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"Follow That Quark!" (and Other Exclusive Stories)

Alan S. Carroll

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Summary

Quarks are considered to be the basic constituents of matter. In a series of recent experiments, Carroll studied exclusive reactions as a means of determining the interactions between quarks. Quantum Chromo-dynamics (QCD) is the modern theory of the interaction of quarks. This theory explains how quarks are held together via the strong interaction in particles known as hadrons. Hadrons consisting of three quarks are called baryons. Hadrons made up of a quark and an antiquark are called mesons. In his lecture, Carroll describes what happens when two hadrons collide and scatter to large angles. The violence of the collision causes the gluons that bind the quarks in a particular hadron to temporarily lose their grip on particular quarks. Quarks scramble toward renewed unity with other quarks, and they undergo rearrangement, which generally results in additional new particles. A two-body exclusive reaction has occurred when the same number of particles exist before and after the collisions. At large angles these exclusive reactions are very rare. The labels on the quarks known as flavor enable the experimenter to follow the history of individual quarks in detail during these exclusive reactions.

Carroll describes the equipment used in the experiment to measure short distance, hard collisions at large angles. The collisions he discusses occur when a known beam of mesons or protons collide with a stationary proton target.

Finally, Carroll summarizes what the experiments have shown from the study of exclusive reactions and what light some of their results shed on the theory of QCD.

Follow That Quark!
(and Other Exclusive Stories)

Alan S. Carroll

Very Rare Failure of the Atom Smashers

To get a physical feeling for the reactions I will discuss, imagine the following: You are out on a dry lake bed somewhere in the western part of the U.S. The sun has just come up, but already there is a slight shimmering as the earth begins to heat up. A gleaming white Corvette, its powerful motor idling, sits astride a dotted line (Figure 1). If we follow the dotted line across the lake bed floor for a hundred miles or more, we come to an identical Corvette pointed back towards the first one. Since this is an important event, there is a satellite camera above, plus the usual mini ams inside the car to record the instruments and reactions of the drivers. The drivers shake hands with their mechanics and buckle up their safety harnesses. As the signal lights switch from red, to yellow, to green, the two cars leap into life and start racing across the desert. As the drivers struggle to keep their powerful cars centered on the dotted line, we see that the speedometers have crept up more than halfway (0.5c). We suddenly remember from some rerun of "Star Trek" that c stands for light speed, 186,000 miles/second! The speedometers nearly reach the upper limits just before the cars collide. There is a brief flash of light, and a resounding click. Then the two cars roar off at right angles (90°) to the dotted line, pop out their parachutes and come to a stop. A little groggy, but physically fine, the drivers climb out of their cars to be congratulated by their friends.

Does this sound like a fantastic picture? One that probably never happens? I would like to discuss some very violent collisions where

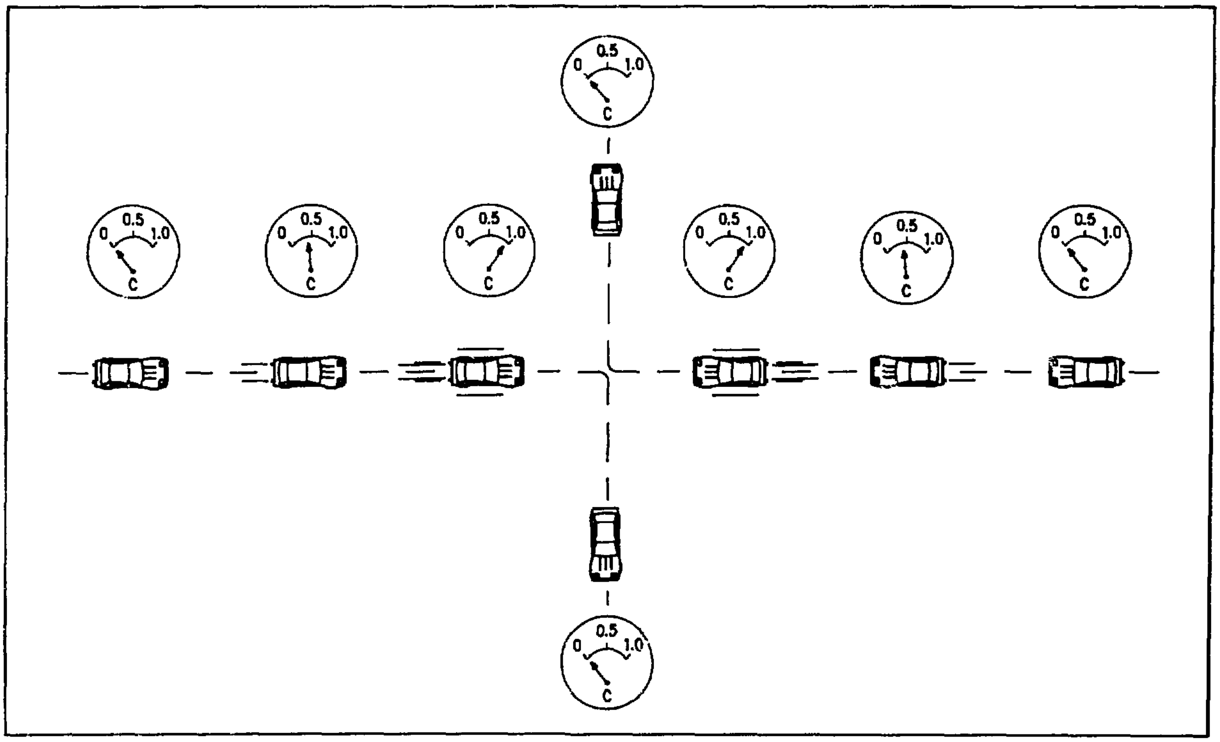


Figure 1. Exclusive collisions between two cars in which they accelerate, collide at very high speed and then go off at 90° to their original direction without suffering any damage.

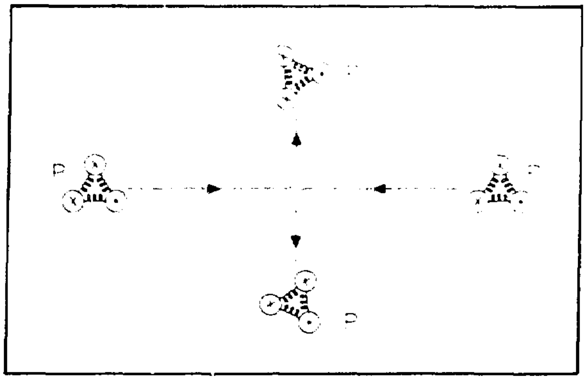


Figure 2a. Exclusive collisions between two protons in which the two original protons are unchanged.

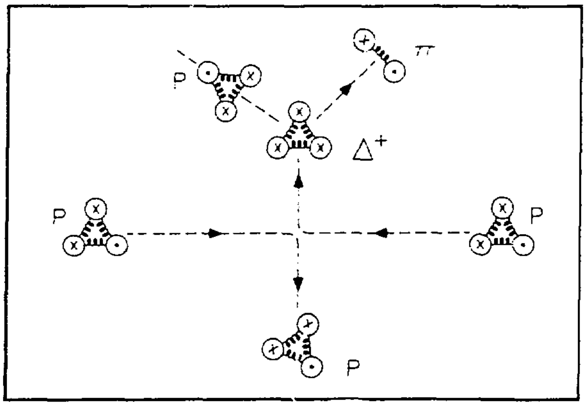


Figure 2b. A collision in which the energy of the collision transforms one of the protons into a Delta (Δ^+) by changing its spin from down (x) to up (·). The Δ^+ subsequently decays to a proton and a pion. Since there are two, and only two, particles immediately after the collision, this is also an exclusive collision.

nothing or very little happens. If we go back to the collision point in the desert, we find evidence that these collisions are indeed very rare, because the ground is littered with the wheels, bumpers and shreds of the last million cars that tried this trick. Thus, a couple of scientific questions: Why do they occasionally stay together? Also what can be learned about their internal structure?

As you might suspect, I am not going to endlessly discuss colliding Corvettes. For one thing, the Alternating Gradient Synchrotron Department (AGS) could not afford to do such experiments. Also, if one wanted to learn about the internal structure of a Corvette, one could just put it on a lift and use a wrench. Instead I will discuss collisions between particles made up of parts, studying the rare examples in which the parts all stay together. The particles are simple compared to cars, consisting of only two or three parts, but they are not one piece. Figure 2a is an example of two protons (p) colliding. The internal forces hold them together, and they are whole. The atom smashers have failed in their task. Collisions in which there are two well-defined particles emerging are called two particle exclusive reactions (exclusives). There can be exclusive reactions in which three or more well-defined particles emerge from the collision, but I shall confine this discussion to two particle exclusives. By our measurements we have excluded the existence of any other particle formed in the reaction. In some cases, such as that shown in Figure 2b, the three internal pieces may use the energy of the collisions to rearrange themselves into new and heavier pieces. Collisions with rearrangements are as if two Chevys collided and came out a Buick and a Chevy. The owner of such a Buick would soon be disappointed as it quickly reverted to a Chevy and a 10-speed bicycle. It is also possible for the pieces from one particle to move from one particle to the other. But since there were only two particles originally coming out of the collision, we call it an exclusive.

