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WHEN IS A PARTICLE?*

(THE RICHTMYER MEMORIAL LECTURE)

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Man's effort to understand what we are made of is one of the greatest adventure stories of the human race. It dates to the beginning of recorded history. Science first flourished twenty-five hundred years ago with the quest of the early Greek philosophers for an underlying unity to the rich diversity observed in the world around them. They realized that the search for an understanding of Nature at a fundamental level in terms of basic processes and constituents necessarily carried them beyond the sensory world of appearance. In his essay on Lucretius, George Santayana described the emergence of this idea that *"all we observe about us, and ourselves also, may be but passing forms of a permanent substance"* as one of mankind's greatest thoughts. We now recognize it as the original search, in its most primitive form, for nature's conservation laws and elementary particles. However the early Greek metaphysicists predated by two millenia the modern scientific method with its insistence on experimental observation. In their inquiry they relied purely on rational analysis freed from the discipline of direct observational content. Not surprisingly, therefore, they went off in widely differing directions in their studies - Leucippus and Democritus to the concept of indivisible atoms; Anaxagoras to the original bootstrap model of infinitely divisible seeds within seeds, each as complex as the whole; and Anaximander, Pythagoras, and Plato to more abstract mathematical concepts of numbers and symmetries.

On occasion since then scientists have arrogantly alleged that the end of this search for nature's basic building blocks is in sight. However such delusions have been short lived, especially in modern times, crumbling midst the debris emerging from increasingly powerful atom smashers. We have come to

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appreciate how much richer Nature's imagination is than is our own vision of what lies beyond the next frontier as we explore with ever more powerful and sensitive instruments on ever shrinking space-time scales. This is particularly true at present after three explosive years of remarkable discoveries of new particles starting with the J/ψ in November 1974. Since this is the first Richtmyer lecture to address the field of elementary particle physics since those discoveries I will explore what has happened to our concept of elementary constituents - or ultimate building blocks - of Nature in recent years.

During the past two decades we have come to the point of accepting into the exclusive family of elementary particles a guest who would not have made the Social Register of an earlier generation. I am, of course, speaking of the quarks which were introduced in 1964 independently by Murray Gell-Mann and George Zweig[1] in an effort to summarize and systematize the great proliferation of nuclear particles that were being produced by accelerators on the high energy frontiers of the 1950's. Regularities were perceived in the masses of these particles as well as in the characteristics of their creation, their interactions, and their decays. Gell-Mann and Zweig showed that these regularities, as well as new ones found later, could be accounted for in terms of the simple motions and interactions of just three different kinds of fractionally charged spin 1/2 quarks. The quantum numbers of these quarks are shown in Figure 1. Several hundred hadronic resonances are successfully interpreted as excited states of just two simple quark configurations: three quarks forming baryons and a quark-antiquark pair forming mesons.

Since the quark hypothesis made correct predictions of new observations as well as providing a systematic organization of a large mass of data, and since it also brought simplicity plus a unifying harmony to our view of nature, the concept of quarks was a crucial step forward more than a decade ago, similar in many ways to the discovery of the nuclear atom by Ernest Rutherford in 1911. The role of quarks in subnuclear spectroscopy is similar to that of electrons in atomic spectra and of neutrons and protons in nuclear spectra. What is new, however, is that in contrast to both our atomic and nuclear experience we do not "see" the individual quarks isolated from one another. When we break apart, or ionize, an atom its electrons and its nucleus are clearly evident and are detected in the debris. The same is true when we identify individual protons and neutrons in the debris stripped away in nuclear collisions. How then do we account for our failure to see quarks in the debris of a shattered proton or of any other subnuclear particle? What does this unprecedented experimental situation do to our very concept of elementary particle? Indeed, when we now ask what we mean by an elementary particle, we can feel a certain kinship with the modern poet who asks *"When is a poem?"*. Modern poetry clearly no longer lives by rigid rules of meter and rhyme - and many times even, or should I say especially, the meaning is obscure. As Archibald MacLeish wrote in his poem "Ars Poetica":

"A poem should not mean
But be."

