time. The simplest kind of quantum mechanical counting is involved in showing that for the proton state it must be just the other way around, two-third chance for case (a) and one-third for case (b). Thus the magnetic moment ought to be the average $\frac{2}{3}(+5) + \frac{1}{3}(-1) = +3$. Actually it is $+2.79$. For the neutron the same calculation gives -2 to compare to experiment's -1.93. The same calculations for Λ and Σ^+ give -1 and $+3$, respectively, while measurements give -0.80 ± 0.07 and $+3.28 \pm 0.58$ for these numbers. (For the Ξ^- we get -1, whereas experiment gives -2.7 ± 1.1, but it is not measured very accurately.)

These results are a little closer than are typical. A better example is the constant (called G_A) whose square determines the rate of disintegration of the neutron into proton, electron, and neutrino. [Its calculation is the same as the above except the u quark contributes $+1$ (instead of $+2$) and the d quark -1]. The theory gives $5/3 = 1.67$ while experiment gives 1.26.

Continuing with such ideas and extending them to cases where orbital motion is involved permit us to calculate many amplitudes (whose squares give probabilities such as various decay rates). Experimental results are available to check some 80 amplitudes; when they are compared in this way 75 percent of them agree within 40 percent. There are a few (three) which are off by more than a factor of 4. In these cases, however, the calculation is delicate in that the difference between two large contributions which nearly cancel is involved. A small misestimate of one contribution would account for the large deviation of the result.

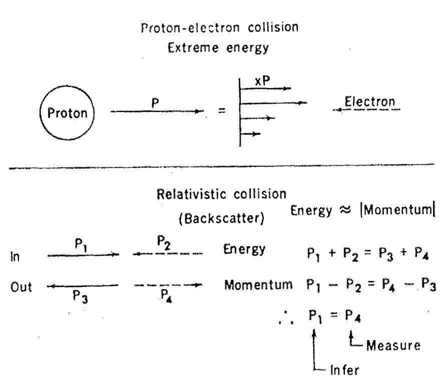


Fig. 8. Proton-electron collision with extreme energy.

All this is evidence that the quarks are really moving about inside hadrons. The fact that these quarks don't come apart must require some new and special explanation.

Quark Pair Production

Our theory is not quantitatively exact, of course, and, as we shall see, we could not expect it to be.

How do we understand collisions and strong interactions—for example, the rapid decay of the Δ^{++} to proton and positive pion ($\Delta^{++} \rightarrow p + \pi^+$)? According to relativistic quantum mechanics, whenever there are interactions between quarks new quark-antiquark pairs can be produced. These are made in matching pairs such as s and $\bar{s}$ or u and $\bar{u}$ or d and $\bar{d}$. In this way we are to understand hadron reactions. For example the Δ^{++} (made of three u quarks, uuu) disintegrates into a proton (uud) and a positive pion (u$\bar{d}$) by the creation of a new pair of d and $\bar{d}$. In making such pairs it will be seen that the *net* number, say of u quarks—by which I mean the number of u quarks minus the number of anti u quarks—can never change in a reaction. That is how we understand the great conservation rules of baryon number, strangeness, and charge. They simply become the three rules that the *net* number of u quarks, of d quarks, and of s quarks is never altered in a strong interaction. For example strangeness, being (minus) the *net* number of s quarks, will not change.

This phenomenon of quark pair production when energy is available implies that our simple model of the hadrons cannot really be quantitatively exact. For example, because of this phenomenon a state with a definite number of interacting particles, such as just three quarks qqq, is impossible. According to the uncertainty principle, even when there it not enough energy available, there is always some probability that the interaction forces create, albeit temporarily, one or more new pairs (we call them virtual pairs) of quark and antiquark. Thus there must be some probability that a proton sometimes looks like four quarks and an antiquark, or like five quarks and two antiquarks. The fact that our model works roughly in calculations must mean only that a baryon, for example, is predominantly in the state of just three quarks. The contribution of the extra pairs of quarks must be small.