So how do we know these rare events occur? We physicists stand off to the side of these collisions and measure the energy of the emerging particles with detectors which can distinguish between different particles. If we plot the number of collisions in which protons emerge with a given interval of energy, we get a graph like the one in Figure 3. Note that the vertical scale is given in factors of 10, as we come down by a factor of a million, where there is a dimple corresponding to proton proton (pp) elastic scattering. There are no more events; we are at the exclusive limit! The absolute maximum energy which can be imparted to particles in this collision is that given to these protons.

Having rambled on, I will now briefly describe the outline for the remainder of the lecture. First I will give a very brief historical perspective, then the elements of the present day theory of the parts (quarks), which make up particles (hadrons), the experiment, results and conclusions. A warning to physicists: I will be making many approximations for simplicity. We shall assume that the energy (E) and momentum (p) of the particles are nearly the same. Instead of the center-of-mass energy squared, I will be substituting a nearly proportional quantity, the incident laboratory energy (E_{inc}). Finally, quantum mechanical effects will be generally neglected.

The Reign, Fall and Partial Recovery of Exclusive Reactions

During the 1940's, physicists studied collisions with cyclotrons. The particles accelerated from the cyclotrons did not have sufficient energy to disrupt the internal pieces of the particles. It was like collisions at five miles per hour with good bumpers. Not much was learned about particles; they behaved almost like simple points.

During the 1950's and 60's, there was much more energy available from accelerators, such as the Cosmotron and the AGS; new particles were frequently produced, but there was still an emphasis on exclusive reactions. In fact, exclusive reactions were often used to discover new particles.

In the 1970's, with the development of the quark picture, physicists became very interested in the substructures of particles. Instead of exclusive reactions, the emphasis switched to inclusive reactions. This was like standing off to the side and studying the energy distribution of hub caps or steering wheels flying out of the collision without regard to the rest of the car. Studying the energy distribution of inclusive reactions is a remarkably useful thing to do and has led to a number of important discoveries. Such experiments are still continuing.

With the more complete development of the theory of quarks and their interactions, it seemed reasonable for a group of us to reexamine the exclusive reactions. This has been our collaboration's project for the 80's.

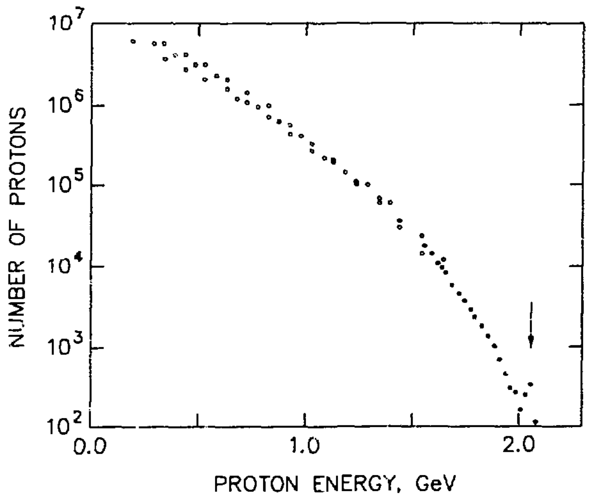


Figure 3. Experimental evidence for exclusive collisions at large energies. As indicated by the arrow, there is an excess number of protons observed at an energy of just over 2 GeV. These protons correspond to elastic scattering at 90° in which its incident protons are unchanged, and hence, they have the maximum possible energy.

Color Me Neutral

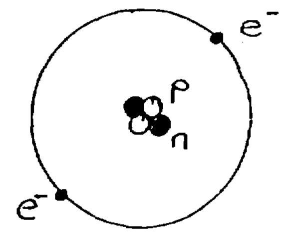
Figure 4 contains some of the ingredients of the Quark Model of Hadrons, which shows how quarks combine to form the category of particles known as hadrons, the particles made up of quarks, which experience the strong or nuclear force. The quark model came out of a sense of desperation; there were too many particles to keep track of. In addition there was good evidence that the hadrons were made of smaller parts.

All the particles I will discuss are combinations of three different types of quarks. There are two more kinds of quarks, plus one suspected kind. The fourth kind of quark, c (charmed), has played a major role at the AGS, but is so difficult to produce by exclusive reactions that it does not have a significant part in the experiments I will discuss. The other two kinds simply cannot be produced at the AGS because there is insufficient energy available.

The quarks are simple point-like bits of matter which physicists now believe cannot be subdivided into smaller objects. But since that sort of statement has been made so often before in the history of science and has been proven to be wrong, I will not make it very strongly. The quarks have labels, "flavors", which in terms of these collisions are permanent (Figure 4). They are up (u), down (d), and strange (s); they also have electrical charges of + 2/3 and − 1/3 of the proton's charge. The u and d quarks are very light, but the s quark is considerably heavier. Finally, they have a property known as spin, which is very important, but I will not discuss it extensively. This spin, which has a value of 1/2, can be thought to be pointed up or down.

• • • • • QUARK MODEL OF HADRONS • • • • •

Flavor	Charge(e)	Spin (1/2)
u(up)	+ 2/3	↑
d(down)	- 1/3	↑
s(strange)	- 1/3	↑



HADRONS

Baryons

Particle	Quark	Charge	Spin	
p(proton)	u	+ 2/3	↑	
	u	+ 2/3	↓	
	d	- 1/3	↑	
		+ 1	↑	1/2
n(neutron)	d	- 1/3	↑	
	d	- 1/3	↓	
	u	+ 2/3	↓	
		0	↑	
Δ^+(Delta$^+$)	u	+ 2/3	↑	
	u	+ 2/3	↑	
	d	- 1/3	↑	
		+ 1	↑	3/2
Λ°(Lambda)	u	+ 2/3	↑	
	d	- 1/3	↓	
	s	- 1/3	↑	
		0	↑	
$\bar{p}$ (Anti-proton)	$\bar{u}$	- 2/3	↑	
	$\bar{u}$	- 2/3	↓	
	$\bar{d}$	+ 1/3	↑	
		- 1	↑	

Mesons

Particle	Quark	Charge	Spin	
π^+(pion$^+$)	u	+ 2/3	↑	
	$\bar{d}$	+ 1/3	↓	
		+ 1	•	0
π^-(pion$^-$)	d	- 1/3	↑	
	$\bar{u}$	- 2/3	↓	
		- 1	•	
ρ^-(rho$^-$)	d	- 1/3	↑	
	$\bar{u}$	- 2/3	↑	
		- 1	↑	1
K^+(kaon$^+$)	u	2/3	↑	
	$\bar{s}$	+ 1/3	↓	
		+ 1	•	
K^-(kaon$^-$)	s	- 1/3	↑	
	$\bar{u}$	- 2/3	↓	
		- 1	•	
K°(kaon$^\circ$)	s	- 1/3	↑	
	$\bar{d}$	+ 2/3	↓	
		0	•	

Figure 4. Quark Model of Hadrons. This diagram illustrates how three flavors of quarks, simple point-like bits of matter, can make up the spectrum of hadrons seen at the AGS. Hadrons are particles, such as the proton, which experience the strong force and are associated with the atomic nucleus. Hadrons come in two categories: Baryons composed of three quarks and mesons composed of a quark and an antiquark.

Using these building blocks, we can proceed to assemble all the 100-odd hadrons which can be produced at the AGS. We start with the baryons. Baryons are hadrons made up of three quarks. In just a minute I will explain why there are just three quarks in a baryon. We start with the proton, the nucleus of the hydrogen atom. It is obviously a very ordinary sort of baryon, so it must contain no s quarks. It has an electrical charge of +1 electronic charges so that the hydrogen atom consisting of a proton (+1) and an electron (−1) is neutral. Two u quarks and one d quark combine to make up the protons. One final detail is to decide how to align the quark spins. The overall spin of the proton is 1/2, so to generate this spin from three quarks 1/2 spins, two of them are parallel and one is antiparallel. So it is rather simple arithmetic, which explains why the Quark Model was so popular even before it was thought to be true.

Now I will quickly run through the remaining baryons (Figure 4). An object known as the Delta$^+$ (Δ^+) looks very much like the proton in terms of its quarks, but its three spins are aligned, giving an overall spin of 3/2. Experimentally we find that this object is more massive; it weighs about 30% more than the proton. The Lambda (Λ°) is an example of a strange baryon, so naturally it contains an s quark. The neutron (n) can be converted into this baryon if a d quark is replaced with an s quark. Finally, there are antiprotons ($\bar{p}$) which have properties the exact opposite of protons: for example, their charge is −1. Antiprotons and other antihadrons contain antiquarks. When an anti-u quark meets a u quark, it can annihilate, disappear into a puff of energy. Quarks with u flavor cannot do this with either a d or an s quark, because the flavor of the quarks cannot disappear in a reaction.

Moving in Figure 4 from the baryons column to the next column, is the meson family of particles. Each of the mesons consists of one quark and one antiquark. The lightest and most common mesons are the pions. In a typical collision of a proton from the AGS, a few of these pions are produced. These are the lightest members (bicycles) of the hadron world, and live long enough to travel 100's of meters. The negative rho is a meson with its quark spins parallel rather than antiparallel. It is heavier than the pions and very unstable, decaying almost instantaneously. The kaons (K+, K−, K°) are the strange cousins of the pions, each containing an s quark. They are produced about one-tenth as often as the pions. Like the pions, they live long enough to travel long distances.