How do we scientists now respond to the question *"When is a particle?"*

In order to appreciate how far we have moved in our modern concept of elementary particles we need look back only to 1930 and the birth of the neutrino. On the historical scale of time this is less than 2% of the way back to the earliest Greek metaphysicists of 2500 years ago, but our concepts of *"When is a particle?"* have evolved considerably during this relatively brief period. Before the neutrino could fully establish its credentials as a socially respectable elementary particle in the 1930's and 1940's many physicists insisted on seeing it carry away both energy and momentum in proper proportion during beta decay. More conservatively some insisted on being able to observe its arrival. In today's world of quarks we have apparently discarded such requirements as a standard against which to test the concept of particle. Indeed according to current dogma we never can nor shall observe isolated quarks or record the emission and absorption of individual quarks. How and why have we come to such a revolutionary new perception of elementary particles? By way of contrast recall first the story of the neutrino.

The neutrino idea was born in 1930 following the accumulation of experimental evidence[2] from the microcalorimetric measurements of the average energy of beta particles from RaE. This evidence showed that the average energy of disintegration in the decay equaled the mean energy of the continuous beta spectrum, rather than its upper limit, and that furthermore there was no appreciable accompanying gamma radiation. Physicists knew that they were confronted with something very puzzling. Pauli, who had closely followed these experiments with great interest, was convinced that the calorimetric results were very conclusive and most significant. In an open letter to Geiger and Meitner who were attending a meeting in Tubingen in December of 1930, Pauli pointed out that in beta decay not only was the energy apparently not conserved, but also the spin and the statistics were not conserved. There is a missing half-integer of angular momentum in beta decay if the beta particle is the only particle emitted. Incidentally, at this same time an understanding of the spins and statistics of nuclei based on the fledgling quantum theory provided a strong argument against the then current hypothesis that the fundamental constituents of nuclei were protons and electrons. For example, in those days prior to the discovery of the neutron how could one explain Bose statistics for N^{14} if its basic building blocks were in fact 14 protons and 7 electrons! Emphasizing the importance of considering spin and statistics, Pauli went on to propose the then outlandish idea of introducing a very penetrating, new neutral particle of vanishingly small mass in beta decay to save the situation. However, as described by C. S. Wu[2] in her fascinating account prepared as a memorial tribute to Pauli, "*....he was most modest and conciliatory in his pleading for a hearing.*" Admitting that his remedy might appear an unlikely one, Pauli commented in his letter:

> *"Nothing venture, nothing win. And the gravity of the situation with regard to the continuous beta spectrum is illuminated by a pronouncement of my respected predecessor in office, Herr Debye, who recently said to me in Brussels, 'Oh, it is best not to think about it at all....like the new taxes.' One ought therefore to discuss seriously every avenue of rescue. So, dear radioactive folks, put it to the test and judge."*

Pauli made public his proposal of this strange new particle at the American Physical Society meeting in Pasadena in June 1931. Insisting on the validity of the conservation laws in beta decay, Pauli proposed that the emission of beta particles occurred together with the emission of a very penetrating radiation of neutral particles, which as yet had not been observed. He insisted that the sum of the energies of the beta particle and the neutral particle (or particles) emitted by the nucleus in one process should equal the energy which corresponds to the upper limit of the beta spectrum. In addition to the conservation of energy, Pauli assumed that linear momentum, angular momentum, and statistics are also conserved in all elementary processes.