An exact result, of course, is that the *net* number of quarks (quarks minus antiquarks) is three. Further, to get the charge, strangeness, and baryon number correctly, the proton must have a *net* number of u quarks (number of u minus number of ū) of 2, a net number of d quarks of 1, and no net number of s quarks (so the number of s equals the number of s̄). The close family relation of neutron and proton, for example, is still maintained. If in the proton state you imagine that each u quark is replaced by a d quark, each d by a u, and each anti u by an anti d and vice versa, then you get the state of the neutron.

Studying the Parts in a Proton: Electron Scattering from a Proton

How can we proceed to verify this idea that protons, say, are made of quarks? We cannot just calculate more reaction rates—if they disagree a bit we say it is inaccuracy of our dynamical model. We need precise predictions from the idea so that we give it a hard test—one where a disagreement with experiment would show that the quark view is wrong. Fortunately we have found a way to make such a test. What it amounts to fundamentally is looking into the proton to see whether it is made of parts, and determining the character of these parts. We can see if these parts are quarks; that is, do they carry spin ½ and charges like ⅔ or ⅓?

What we do is scatter a known pointlike object (an electron in the first experiments) off the proton. This is done at very high energy. The distribution in energy of the electron which bounces off is measured. This is determined by the motion of the parts within the proton. It is analogous to studying a swarm of bees by radar. If the swarm is moving as a whole the frequency of waves reflected back determines its speed. But if instead individual bees are moving about in the swarm, the returning wave has a range of frequencies corresponding to the range of velocities of the bees in the swarm.

The experiment is done in the laboratory with stationary protons and very energetic electrons. However, to analyze this we use a frame of reference in which we suppose the proton is moving very near the speed of light, with very high momentum P, from the left, and the electron is coming in with high momentum from the right. In such a frame the transverse (for example, up and down in our frame) movements of the parts of the proton are small (compared to P) and we can disregard them, and just think of the large momentum that the parts have along the direction of P. These parts share the momentum of P in various fractions. The quantities that characterize our proton are then distributions like the statistical probability that a particular kind of part carries a fraction x of the proton's momentum (that is, has momentum xP, in a small range of x). Thus if protons were made of quarks we would need six such functions of x giving the distribution in momentum of u, d, and s quarks and of their antiquarks.

The way these distributions can be studied is best seen by looking at the case (in the frame of reference we are using) where the electron is scattered directly backward (see Fig. 8). For a collision at such relativistic momenta (where energy and momentum are practically equal) the conservation laws of energy and momentum simply say that the particles exchange momentum. The momentum of the electron scattered back gives directly the momentum of the part from which it scattered. We use high energy so that the analysis by conservation of energy and momentum of the electron and one part is not overly distorted by the interaction of this part with the other parts in the proton.

Thus the momentum distribution of the returning backscattered electron gives directly the distribution of the *charged* parts. Charged parts only can be seen because the electron would not scatter from neutral parts. The chance of scattering an electron is directly proportional to the square of the charge of a part. Thus u (or anti u) quarks would have an effect 4/9, d quarks 1/9, and so forth, of what they would have if they carried a unit charge like the electron.

We can check our ideas about how this scattering takes place, and whether there are parts at all, by seeing whether we get the same distribution if we use a different energy for the incoming electron in the experiment. Indeed we do—protons are made of parts. Again we need not just use backscattering, we should get the same result if we scattered the electrons at other angles. Again we do. But this time we find out something else. To compare results at one angle and another we shall have to know about the primary law of scattering of electron and part. We need to know the chance that a given kind of part with a given momentum scatters an electron at a particular angle. But we have (from the relativistic quantum theory of electrodynamics) the formula for that, except that the formula depends on whether we are scattering from parts of spin ½, or spin 0, or some other spin. Therefore from the angular variation we can see what the spin of the charged parts are. The quark theory says they should be ½. Experiment agrees, the charged parts have spin ½. (The contribution from spin 0 parts, say, cannot be more than 15 percent, and could be zero.)