One final note, since hadrons like the Δ^+ are heavier (contain more energy) than a pion$^+$ (π^+) and a n, there is nothing to prevent a Δ^+ from decaying. The quark diagram for doing this shows how one of the u quarks goes off with a spontaneously formed $\bar{d}$ quark to form the π^+, leaving a n behind formed from the newly created d quark (Figure 5). A similar diagram can be drawn for the rho meson.

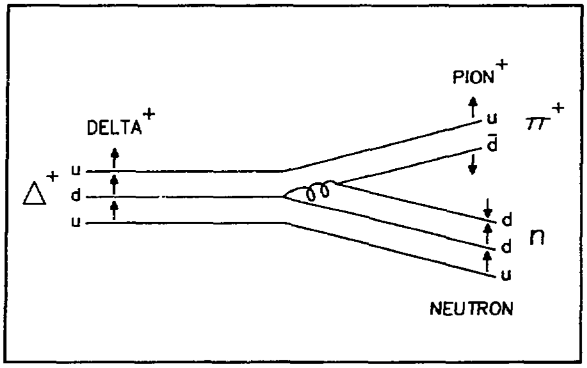


Figure 5. An illustration of the heavier Δ^+ particle decaying into a lighter neutron (n) and a positive pion (π^+) by the creation of d and $\bar{d}$ quarks. Since the d and $\bar{d}$ are antiparticles with respect to one another, the number of quarks before and after the decay is considered to be the same.

Now I will discuss what holds the quarks together in the hadrons. What are the forces between them? I first want to mention a diagram that high energy physicists use (Figure 6a). Let us display the collision of the two cars in such a graph. The cars come together and then fly apart, and this is illustrated by the lines coming together and then going apart. The piece of paper limits us to time and only one space dimension, so we do not attempt to show the actual directions after the collision, just the separation. What happens in these collisions is perhaps more like a spacecraft approaching a planet than a collision. They do not actually bump into one another, but as the particle approaches, the gravitational force attracts and changes the spacecraft's direction.

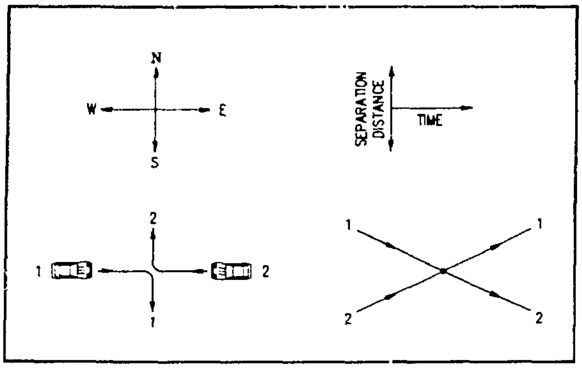


Figure 6a. A space-time diagram of collisions. On the left is the spatial diagram of two cars travelling East-West, colliding, and then going apart in the North-South direction. On the right is a space-time diagram of the same collision. As time increases to the right, the separation distance between grows smaller. Then the cars collide and the separation distance increases again.

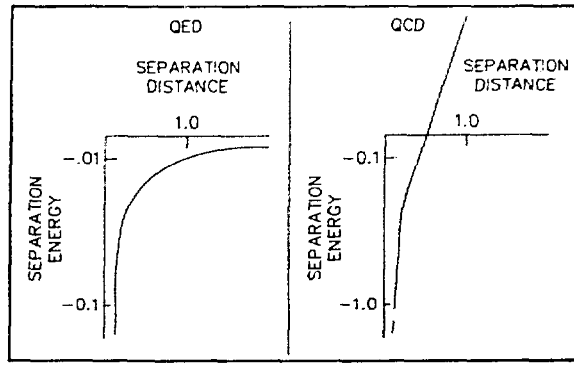


Figure 6c. The separation energies versus separation distances for QED and QCD. The forms of these curves are the same at short distances, although the QCD force is stronger. At large separation distances the QED force goes to zero, but the QCD forces grow to infinity. Thus, it is possible to separate electrically charged particles, but not color charged particles.

Before discussing the forces between quarks, let us examine a more familiar situation: the force between two electrically charged particles, for example, an electron and its antiparticle, the positron. In Figure 6b the electron and positron move toward one another and experience a force and move apart in a different direction. For those of you who suffer from "static cling" during the winter months, you realize that electrically charged objects can attract each other at a distance. Similarly, the electron and positron can attract each other at a distance. The mechanism for this attraction developed by physicists is the exchange of a photon. The modern theory of electromagnetic interactions is called Quantum Electro-Dynamics (QED). A photon leaves the electron and then is captured by the positron or vice versa. What is a photon? It is a particle of light—no mass, no charge, only energy. Such a particle could be visible light, ultraviolet light, x rays or if even higher energy, gamma rays. They are all light particles, just different energies. The energy required to separate an electron and a positron are given in Figure 6c. If they are close together it takes a lot of energy to separate them, and if they are far apart it takes very little energy. The force is very weak at large distances. This is the force that binds electrons to the nuclei atoms. When an electron or other charged particle undergoes a violent change of direction (acceleration) it frequently "shakes-off" a photon as shown in the figure. The photon is emitted, but it is never reabsorbed. Such processes are responsible for the light which comes out of the National Synchrotron Light Source (NSLS). An electron and a positron can also annihilate into a photon, which then can recreate another electron and positron.

Now let us turn to the forces between quarks. The Quantum Chromo-Dynamics (QCD) diagram, has many similarities to the QED diagram describing the forces between an electron and a positron. Two quarks come together and fly apart after exchanging a "something". In fact, the form of the force is the same for QCD as for QED for short distances between the quarks. Our experiments are done in this short distance region.

Next come the differences. The charges in the theory of QCD come in three kinds, given the somewhat confusing names of color or color charges. This is a theory to describe a new force, so QCD has a new kind of charge. These colors remind us of an essential feature of the theory. In QED, systems of particles like to become electrically neutral: electrons bind together with positive protons to form neutral atoms. Similarly in QCD, red quarks bind to anti-red quarks, blue quarks to anti-blue quarks, just like positive and negative charges. In the baryons where there are three quarks, a