In his reverence for conservation laws Pauli adopted a very different approach from Niels Bohr, who had suggested some years earlier that energy and momentum may be conserved only statistically and not in individual nuclear processes. Let me quote here from Bohr's 1930 Faraday Lecture:[3]

> *"At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations, and are even led to complications and difficulties in trying to do so."*

After conceding some difficulties in so radical a departure from the principle of energy conservation, particularly with regard to time reversal, Bohr remarked,

> *"Just as the account of those aspects of atomic constitution essential for the explanation of the ordinary physical and chemical properties of matter implies a renunciation of the classical ideal of causality, the features of atomic stability, still deeper-lying, responsible for the existence and the properties of atomic nuclei, may force us to renounce the very idea of energy balance."*

From our present perspective, the radical Pauli with his insistence on maintaining conservation laws, even at the expense of introducing a new and invisible particle, was really the conservative in his approach. However, this hypothesis of a new undetectable particle met with skepticism, as it was too radical for most physicists to accept with ease. Indeed the radical Pauli was in fact so conservative that he did not publish this proposal. Only after the discovery of neutrons in 1932 by Chadwick[4] and the consequent collapse of the proton-electron picture of nuclei did Pauli put aside whatever reservations he might have previously had about his neutrino hypothesis.

At the Solvay Congress in 1933 Pauli correctly conjectured the neutrino to be a massless, spin 1/2 fermion with a penetrating power far greater than that of photons of the same energy. He did this because of conservation laws and in spite of the fact, as he noted, "*....that experiments do not provide us with any direct proof of this hypothesis*", and furthermore "*we don't know anything about the interaction of neutrinos with other material particles and with photons.*" Pauli also argued forcefully against Bohr:

> "*The interpretation supported by Bohr admits that the laws of conservation of energy and momentum do not hold when one deals with a nuclear process where light particles play an essential part. This hypothesis does not seem to me either satisfying or even plausible. In the first place the electric charge is conserved in the process, and I don't see why conservation of charge would be more fundamental than conservation of energy and momentum.*"

Pauli also emphasized the crucial importance of investigating the relation between the energy and momentum carried away by the neutrino by means of sensitive measurements of the nuclear recoil.

> "*....the experimental study of the momentum difference in beta disintegrations constitutes an extremely important problem; one can predict that the difficulties will be quite insurmountable because of the smallness of the energy of the recoil nucleus.*"

Shortly after the close of the discussions at the Solvay Congress Fermi[5] gave a quantitative formulation of the neutrino hypothesis, and from 1934 on this hypothesis gained enormous strength from its successful predictions of the energy spectrum and of the angular momentum selection rules in beta processes. However, the evidence for the neutrino was still indirect and would remain so for more than 20 years until it was directly observed as a particle. Recall that until the advent of the nuclear reactor there were no intense neutrino sources. As a result, even though all observations and predictions were as if the neutrino were emitted in beta decay, one could still adopt the agnostic stance of weak faith and worry that nature was simply fooling us. We could invent the neutrino, but did we actually <u>need</u> it? Could we do without it?

I remember the reality of such questions when I entered graduate school at the University of Illinois in Urbana and was witness to the first of the series of delicate and ingenious measurements of the nuclear recoils[6] in beta decay that Chalmers Sherwin initiated in 1947. These were the measurements that Pauli had judged to be insurmountably difficult at the Solvay Congress in 1933 but which Sherwin accomplished using a thin film source of radioactive ^{32}P and time-of-flight techniques with then "fast" electronics. He clearly demonstrated that the ratio of the missing energy to momentum was given approximately by the velocity of light. Hence within the errors of his measurements the neutrino was, if it indeed existed at all, behaving kinematically as a massless particle.

By then there was in fact little if any doubt about the neutrino, and skepticism on this score was hardly stylish. But I remember vividly a physics colloquium debate in 1948 between Maurice Goldhaber and Sid Dancoff on whether the neutrino really existed. With a conservative logic that, in these days of confined quarks, seems downright reactionary, Goldhaber advised caution, even in the light of Sherwin's results, and emphasized the importance of looking for evidence of neutrino absorption. After all, we may see it disappear but before all disbelief or doubts can be removed he advised that we should see the neutrino arrive and hit us over the head - this was the ultimate litmus test for the full respectability of an elementary particle. To which Dancoff replied, in the spirit of the logical positivist, that we had a respectable wave function, a dignified Dirac wave equation, and the unambiguous principles of quantum theory for describing, predicting, and analyzing neutrinos in beta processes. What more did we need? The neutrino was in fact no less respectable than, say, the proton! Of course, no skeptics whatsoever remained eight years later, in 1956, when C. Cowan and F. Reines[7] used a powerful nuclear reactor as an intense neutrino source and observed its effects. The importance attached by some to being able to detect the arrival as well as the departure of neutrinos is reflected in the 1963 edition of the Encyclopedia Britannica:

"Were it not for the quite convincing experimental evidence of their existence by F. Reines and C. L. Cowan of Los Alamos, New Mexico, and others, one might regard neutrinos as the necessary but undetectable scapegoats whose subtle function was to permit the application of conservation of energy and momentum to atomic reactions."

I have sketched this history of the neutrino and its development from a radical idea to a respectable particle in order to contrast and compare it with the current quark theory and dogma. Where do we stand now with the quarks? On one hand, we still lack conclusive evidence of ever having "seen" isolated quarks in the laboratory, in spite of many efforts to find them.[8] On the other hand, shouldn't we insist on seeing them if they are indeed the building blocks of the proton? Isn't such observation required in the spirit of the modern scientific method, with its primary aim and its central goal, as characterized by Helmholtz[9] in paying tribute to Faraday and his work, "....*to purify science from the last remnants of metaphysics*."?

Early in this century the remarkable art of experimentation developed to the extent that it was possible to study the properties of individual atoms. As a result of this fantastic sensitivity of measurement our entire conception of "seeing" underwent revolutionary changes. On the atomic frontier the most profound and radical change occurred when it was realized that it is necessary to take into account the effect of the observation itself on the physical system being observed. This fundamental limitation of the measurement process led to a major revolution in our concept of the elementary particle, driving us beyond classical ideas alone to a quantum description. But there is no uncertainty in what is meant when we say that we observe an electron as an elementary particle. Now that we have come upon the quarks, however, the situation today is very different. Are they objects whose existence can be inferred only from the properties of larger, complex structures such as a proton in which they are the constituents confined to one another by unbreakable bonds? If quarks are indeed not observed singly or in isolation and if they never get beyond being the *"undetectable scapegoats"* of the Encyclopedia Britannica phrase, will we still attach so central and fundamental an importance to them, or even to the elementary particle concept itself?

For the quarks to survive as fundamental there are two possibilities. The first is that they will be discovered, i.e., they will be observed singly. In this case they presumably will constitute the atoms of yet another layer of matter, with an internal structure of their own to be studied by another generation to come. The second alternative is that they will not be discovered in the same sense as the neutrino was, but that they will persist in fulfilling the goal that motivated their being introduced in the first place - i.e., they will provide a simple basis for explaining the observed multiplet structure and properties of subnuclear particles. We know that there exist simple general laws in terms of which the rich diversity of Nature can be explained. This is our fundamental faith as scientists. If the quarks are indeed not observed directly, their survival as vital ingredients in the structure of matter will depend on how successful the quark idea is in unifying, simplifying, and correctly predicting diverse observations, and thereby leading us to such general laws. At least from today's perspective, the quarks seem to have done enough for particle physics that there is little danger of their fading away with the aether. In brief, what is the evidence most strongly supporting quarks?

The original quark idea was put forward to explain why baryons occur with the observed multiplet structure of an octet of spin 1/2 and a decuplet of spin 3/2, and why mesons form nonets of spin zero or one. General features of the hadronic mass spectra, their transition matrix elements and static properties such as baryon magnetic moments, could be understood in terms of their quark content; i.e., three quarks for baryons and a quark-antiquark pair for mesons. What emerged was an intuitively simple picture of relatively light point-like quark constituents moving approximately as independent particles within a hadron.