Neutrino Scattering from a Proton

How about the charges? Can we not discover whether the u quarks are contributing with weight 4/9 to the electron scattering? We could, only if we could measure the number of u quarks in some other manner. But we can do that, this time by scattering neutrinos. We reason from the point of view that the proton's constituents are quarks. The neutrino interacts with a d quark and is scattered back as a negative muon (converting the d quark to a u one). This is mediated by the weak interactions about which we have only partial understanding, but there are many internal checks we can make in these experiments to verify that we do understand them well enough. The same neutrino could also interact with an anti u quark, but here the angular distribution of backscattered muons is different. (It can also interact with strange quarks, but with only 6 percent of the strength, and we will disregard it.) Thus from such an experiment we can determine the distribution of d quarks and the distribution of anti u quarks separately. Further, by using antineutrinos instead of neutrinos, we can determine the distribution of anti d quarks and of u quarks all independently. We can assemble all these functions with weights 4/9 and 1/9 as appropriate, to see if we can reproduce the curve determined by electron scattering. We are, of course, lacking the distribution of strange or antistrange quarks, but they should contribute only a small (and necessarily positive) amount, both because their weight is only 1/9 and because we do not expect many $s\bar{s}$ pairs in the proton state. Therefore these experiments provide a stringent quantitative test of our theory of the constitution of the proton. They test whether the charges carried by the parts are ⅔ or ⅓ as we expect.

And what is the judgment of experiment? Unfortunately the full detailed experiments described above have not yet been done. We do, however, have some preliminary results of an experiment exposing a large bubble chamber (called Gargamelle) to neutrinos generated by the high energy machine at CERN. The liquid of the bubble chamber contains as many neutrons as protons and we cannot separate the effects of each.

This means that we confuse u and d quarks and cannot determine each separately; we only determine the average number of nonstrange quarks (u's plus d's). We can determine this and, independently (antineutrinos were also used), the number of nonstrange antiquarks, $\bar{u}$ plus $\bar{d}$. However, this still permits a stringent test of our model, for we can compare these to the average scattering of electrons from protons and neutrons. We have measured this quantity by scattering electrons from heavy hydrogen, deuterium, whose nucleus has one neutron and one proton. This also averages the contribution from u and d quarks—the average nonstrange quark coming in with weight $\frac{1}{2}(4/9 + 1/9) = 5/18$.

Therefore, knowing the distribution of nonstrange quarks and of nonstrange antiquarks from the neutrino experiments, we can make two tests. First, by putting them together and multiplying by 5/18 do we get a close fit to the electron scattering data (to within the uncertain contribution possible from strange quarks)? I have just returned from Hawaii where D. H. Perkins has told me the results: Yes, we do. The 5/18 factor is correct to the experimental uncertainty of ± 20 percent (see Fig. 9).

The second test is this. The *net* number of quarks (quarks minus antiquarks), whatever momentum they may have, should be three as we have seen. Perkins tells me his neutrino data give 3.5 ± 0.5 (but the uncertainty may be a bit larger for the data are not too well known for small x, and the answer is sensitive to that).

These two tests are satisfied by no other theory. It is true that the experiments are not as accurate as we would like and are not done at as high an energy as we would like. Other experiments are being done at the National Accelerator Laboratory—in fact for one the data have been taken but are still being analyzed. But there is a great deal of experimental evidence for, and no *experimental* evidence against, the idea that the hadrons consist of quarks. [*Note added in proof*: This is no longer true. An experiment done at the Stanford Linear Accelerator Center (reported by B. Richter at the 1973 High-Energy Physics Conference at Irvine) indicates that the rate at which hadrons are produced by annihilation of electrons and positrons is much higher than expected by the quark model.] Let us assume it is true.