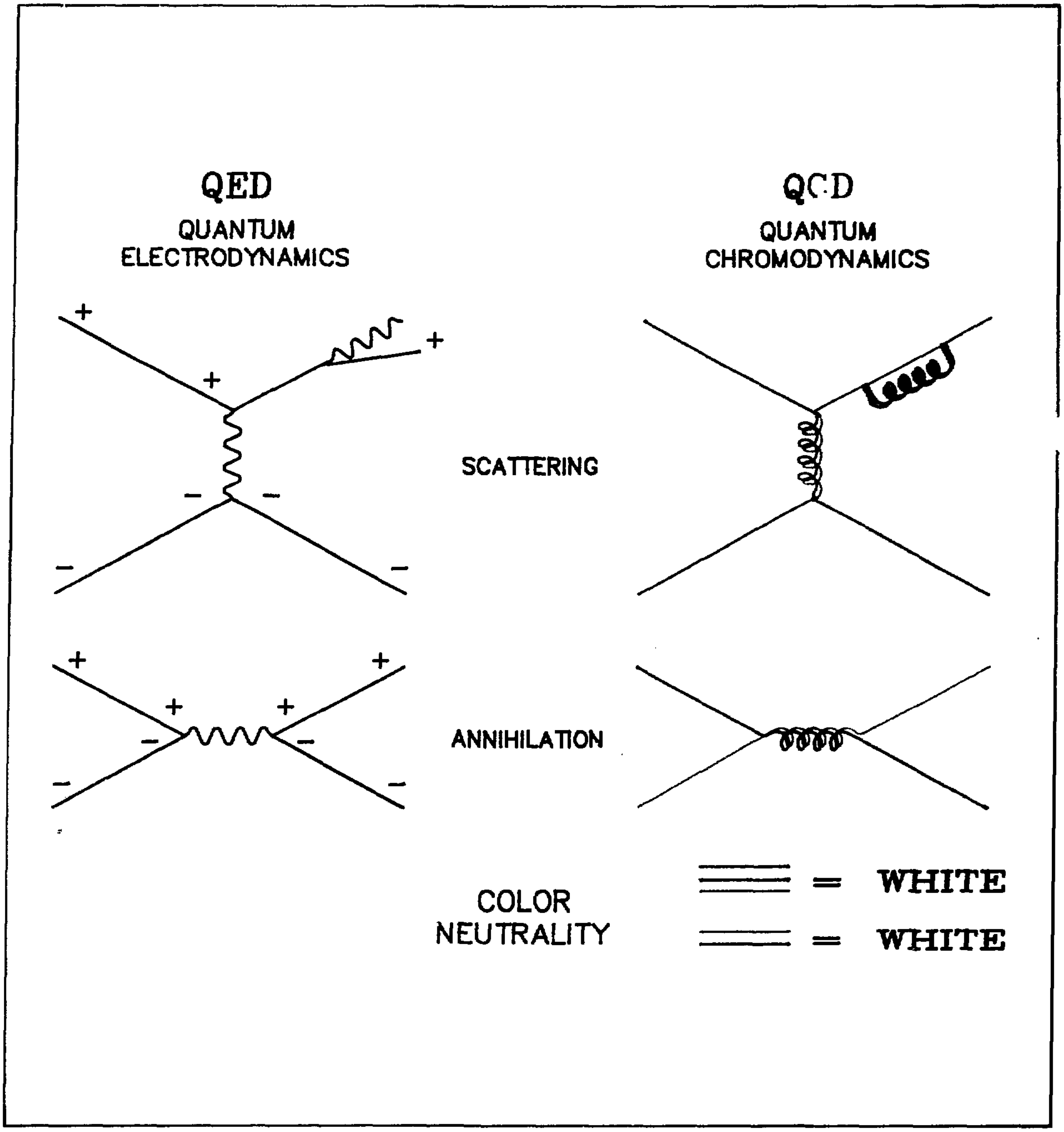


Figure 6b. A space-time diagram of collisions between positive (+) and negative (−) electrically charged particles in the modern theory of electro-magnetism (QED), and between different colored quarks in the theory of QCD. The electrically charged particles can scatter by exchanging a photon (wiggly line). If they are anti-particles of one another, they can also annihilate to a photon and then create a pair of particles again, as shown in the lower figure. In QCD the force is carried by gluons (looping lines), which like the quarks have color charges connected with them. So in general, the quarks change their color charge after a collision. In QED the electrically charged particles can "shake-off" a free photon as the result of the collision. Any gluon emitted will be attracted and reabsorbed due to the color charge that it carries. Gluons are never free. Electrically neutral systems, such as atoms, are formed by having equal number of + and − charges. Color neutral systems may be formed by combining color (green) and anti-color (red-blue), or all three colors: red, green, and blue. The former correspond to mesons and the latter baryons.

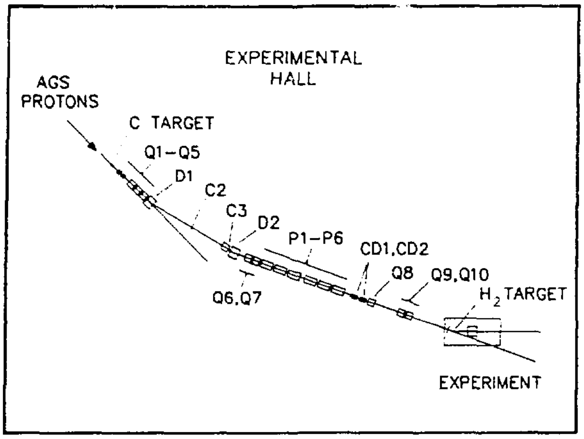


Figure 7. The system of magnetic lenses and prisms (beam line) which focuses and selects the particles produced by interaction of protons from the AGS in a heavy metal target. The produced particles are conducted along 100 yards of the beam line to the experiment where they are identified by its two Cherenekov Counters, CD1 and CD2. Finally, many of the particles collide with the protons in a hydrogen target (H_2).

red, a green and a blue can combine again to form a system whose color charge is neutral. This is in analogy to the fact that the proper combination of red, green and blue light forms white light. An important simplification is that the QCD force does not depend upon the flavor of the quarks.

Let us turn our attention to the "something" which was exchanged between the two quarks. At this point the theory becomes more than "passing peculiar." The something, which has the not too subtle name of gluon, has color itself, in this case, red and anti-blue (yellow), unlike the photons which had no charge. So when the gluon is exchanged, the quarks change color. Can the quarks shake-off gluons in a collision? The answer is no. When the implications of this picture are worked through, the force between two quarks works as follows. At short distances the energy to separate the quarks is similar in form to the QED case but much larger. At large distances the energy to separate two quarks becomes very large, going to infinity. The infinite energy for separation means that we never have free quarks or free gluons. However, if we can do our experiment at short distances, we may be dealing in a regime, which because it is like QED, can be understood and calculated with considerably less complication.

An important distinction between QCD and QED is that we never scatter single quarks from one another, but we must always deal in bunches of quarks, called hadrons. The current status of these theories is that QED can calculate things to 1 part/billion, the ninth decimal place, but that QCD achieves on an accuracy of only about 20%, or the first decimal place.

Things That Go Bump in the Night

As a break from all this theoretical discussion, let us look at an experiment which can bounce one hadron off another at large angles. An overall schematic of the experiment is shown in Figure 7. The high energy protons from the AGS produce large numbers of secondary particles by collisions with a chunk of metal. A system of magnetic lenses and prisms, about 100 yards long, focuses and selects particles of a particular electric charge and energy. The beam produces about 50 million particles every three seconds. Two devices in the beam, known as Cherenkov Counters, identify on a particle by particle basis whether the hadrons striking the protons in the hydrogen target are pions, kaons or protons. The proton target is a one meter long vacuum flask filled with liquid hydrogen. The energy of the incident beam was 10 GeV, or 10 billion electron volts.

The quantities we wish to measure with our apparatus are angles, energies, and particle types (velocities) as shown in Figure 8. One-half of the apparatus measures all three. It consists of wire chambers which measure the positions of the particles at several points along its trajectory to an accuracy of better than a millimeter. By connecting the dots, the locations and angle of the track can be accurately determined. The types of particles are identified by two large tanks containing a dense gas known as Freon. When a particle exceeds a given velocity, it emits light which is sensed by a photomultiplier. The first tank responds only to the fastest and hence, lightest particles, the pions. The gas in the second tank is pressurized, enabling it to respond to the next heaviest particles, the kaons as well as pions. Protons are heavier than either the pions or kaons so that neither tank responds. From this we can make up a table, depending on signals received from the two Cherenkov Counter tanks. The "confused"

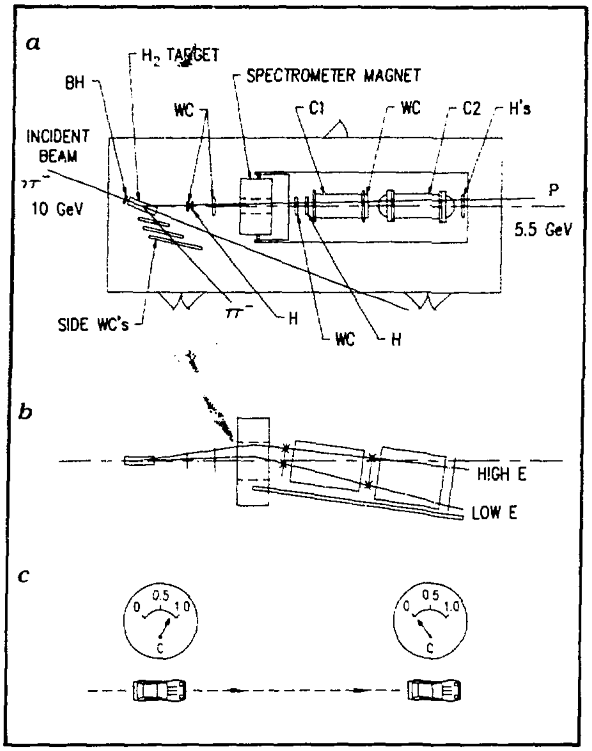


Figure 8a. A top schematic view of the experimental apparatus. In this figure an incident pion (π^-) scatters from a proton in the liquid hydrogen (H_2) target. The recoil proton passes through a number of wire chambers (WC), trigger hodoscopes (H), and the spectrometer magnet. The angle of the scattered π^- is measured in the side array wire chambers. The Cherenkov Counters C1 and C2 are used to measure the particle types. b. A side view of the apparatus illustrating the deflection of the particles in the spectrometer magnet. Electronic circuits allow the selection of only high energy particles (upper trajectory) corresponding to exclusive collisions. c. In this experiment the collisions take place in the laboratory system where the fast beam particle strikes a stationary proton like the collision between a moving and a parked car.

entry should not occur physically, and represents a failure of the detector.

TABLE I.

The response of the two tanks of the Cherenkov Counter and our deduction about the type of particle (See text for details.)

Cherenkov Counters by Response		
Tank 1	Tank 2	Particle Type
Yes	Yes	Pion
No	Yes	Kaon
No	No	Proton
Yes	No	"Confused"

Energies are measured by seeing what happens to the particles as they pass through the field of a strong electromagnet. The magnetic field bends positively charged particles downwards. The more energetic the particles are, the less they bend, so a measurement of their bend angle is a measurement of their energy. We measure the bend angle with sufficient accuracy to determine the energy to within 0.5%.