One had to pay a price for these successes. At the very outset it was realized that a successful classification scheme for the three-quark baryonic spectra required that the quarks be assigned to symmetric configurations. This was in apparent violation of the heretofore sacred relation between spin and statistics which requires half integral spin particles such as quarks to be in antisymmetric configurations. The way out of this dilemma was to assign to the quarks a new quantum number, colloquially dubbed color,[10] which could take on any one of three values, and to require the baryon wave functions to be antisymmetric in color. Effectively this triples the number of quarks and is thus reminiscent of Pauli's original proposal for the neutrino. He also introduced a new particle, in part, in order to satisfy the requirements of statistics in beta decay. The added quantum number of color introduces the possibility of many additional but unobserved states corresponding to hadrons of different colors. In order to remove this difficulty we must insist that the three quarks forming a baryon are in an antisymmetric color singlet state. Similarly the quark-antiquark pair composing a meson must form an anticolor pair, with each color occurring in equal parts. All other hadronic states which fail to hide their color in this way are ruled out. An explanation of why nature is color-blind is fundamental to a complete theory of quarks. Although a theoretical derivation of color-blindness still remains to be given, one can correctly and simply describe the observed spectra with no unwanted states by insisting that color remain Nature's secret.

The existence of point-like constituents within the hadron also provided a basis for understanding the observed character of hard, very inelastic high energy collisions between two hadrons or between a hadron and an electron, a neutrino, or a muon. The nature of the observed scattering patterns between an electron and a proton, for example, required the existence of strong local electromagnetic currents within the proton - i.e., of point-like constituents which were presumably the quarks.[11] They played the same role as the nucleus in Rutherford scattering. Large angle electron scattering from atoms in the 100 KeV energy range looks like scattering from a point nucleus whose total charge it measures. Large angle scattering from nuclei in the 100 MeV energy range looks like scattering from point protons of unit charge. In the same way the very inelastic collisions of electrons of energies above a few thousand MeV with nucleons revealed point-like quarks of fractional charge. The analysis of this process showed again that these hadrons were behaving as structures built of weakly interacting and relatively light point-like quarks. Specifically, the constituents of the proton scattered the high energy incoming electrons in high momentum transfer collisions as if they themselves had no inner structure, or form factor, and as if they were relatively light and essentially unbound. Further confirmation of this picture - referred to as Bjorken scaling - as well as a detailed mapping of the quark wave functions has also been obtained from the deep inelastic scattering of neutrinos and muons from hadrons.[12]

The high-energy inelastic scattering measurements further emphasize the enigma of unobserved quarks. We resort to quark constituents for the most direct and simple interpretation of the observed scattering pattern. However the proton or neutron, smashed hard and shattered into bits and pieces in the collision, does not spill out quarks in its debris - just other normal hadronic states of mesons and baryons in accord with all the known conservation laws.

Unquestionably the most important recent evidence that decisively supports the quark picture was provided by the new discoveries of charmed matter, beginning with the J/ψ particle little more than three years ago.[13] The J/ψ sent an explosive shock through the scientific community because, on the subnuclear scale of times, it was an almost stable very narrow resonance that could not be accommodated in the existing quark scheme. These properties differentiated it from the hundreds of other hadronic resonances whose decay widths are typically 10's to 100's of MeV unless they are suppressed by selection rules. The J/ψ, however, was determined to have a total decay width of only 70 KeV for a mass of 3095 MeV. Evidently there was a selection rule operating in order to account for the narrowness of this state. Since the new particle is heavy - weighing more than three times as much as the proton - there is no inhibition in its decay due to threshold effects or lack of phase space. Hence the suppression of its decay cannot be explained on kinematic grounds alone. Moreover the measured quantum numbers of the J/ψ are quite conventional: zero charge, one unit of angular momentum, and zero strangeness - just like the photon which is its source in electron-positron annihilation. Also its decay products are familiar particles - predominantly electrons, muons, and pions. Therefore the narrowness of the J/ψ could not be explained in terms of a selection rule corresponding to the conservation of known quantum numbers. What then was holding it together for such a long time - about a thousand to ten thousand times longer than expected? A new quantum number was required above and beyond what could be accommodated in the three quark scheme that was now found to be too restrictive. This new quantum number had been previously dubbed "charm" by James Bjorken and Sheldon Glashow. Indeed the existence of a fourth quark with "charm" was anticipated by Glashow and colleagues[14] for several years as a simple and natural way of theoretically suppressing unobserved weak decays which involved a change of strangeness but not of electrical charge between the interacting particles. The easiest way to account for the J/ψ and its long lifetime was to assume it to be a meson made up of a massive new charmed quark bound to its antiparticle. This is illustrated in Figure 2.