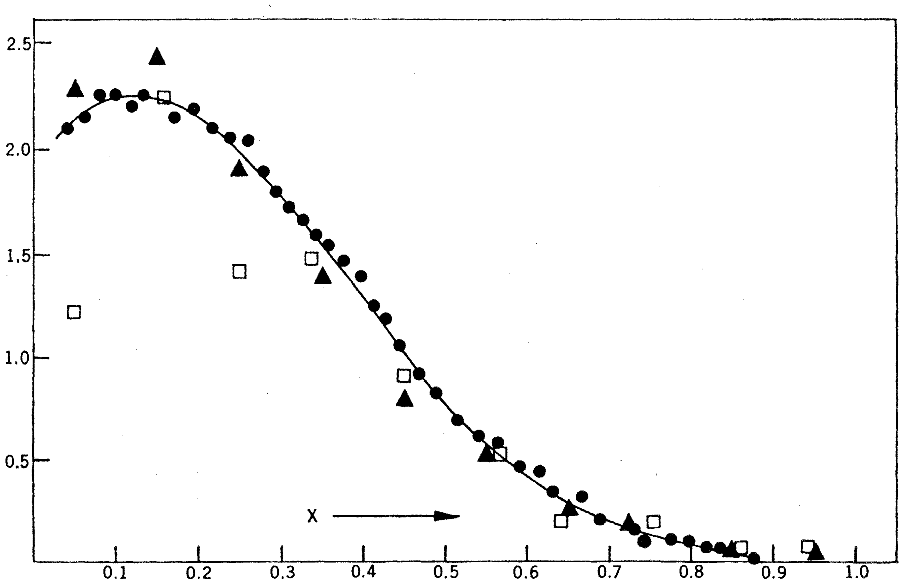


Fig. 9. The distribution of momentum of a fast proton carried by nonstrange quarks $q(x)$ and antiquarks $\bar{q}(x)$, as a function of x, the fraction of the proton's momentum, is determined in two ways. Scattering from electrons (solid curve) and neutrinos (triangles) should give the same result for the sum $2(q + \bar{q})$ if (a) a small contribution at small x from strange quarks is neglected and (b) the electric data is scaled up by dividing 5/18 the mean square charge of nonstrange quarks $\frac{1}{2}[(2/3)^2 + (1/3)^2]$. The agreement shown confirms the expected charge values for the quarks. [The neutrino data are also capable of giving the difference $2(q - \bar{q})$ (squares).] I thank D. H. Perkins for reporting these data to me at the Hawaiian Summer School, 1973.

Theoretical Questions

There are, however, a number of theoretical arguments against this idea. So strong are these arguments that at first they seemed to lead to paradoxes. But one by one we are learning how it may be possible to get around these paradoxes. We are perhaps getting the first glimpses of a truly dynamic theory of the hadrons.

I will discuss these points one by one, starting with the ones that seem easiest to avoid.

The first question is this: The charges on the quarks are funny fractions, like $+\frac{2}{3}$, of the fundamental charge unit (the negative of the electron charge), yet all observed particles in nature have integral multiples of this unit.

But we have never understood this fact, we have never proved that the charges in nature must be integral. We do not know what to say, but no fundamental inconsistency seems to arise from these nonintegral charges. (It was this fact, that nature's charges are always integral, which made Zweig and Gell-Mann's hypothesis so daring and so hard to think of.)

Our next problem is that if we add up all the momenta of the quarks and antiquarks which we see in the electron and neutrino scattering experiments the total does not account for the momentum of the proton, but only for about half of it.

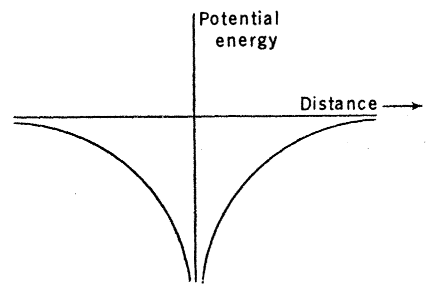
This must mean that there are other parts in the proton that are electrically neutral and do not interact with neutrinos. Yes, and even in our model of three quarks we had to hold the quarks together somehow, so they could interact and exchange momenta. This may well be via some interaction field (analogous to the electric field which holds atoms together) and this field would carry momentum and would have quanta (analogous to photons). We call these quanta gluons, and say that besides quarks there must be gluons to hold the quarks together. These gluons contribute the other half of the momentum of the proton. It might, in fact, have been embarrassing if all the momentum were accounted for by quarks. We might not know how to describe their interaction. The simplest theoretical possibility is that gluons are of spin 1 (like photons).

Third, how can the nonrelativistic quark model work even approximately? The energies of excitation of motion are a sizable fraction of the unexcited state masses. This indicates strong forces and there should be many pairs, so just three quarks would not work for baryons, for example.