You may have noticed that this experimental situation is different from the head-on car collisions in that the one energetic particle strikes

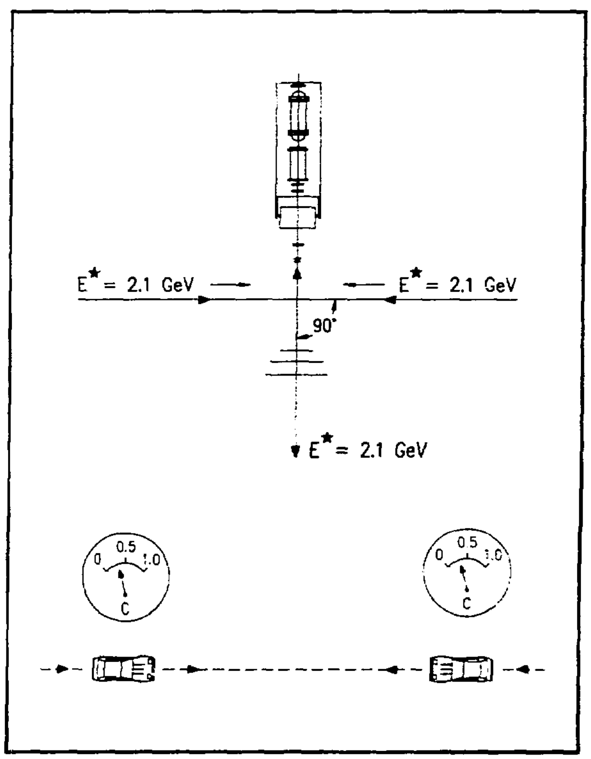


Figure 9. A view of the apparatus as it would appear if the collisions occurred in the center-of-mass (head-on) frame instead of the laboratory frame. The apparatus has rotated from 22.5° as in Figure 8 to 90° and the two incident velocities are smaller and equal.

a stationary proton in the target. The collision with a stationary target is in the laboratory frame, and the head-on collisions, where the two particles approach each other with equal energies, are in the center-of-mass frame. There is a mathematical relationship between the two frames, given by Einstein's Special Theory of Relativity. At the energies where we do our experiments, the angle of 90° in the center-of-mass corresponds to 22.5° in the laboratory. For simplicity, I will describe the experiments as if the collisions occurred in the center-of-mass frame as shown in Figure 9.

Figure 10 is a photograph of the framework of the experiment before it was enclosed in a building. The hydrogen target is on its stand, which will support the side array of the chambers. The big object in the middle is the magnet, followed by the two shells of the Cherenkov Counters. Artfully draped over the support structure are some of the riggers, technicians, surveyors, engineers and physicists who helped to put this all together. This provides an opportunity to test the hypothesis that you can always pick out a physicist in a crowd; there are five here. The mechanical framework of the experiment was quite ingenious; we wanted to be able to change the angle of scattering so that the whole support structure rolled on wheels. The back platform tilted down to optimize the bend angle. One slight hitch to the ease with which this all moved, was that a couple of times after very strong northeast winds, we found that the house had moved by about one-half inch despite the presence of wedges under the wheels. We now use chains.

Figure 11 is a drawing of a computer reconstruction of a single exclusive elastic scattering

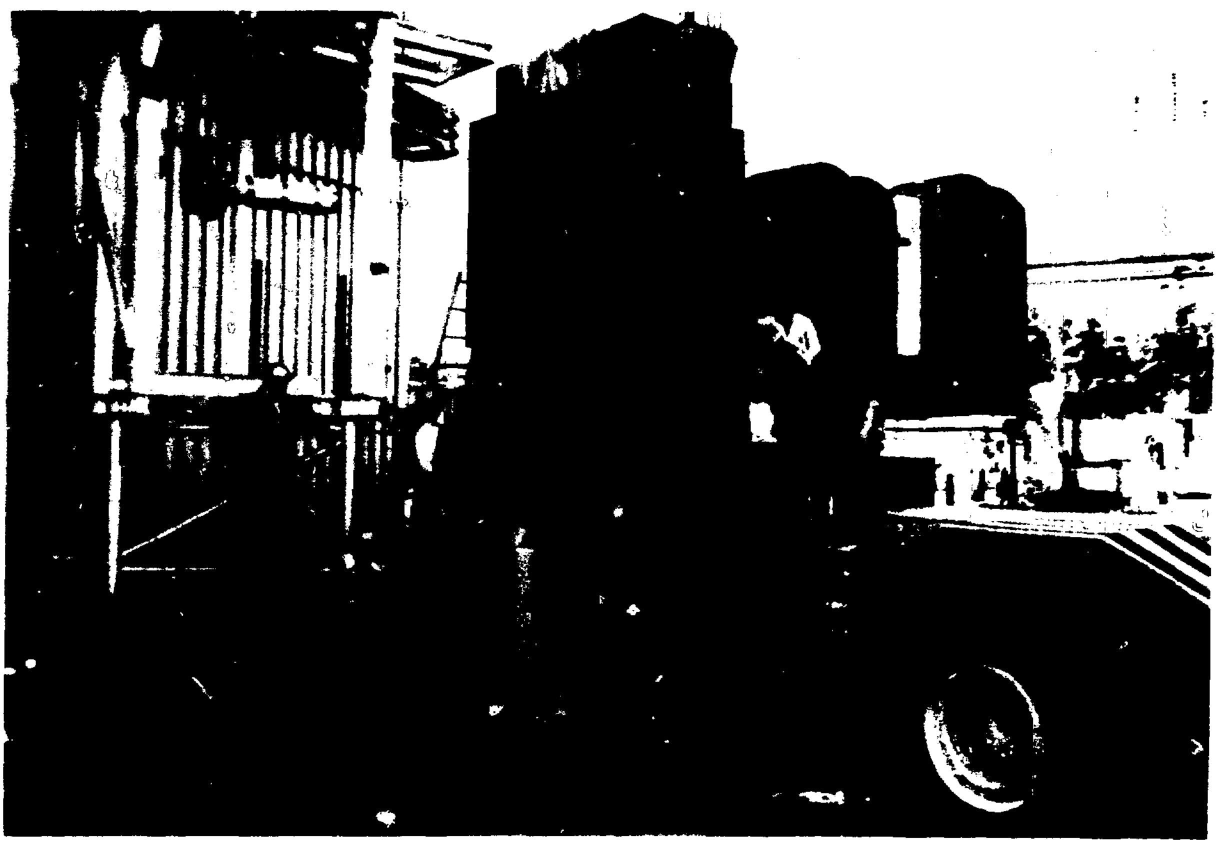


Figure 10. The framework of the apparatus with some of the major pieces of equipment is illustrated by this photograph taken during the construction outside of the AGS experimental halls. From the left the major pieces of equipment are the liquid hydrogen target, the electromagnet (covered with tarp) and two Cherenkov Counters. Many of the riggers, surveyors, technicians, engineers, and physicists involved with the experiment are here. Can you pick out the physicists?

event. The red lines indicate the individual wires which sensed a particle going by. Then a computer program connects these "hits" to determine the particle trajectories shown in green. The bend in the magnetic field is clearly seen.

Having gathered up all of this information on tens of millions of possible examples of exclusive scattering, we have to sort through and identify the few thousand actual cases. How do we do this? The most important quantities we measure are the energy and angles of particles emerging from the collision. As I mentioned earlier, I will display the results as if they had occurred in the head-on, center-of-mass system. For variety, I display an incident π^+, with a scattered π^+ identified by the Cherenkov tanks beyond the magnet (Figure 12). At the maximum limit of 2.1 GeV, we see the elastic scattering of π^+ on protons, that is, the incident and outgoing particles have the same energy. At lower energies we see the inclusive background rising up in a smooth fashion. Just below the peak corresponding to elastic scattering, there is an interesting shoulder, which when fit by a computer program, resolves itself into a second peak. The mass of the second peak at 1.23 GeV is the same as for the Δ^+ baryon. In addition to this second peak having the correct mass for the Δ^+, the side array detected an angular distribution of single particles, which correctly corresponded to the decays of the Δ^+. So this example illustrates how the apparatus can identify exclusive reactions by determining the mass of an unstable particle by a measurement of energy of the stable particle. This is the technique that we will use for many of the reactions.