The value and beauty of such a simple model lies in its predictive power and successes. For this model they have been extensive. And although the new discoveries were a shocking surprise they are now recognized as contributing importantly to the impressive successes of the quark hypothesis. In the decade preceding these new discoveries it had been established that every known hadron could be explained as a combination of a quark and an antiquark for the mesons and of three quarks for the baryons. Moreover all possible combinations of these three ordinary quarks correspond to a known hadron, without fail. Figure 3 shows the baryonic zoo as of two years ago. With the discovery of the new particle and its interpretation in terms of the theoretically anticipated fourth, or charmed, quark there was a whole new set of spectroscopic levels to hunt for and interpret. In particular one should observe a complete spectrum of charmonium[13] - i.e., of the bound states of a charmed quark-antiquark pair. This is analogous to positronium with its spectrum of excited states. In fact the next two figures show how far we have advanced already with charmonium spectroscopy. Figure 6 shows the fine-structure splitting of positronium for the n = 2 levels for comparison. The n = 1 level is much further down, separated by Ry relative to the fine structure of order α^2Ry. The energy spacings and branching ratios in charmonium can be understood qualitatively in terms of the binding of heavy quark-antiquark pairs. Detailed analyses of the fine structure reveal information of the shape of their interaction potential. Furthermore there will be new mesonic states formed when a charmed quark binds with an ordinary uncharmed antiquark as shown in Figure 7. These too - the D mesons -

have been observed and fit into the four-quark SU(4) classification. Already there are starts toward the spectroscopy of a charmed quark bound to a strange antiquark, the so-called F meson, and toward the spectroscopy of charmed baryons.

Another very important parameter for the quark hypothesis is the ratio of the cross section for an electron-positron pair to annihilate to hadrons, summed over all configurations, to the cross section to annihilate to a pair of muons, illustrated by Figure 8. Muons like electrons are point-like members of that other family of particles known as leptons - that is particles that do not experience the strong nuclear forces at all. The muons are charged and, of course, interact through the well-tested and well-understood electromagnetic forces. In this context the weak forces are negligible. When the electron and positron annihilate to form hadrons at high energy we believe that a single quark-antiquark pair is the intermediary even though the quarks themselves do not appear in the final states. If the quarks are point-like their contribution should exhibit the same energy dependence as found in pair production of point-like muons and the ratio of cross sections should measure the sum of the squares of the quark charges as well as being approximately energy independent.

Figure 9 shows[13] the measured ratio and adds considerable support to the quark picture by showing two regions of approximate constancy of R. In the lower energy region between 1.5 and 3.1 GeV, i.e., above the individual resonances, but below the onset of the new physics, there is a plateau with $R \approx 2\frac{1}{2}$ Above the charmonium region from 5-8 GeV the plateau rises to $R \approx 5$. The 4-5 GeV region is very rich with new physics associated with the creation of charmed particles as well as of pairs of a very likely new heavy lepton, the tau of mass 1.8 GeV. These values of R provide clues of the greatest importance about the nature and properties of the quarks. As illustrated, they are close to what one predicts for three varieties, or so-called flavors, of quarks below the region in which charm is excited, and for the four flavors including the charmed quarks in the higher energy region, provided each flavor occurs in three colors. Otherwise, without color, there would be a sharp discrepancy of a factor of three. These results thus represent a triumph for the hypothesis of color triplets of quarks. Evidently on a descriptive level the quark hypothesis very well accounts for a broad set of observations. Furthermore does anyone seriously doubt that R will increase onto a higher plateau when the total energy of the colliding electrons and positrons exceeds 9.4 GeV, the threshold for producing the upsilon meson recently discovered at Fermilab? The upsilon is believed to be a bound quark-antiquark pair like charmonium but built of yet another new flavor of quark pairs.