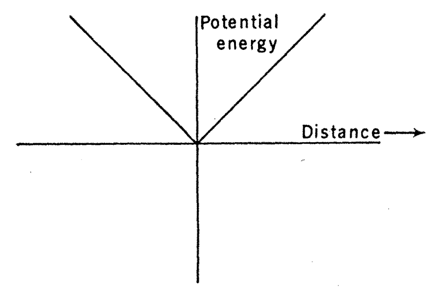
I do not know. It is possible that these expectations come from experience with hard forces (forces varying rapidly with distance, like the electrical forces). The interquark forces may be softer (varying more slowly with distance). At any rate, the number of pairs is determined by our experiments with electrons and neutrinos and it appears that there are not many—the experiments indicate that of the total momentum carried by quarks probably less than 15 percent is due to such pairs. This at least is consistent with the low energy model view that neglect of pairs is not serious. There are also indications, in high energy collisions among hadrons, that forces may be soft at short distances.

The next problem is more serious. Relativity and quantum mechanics require for spin ½ particles a principle, called the Pauli exclusion principle, that no two particles of the same kind can be in exactly the same state. But for Δ^{++}, for example, with vertical angular momentum $+\frac{3}{2}$, we say there are three quarks, all of the same kind, u, all in the same state—spinning with $+\frac{1}{2}$ angular momentum component.

The only way out of this seems to be to say that the three quarks in a baryon are not really all the same. We shall have to say that quarks have another property, say "color," and that they can be either red, yellow, or blue. Thus there are now nine varieties of quarks; red u ones, red d, red s, yellow u, yellow d, and so forth. Then the



a) Potential of electricity



b) Potential from Kauffmann's equation

Fig. 10. Variation of potential energy with distance for (a) electrical force and (b) Kauffmann's force.

three u quarks in a baryon such as the Δ^{++} are not all in the same state: one is red, one is yellow, and one is blue. This does not affect the meson states. For them the quark and antiquark, being different already, can be both red or both blue or both yellow, in fact with equal probabilities.

Another problem: quarks never come apart—separate quarks have not been seen. It is suggested that quark masses are very high so that we have not yet enough energy to make them, but this is no easier to understand than if they cannot be made at all. So we shall suppose the latter, that free quarks do not exist. How could that be?

We can get an idea from electrical forces, where like charges repel and unlike attract. Suppose quarks repel but quark and antiquark attract by a force with a very long range (I shall take it as infinite later). Then a meson-like pair quark-antiquark would hold together but would not influence another quark at long range because the other quark would be attracted by the antiquark but equally repelled by the quark in the meson. Thus no long range force would appear between mesons (as must be, for none is observed). But the quark and antiquark of the meson could really never come apart because the energy needed to pull against their long range attraction continues only to grow and grow as you pull them further and further apart. To get them truly free would require infinite energy.

How could such a long range force arise? Nobody knows. Here is where all the careful thought must go. I shall describe one suggestion due to Kenneth Kauffmann. Electrical force arising from a charge gives rise to a potential energy satifying a second order differential equation $\nabla^2\phi = 0$. The solution is that the potential varies as the reciprocal of the distance from a charge (see Fig. 10a). This generates a force falling inversely as the square of the distance. This falls off too fast with distance to work for us—and, as we know, electrons can be permanently torn from atoms with only a finite energy. But Kauffmann points out that if the force satisfied a fourth order equation like $\nabla^2\nabla^2\phi = 0$ the solution is $\phi \approx r$, an energy rising with distance (as in Fig. 10b) leading to a force which is the same at all distances and reaching to infinity.

It will be noticed, by the way, that Kauffmann's suggestion also leads to a softer force (constant) at short distances than the conventional theory does (inverse square of distance). This will help with an earlier point that we mentioned.

But even with all that we are left with another puzzle. Why are there just three quarks in a baryon? The view just explained—long range repulsion between likes—will not explain why the three quarks of a baryon do not mutually repel. It does not explain why, in fact, the three quarks of one baryon do not repel at long range the three quarks of another baryon, so that two protons, for example, do not strongly repel at large distances. Again, why are just three quarks, not four or two, so satisfied to stay together?

Had the number which held together been just two instead of three, it would be easy to explain. We could say that the quarks come in two varieties, say red and blue, and the long range interactions are such that likes repel and unlikes attract. Thus all baryons would consist of two quarks, one red and one blue attracting. Between two baryons there would be no long range force because the plus and minus effects cancel out. We say the forces saturate at two particles.