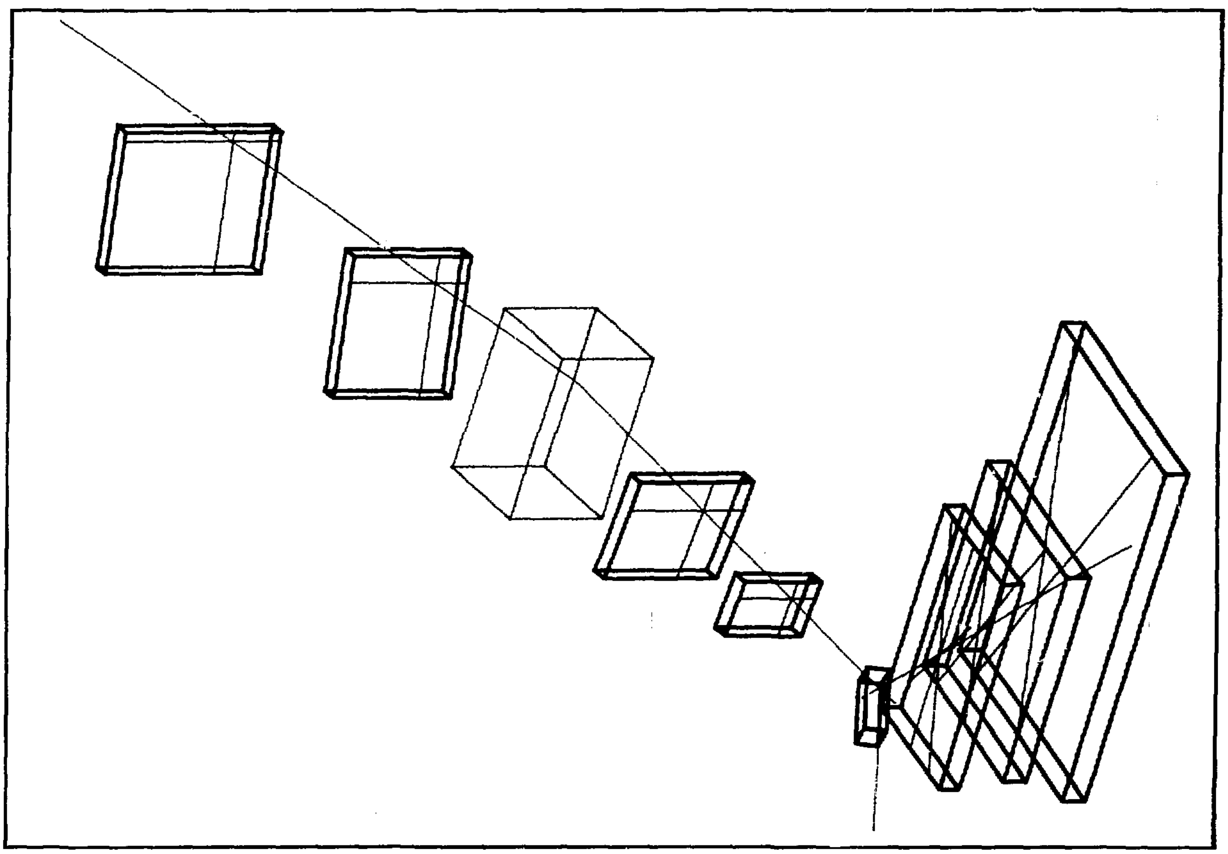


Figure 11. This computer reconstruction shows the trajectories of the particles from an elastic scattering event. The beam particle enters from the left and scatters to the right. The recoil proton from the hydrogen target traverses the magnetic spectrometer to its left. The wires which sense the passage of the particles are drawn in red, and the reconstructed particle trajectories are indicated by the green line.

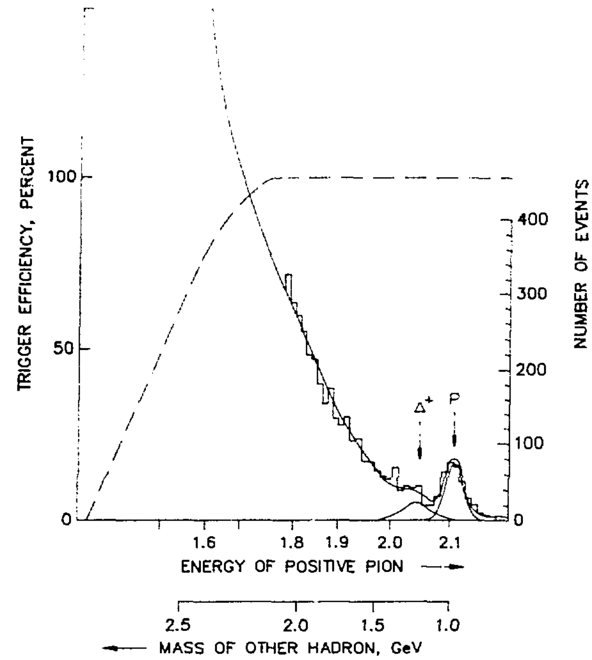


Figure 12. Plot of numbers of events versus the energy of pion measured by the magnet. The incident particle has also been identified as a pion. The measured pion energy can be used to deduce the mass of the other particle leaving the collision as shown in the lower scale. The jagged line indicates the actual number of events, while the solid, smooth curves are computer fit to the background, elastic peak (p) and the Δ^+ resonance. The dashed line is a representation of the efficiency of the electronic selection logic versus the energy of spectrometer pion. Only high energy particles near the exclusive limit are selected.

I mentioned that we had written on magnetic tapes the information about tens of millions of collisions. We had trillions occur in the hydrogen target. Most were lost because they simply were not pointed in the right direction and did not make it into the aperture of the magnet. The magnetic field bends many of the low energy particles sufficiently so that they do not get through the magnet. A further reduction of a 1000 in the number of events was required to avoid filling up our already crowded trailer with computer tapes. The technique was to make a very fast, one microsecond selection of wire correlations in the two wire chambers downstream of the magnet to pick only those events whose energies were close to the exclusive limit as determined by the bend angle. (See the trajectory labeled High E in Figure 8b.) This produced a cutoff in the spectrum shown in Figure 12.

For elastic events (those where the incident and outgoing particles are the same) there are two additional measurements which help in the selection. These are powerful constraints, and explain why most exclusive measurements in the past above 5 GeV only included elastic scattering. First there is the azimuthal opening angle. If there are only two outgoing particles, they have to lie in a plane. As shown in Figure 13, they do. The same thing can be done for the polar angle, that is, the angle in the plane of the scattering. Again they show a peak at 180°.

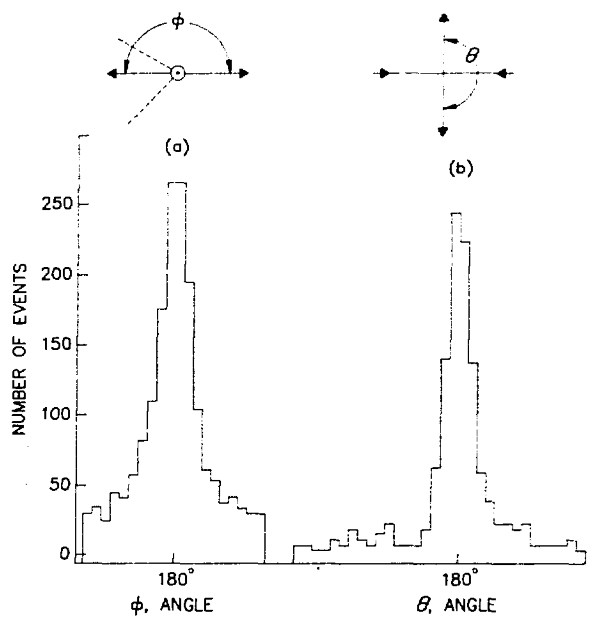


Figure 13. Two additional measurements which help to identify elastic scattering events. In the center-of-mass system, the particles have to emerge back-to-back (at 180°) with respect to one another. The presence of other particles (dotted lines in (a)) removes this correlation.

Smaller and Smaller

What is the result of our experimental measurement? We measure the number of particles emerging from an exclusive reaction which end up in a given angular region. Figure 14 shows a plot of such a number distribution for the elastic collision of negative pions (π^-) on protons from forward (0°) to backward (180°) at 10 GeV in lab energy. Note that we do not plot the angle, but the cosine of the angle. The reason we use the cosine of the angle is that if we imagine a sphere surrounding the center of the collision, then equal intervals in cosine of the angle correspond to equal areas on the sphere. So at random, uniform distribution of scattering angles would result in flat curve on the plot. Very low energy proton-proton (pp) scattering has this form.

Our experiment was at 90°. The number of elastic scattering events we measure are more than a million times smaller than the number for scattering at 0°. We descend into deep, dark canyons rather than ascending lofty mountain peaks.

If we look at the relative number of events for elastic scattering at one fixed large angle, say 90°, for a variety of energies, then an interesting pattern appears (Figure 15). Here we include data from a variety of experiments. These numbers are plotted on logarithmic scales. The numbers fall off extremely rapidly with increasing energy. For the elastic scattering of π^- on protons, if the energy is doubled, the probability of scattering to the same center-of-mass angle goes down by a factor of 256. A similar plot for the elastic scattering of protons on protons, shows an even steeper falloff with energy. If 1,024 events are detected at 10 GeV, then only one would be detected at 20 GeV. We say that it falls like $1/E^{10}$. This is a major reason why these experiments are not done at higher energies where our theoretical colleagues would prefer us to be.

What might be the reason for this rapid falloff with increasing energy? Since short distance QCD is a lot like QED, what is the corresponding law for scattering electrons and positrons? A plot was made for this reaction, and it falls like $1/E^2$, a factor of four for an increase in energy

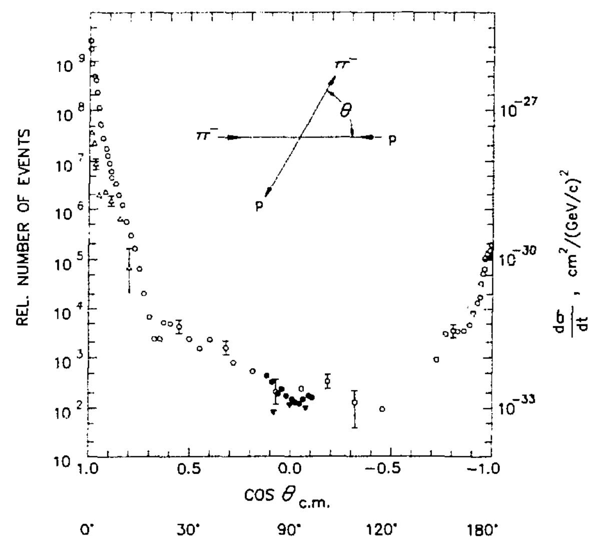


Figure 14. The relative number of π^-p elastic scattering events are plotted versus the cosine of the scattering angle, θ. The open circles are previous measurements, and the closed circles are our measurements near 90° in the center-of-mass. Note that the number of events falls by more than ten million between 0° scattering and 90° scattering. The open and closed triangles are measurements of the reaction $\pi^-p \rightarrow \rho^- p$, which has a similar magnitude. The closed triangles represent the first measurement of this reaction near 90° by our experiment. On the right, I have included the more conventional scale for physicists.

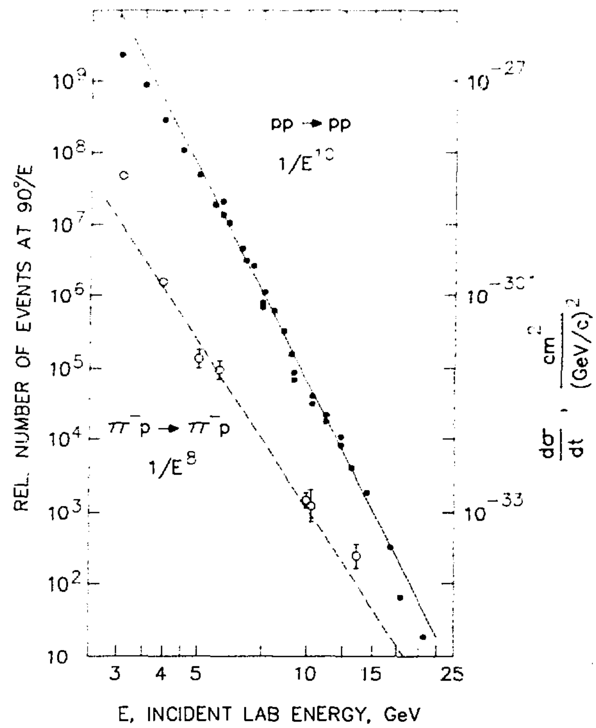


Figure 15. We plot the relative number of events scattered at 90° for π^-p (meson-baryon) and pp (baryon-baryon) elastic scattering. For every factor of 2 increase in energy for π^-p scattering the number of events falls by 256, whereas for pp scattering it is 1,024, which is indicative of dimensional scaling law of Brodsky and Farrar. Also, this very rapid falloff is the reason that these exclusive measurements have not been extended much beyond AGS energies.

by a factor of two. However, we are not dealing with the collision of just two quarks, but six quarks in the case of pp collisions.

The very rapid falloff of the number of events with increasing energy is described by a remarkable principle known as *dimensional scaling*. This principal, formulated by Stanley Brodsky and Glennys Farrar, states that the basic scattering process occurs as if the two hadrons were point particles interacting as in QED, provided that all the quarks within the hadrons are confined to a very small region of space. The reason that the number of events falls much faster than $1/E^2$, is due to the low probability for all the quarks to be within a small volume which decreases with increasing energy. In the case of hadron a colliding with hadron b to produce hadron c and hadron d, the rule is:

$$\text{Number} = K/E_{inc}^{(n_a + n_b + n_c + n_d - 2)}$$

where K is an arbitrary constant of proportionality and E_{inc} is the incident energy. Since n_a, n_b, n_c and n_d are the number of quarks in each hadron, we can count the number of quarks in the collision simply by observing the slope of the curve given in Figure 15. This interesting and useful rule was one of the factors motivating us to do these experiments. A consequence of this description is that the size of the hadron at the moment of collision is decreasing as the incident energy gets larger.

There is a clever way of experimentally checking whether protons and mesons which scatter at large angles get smaller and smaller with increasing energy. In fact, we have recently completed Experiment 834, which did this very thing this past winter. A more complete description of this experiment will have to await a future lecture, though, because of time limitations.

Follow That Quark

Up to this point we have looked at the general features of generic quarks as they undergo these violent collisions. Now we would like to follow the individual quarks so that we can learn about the mechanisms by which the hadrons interact with one another. From this we may be able to deduce some of the properties of the basic quark-quark interaction. An important feature of these exclusive reactions is that since we identify only two hadrons coming out of the collision, we have accounted for all of the quarks.

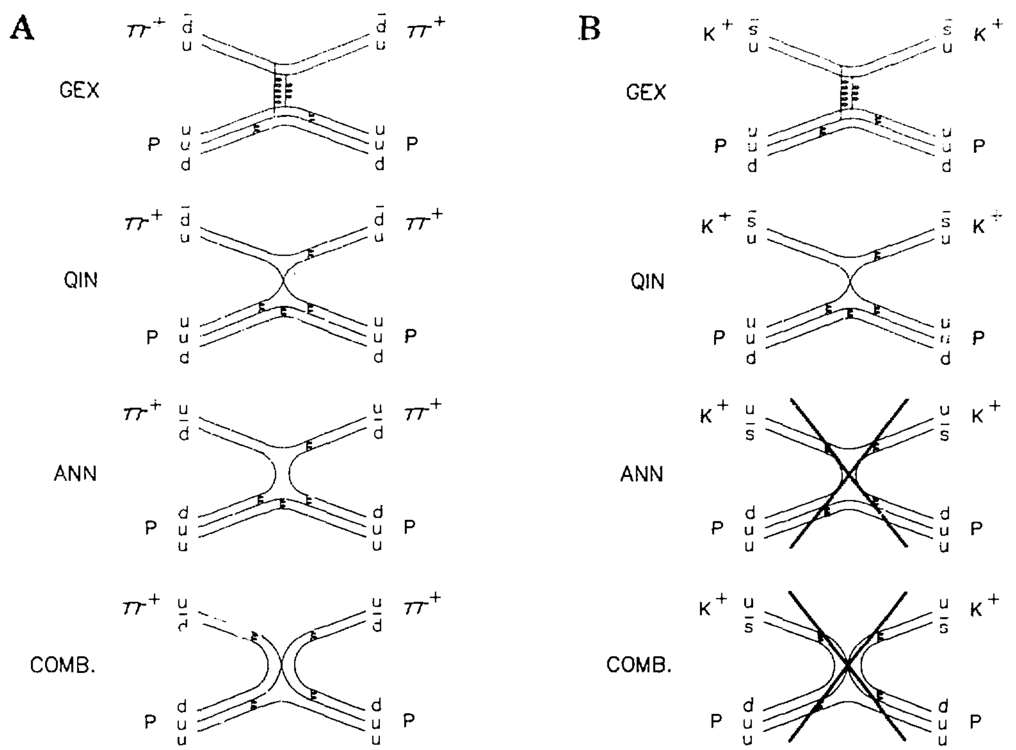
If we study mesons colliding with baryons in exclusive reactions, there are four basic diagrams which are important as shown in Figure 16a. In the diagram we have a quark-antiquark pair in the meson scattering from a triplet of quarks in the proton. In the gluon exchange diagram (GEX) there are only gluons passing from the meson to the baryon. There have to be at least two gluons because the meson and the baryon must remain color neutral after the collision. Since no quarks have been interchanged, the flavor of the meson and the baryon remain the same before and after.

The next diagram in Figure 16a involves quark interchange (QIN). A quark on the meson moves to the baryon, and a quark on the baryon takes its place in the meson. If the quarks have the same flavor, then experimentally we cannot distinguish this diagram from the gluon exchange. But if the flavors of the quarks exchanged are different, then the hadrons after the collisions will be different from that before. Note that the antiquark cannot be interchanged because then the baryon would cease to be a baryon.

The third diagram is called quark annihilation (ANN) because the antiquark in the meson annihilates with a quark in the baryon. Then a new quark-antiquark pair is created to reform a meson and a baryon. For this diagram, new flavor can appear in the outgoing meson and baryon which were not present in the incoming hadrons.

Finally, there is a combination of annihilation and interchange (COMB), which turns out to be very small in magnitude, and hence, can be neglected.

In Experiment 755 we measured or set upper limits for 11 meson-baryon reactions and for pp and $\bar{p}$p elastic scattering. For the six kinds of elastic scattering we use the three measurements of energy and two angles to clearly identify the various reactions. For incident kaons and antiprotons the determination is poorer because the associated beam contains only about one percent of these particles. The other reactions involve measuring the angle and energy of just one particle in the spectrometer and deducing the mass of the other unstable particle. These measurements are difficult to do



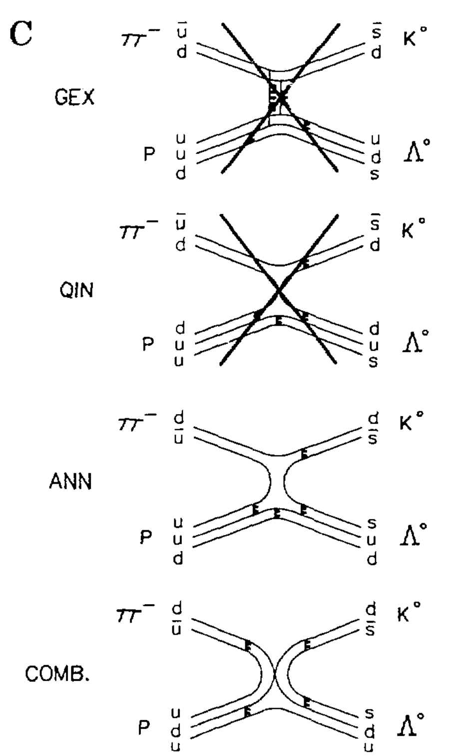


Figure 16A). The four types of quark diagrams which contribute to the scattering of mesons by baryons: gluon exchange (GEX), quark interchange (QIN), quark annihilation (ANN), and the combination of interchange and annihilation (COMB). The solid lines show the space-time development of the five quarks which are involved in the collision. The small loops show the minimum number (four) of gluons needed to transmit the force required to change the directions of the five quarks. All four diagrams can contribute to $\pi^+ p$ elastic scattering. B). For $K^+ p$ elastic scattering, only the GEX and QIN diagrams can contribute because the $\bar{s}$ quark cannot find a corresponding s quark with which to annihilate in the ANN and COMB diagrams. C). The GEX and QIN diagrams cannot contribute to the reaction $\pi^- p \rightarrow \Lambda^\circ K^\circ$ because the $u\bar{u}$ pair must annihilate and a $s\bar{s}$ pair created to form the pair of outgoing strange hadrons.