To make the same thing work with three particles instead of two we must be a bit more clever. I am sorry that I cannot describe this neat idea in a simple manner here, but it uses what we call exchange forces to generate the saturation. The quarks must come in three varieties, red, blue, and yellow. The force has the effect of exchanging colors. The mathematical theory of this is rather simple. In fact the equations for such a theory were written down over 20 years ago by Yang and Mills, who saw no application of them but published them because they looked so beautiful and symmetrical. With this theory there are eight kinds of gluons (depending on which pairs of colors they exchange). The saturated states are those which have no net color, that is, which are completely neutral as to color. A single quark or two quarks could not be neutral, but a group of three is indifferent to color if one is red, one blue, and one yellow.

They must be in just the condition we need to explain how three u quarks can appear to be in the same state in spite of the exclusion principle.

We have been led by two different arguments to this need for colored quarks.

If experiments continue to confirm the need for quarks in protons, this is the way the theory will apparently develop: quarks of three colors, so nine in all, and eight kinds of gluons. This part sounds elaborate but is mathematically simple. And a long range force—which sounds simple but appears mathematically a bit unnatural. Suggestions to explain this long range force, such as Kauffmann's, all seem a little awkward and without an inner beauty we usually expect from truth. But sometimes the truth is discovered first and the beauty or "necessity" of that truth seen only later. At least it seems now we have a very good guess to work on.

Beside our eight gluons and nine quarks there would still be the electron, muon, photon, graviton, and two neutrinos, so we would still leave a new proliferation of particles to be analyzed by the next generation. Will they find them all composed of yet simpler elements at yet another level?

Female Steroid Hormones and Target Cell Nuclei

The effects of steroid hormones on target cell nuclei are of major importance in the induction of new cell functions.

Bert W. O'Malley and Anthony R. Means

Studies designed to elucidate the sequence of events responsible for steroid hormone effects in endocrine target cells have led many investigators to consider the nucleus as the primary site of hormone action. Numerous experiments have supported the suggestion that steroid hormones regulate cell function by influencing the synthesis of proteins in the target tissue (*1–5*). In most instances, the stimulation of such protein synthesis by steroid hormone is preceded by quantitative and often qualitative changes in the synthesis cellular RNA. Stimulation of nuclear, rapidly labeled heterogeneous RNA followed by increased production of ribosomal RNA and often transfer RNA are frequently observed effects on RNA metabolism (*6–7*). It is likely, but has not been proved, that the messenger RNA (mRNA) of animal cells is a component of the giant heterogeneous nuclear RNA. Additional support for a primary effect of steroids on nuclear gene transcription is provided by the ability of actinomycin D and other inhibitors of RNA synthesis to block most steroid hormone–mediated cell responses. General theories in which stimulation of mRNA is regarded as the primary event should not be overestimated, however, since some evidence suggests other possibilities (*8*). On the other hand, recent experiments have conclusively demonstrated that steroid hormones are capable of inducting a net increase in specific mRNA molecules in target cells (*9–12*).

If steroids do in fact regulate nuclear gene transcription, certain considerations should be compatible with such a theory. There must be a mechanism for limiting the steroid-induced response to target tissues. There should be a defined sequence of events which results in the transport of a steroid molecule to its presumed nuclear site of action following penetration of the target cell membrane. The existence of mediators or "second messengers" must be delineated. The steroid hormone itself or an intracellular mediator should be capable of interacting at certain predetermined sites in the nucleus prior to alterations in DNA transcription. Changes in nuclear RNA synthesis should finally result in a net increase in the amounts of specific mRNA's, which should, in turn, be limited to steroid hormone target tissue and inducible by only the steroid in question. Increases in the intracellular concentrations of these mRNA molecules should precede fluctuations in the rate of synthesis of the corresponding specific proteins. Over the past decade many experimental data relating to these theoretical considerations have accumulated. In this article we summarize the evidence favoring our prejudice that the target cell nucleus is a major determinant in steroid hormone induction of new cell functions. Our discussions are limited primarily to the activity of estrogen in the rat uterus and chick oviduct and the activity of progesterone in the chick oviduct because most experimental data on mechanisms of female sex steroid action emanate from these model systems. However, the generality of these observations as applied to mechanisms of action of all steroid hormones has been recently reviewed (*13–15*).

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