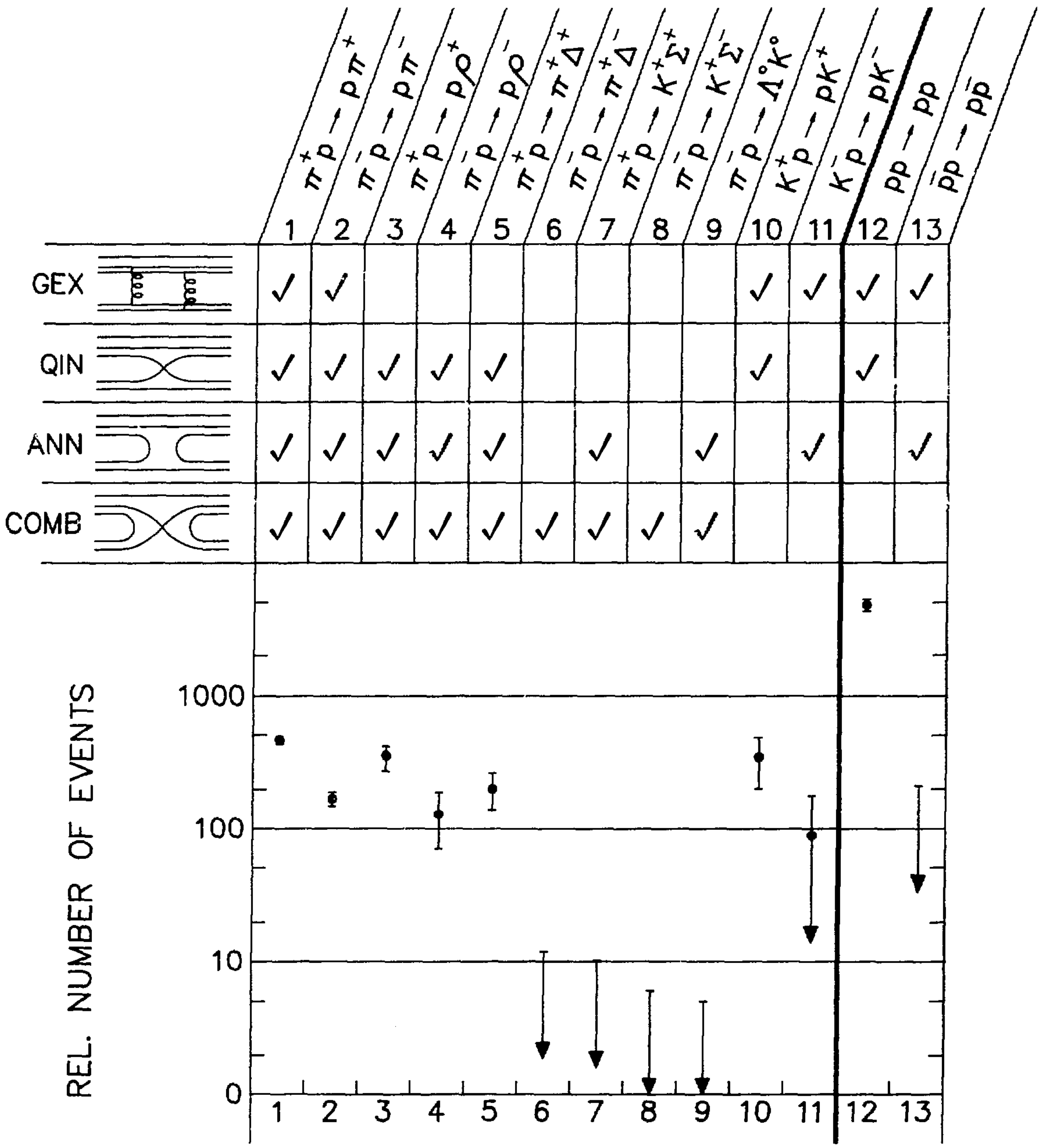


Figure 17. A summary of 13 reactions measured in this experiment. The reactions are listed at the top of the figure. In the middle section the check marks indicate which of the four types of quark diagrams can contribute to each of the reactions. For the baryon-baryon reactions (12) and (13), the quark diagrams have an additional quark added, but involve the same mechanisms. The relative number of events found for each reaction is found in the bottom part of the figure. The circles with cross bar indicate that this reaction was observed. The bar with an arrow pointing down means that no examples of this reaction were found, and only an upper limit corresponding to bar was set. The actual number is expected to lie somewhere between the bar and zero. The relative number of events for reactions with contributions only from ANN and COMB is small. The reactions with a large number of events measured all have QIN contributions independent of whether the GEX diagram can contribute. From this pattern we conclude that the QIN diagram is the dominate contributor.

and represent the first of their kind at these high energies.

Let us see how knowing these different reactions helps to sort out the mechanisms. Figure 16a shows that elastic scattering of pions and protons, $\pi^+p + \pi^+p$, can go via any of the four diagrams, so if we just did this elastic reaction, we would not be able to discriminate between any of the diagrams.

For the case of elastic scattering of K^+ on p shown in Figure 16b, the presence of the antistrange quark in the K^+, restricts us to just two diagrams. Since there are no s quarks in the proton with which this quark can annihilate, neither the annihilation or combination graphs can contribute. *This reaction is comparable in* size to π^+p elastic scattering. The reaction $\pi^-p + K^\circ\Lambda^\circ$ involves strange and antistrange quarks in the outgoing hadron which did not exist in the incoming hadrons (Figure 16c). So there had to be an annihilation and neither the gluon nor quark interchange can contribute. This reaction is at least 40 times smaller than the π^-p elastic.

The reaction $\pi^-p + \pi^+\Delta^-$ is an example in which only the combination type of diagram can contribute, since the charges on the meson and baryon change by two units. This reaction has a very small upper limit.

All this information is summarized in Figure 17. The reactions are listed across the top, and the relative numbers for these reactions at 90° at 10 GeV are shown at the bottom. The points with cross bars mean that we observed the cross section, and the bars with arrows pointing downward indicate that we did not observe the reaction to occur, but set an upper limit on the number. In the middle section, the four quark diagrams are shown, and it is indicated by check whether or not this diagram contributes to the reaction in that column.

A short scan of the chart indicates a remarkable regularity. Those reactions which can only occur via the ANN or COMB diagrams are very small. The reactions which have large number of events all have a contribution from the QIN independent of whether or not the GEX is present. With some simplifying assumptions, this chart can be fit by saying that the QIN is about three times greater than the GEX, which in turn is very much larger than either the ANN or COMB diagrams. This is a surprising and appealing simplicity.

We can look to other reactions to see whether this pattern persists. We can see that the $\bar{p}p$ is much smaller than the pp elastic scattering. Proton-proton and antiproton-proton scattering are similar to the meson-baryon collisions. Proton-proton collisions can go via GEX or QIN. Antiproton-proton collisions involve GEX or ANN. The antiproton scattering is much smaller than that of the proton. In QED, the ANN is smaller by a factor of four from the photon exchange. Probably the same mechanism operates here.

One would like to calculate these reaction probabilities from the basic equations of QCD. In principle, this is possible because the equations of QCD are known, and in this case they are not enormously complicated. But the equations are very long and very tedious because of the very large number of combinations of quarks, spins and different color—about 30,000 of them. But computers can do very long and tedious equations, especially if they are basically repetitive. In this case it is repetitious algebra. Researchers at Rutgers University are in the process of carrying out these calculations. When they are finished it will be interesting to see if they calculate the same underlying pattern that we see in our experiment.

Quitting Time

To finish, I will state a couple of conclusions. First, exclusive scattering of hadrons at large angles and moderately high energies appear to be a good place to study the interaction between quarks. The quark-quark collisions occur at short distances, and we have knowledge of all the quarks before and after the collision.

Second, our study of many different exclusive reactions indicates that the dominant mechanism for the scattering of hadrons is quark interchange. They would rather switch than annihilate!

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Alan S. Carroll earned his undergraduate degree in physics from Oberlin College. He completed his Ph.D. in physics in 1963 at Harvard University, where he was a National Science Predoctoral Fellow. From there he went to the Rutherford High Energy Laboratory in England. He came to Brookhaven National Laboratory (BNL) in 1965 as a physicist in the Physics Department, carrying out a number of experiments at the Alternating Gradient Synchroton (AGS) and Fermilab, connected with strong interactions and rare kaon decays. Since 1974 he has been a member of the Experimental Planning and Support Division of the AGS Department. There he is responsible for assisting universities and BNL groups with their research. Last February he was chairman of the BNL Neutrino Workshop.

Alan Carroll is married and has two children. His outside interests include bicycling, square dancing, traveling, and involvement with a local church. Arms control and other peace issues also are his important concerns.