By now we have had such a proliferation of quark degrees of freedom - presumably at least five flavors times three colors, or fifteen - that it can hardly be said they they are entering a very exclusive Social Register!

Looking back once more to the 1930's the neutrino became a strong, and to most a persuasive, candidate for the Social Register of elementary particles long before it was seen, when Fermi provided it with effective and indisputable theoretical credentials. There is optimism, at least among many theorists, that quarks have also been gaining the dignity of a pedigree during the past few years. The reason for this optimism is recent theoretical progress that has identified important features of a successful quark dynamics in a well defined class of quantum field theories known as non-abelian gauge theories.[10, 15] These are a generalization of the precisely tested and unfailingly successful theory of quantum electrodynamics. The photons, which are the vector quanta of QED, are themselves electrically neutral. This is characteristic of an abelian gauge theory. A non-abelian gauge theory represents the generalization of QED, as pioneered in 1954 by C. N. Yang and R. L. Mills, to a theory with vector quanta - colloquially dubbed gluons - which themselves carry the charge. The gluons can exchange this charge between sources, or among themselves. The color quantum number plays the same role in the theory of quarks and gluons known as quantum chromodynamics, or QCD, as does the electric charge in QED. In QCD an octet family of colored gluons replaces the single photon of QED as the messenger of the color electric and magnetic fields.

The case for QCD, pioneered in 1973 by H. D. Politzer and by D. Gross and F. Wilczek, is based on the crucial observation that such theories can lead to forces between the quarks, as mediated by the gluons, that grow weaker at short distances. This behavior is known as "asymptotic freedom". As illustrated in Figure 10, it is in contrast to the familiar forces of electromagnetism which grow even stronger than the $1/r^2$ of the Coulomb law at short distances when quantum effects - in particular vacuum polarization - are included. Asymptotically free forces between quarks provide a basis for explaining the observed behavior of the hard collisions, such as Bjorken scaling, which look like scattering from almost free, point-like light quarks within the hadrons. These forces must remain in effect for large separations, however, so that the quarks which behave as almost free at short distances on the scale of hadronic sizes will be confined and cannot be pulled apart. Furthermore, the theory must allow only color singlet states to form in order to account for the observed spectra and quark structure of hadrons. In QCD the simplest quark configurations that can form color singlet states are just the observed ones with three quarks or a quark-antiquark pair.

In the framework of QCD quark confinement becomes synonymous with color confinement. Color confinement is the other basic ingredient in addition to asymptotic freedom that we want to find in QCD if it is to form the basis of a fundamental dynamical theory of hadrons in terms of gluons and quark constituents. The theoretical challenge to prove whether or not QCD actually confines is formidable because of the difficulty in solving - or even attempting to solve - quantum field theory without resorting to weak coupling perturbative treatments. Although forms of perturbation theory are applicable in studying the short distance behavior of QCD where the forces grow weak and the quarks are "asymptotically free," such methods are not applicable in the large distance region of strong forces and confinement. The technical challenges of trying to construct a convincing proof of confinement have driven many particle theorists to learn the methods of our more sophisticated bretheren of statistical mechanics and solid state theory as we work on lattices and learn about phase transitions and other critical phenomena.

With an appropriate dash of the theorists' optimism, let us suppose for a moment that these technical challenges will be surmounted and a convincing case made for color confinement in QCD. We may even further imagine that approximately correct mass spectra will be calculated for the hadrons; this includes understanding why the pion is much lighter than all other hadrons. How compelling will this make the case for quarks as elementary fundamental constituents of the hadron?

Relative to the neutrino back in 1934 following the Fermi theory, the case for quarks might appear more compelling because we see all the elements of a grand synthesis in place. The quantum chromodynamics to which we have turned for a theory of hadrons is a non-abelian local gauge theory of the same formal structure that has also been introduced in unifying the weak and electromagnetic interactions. Steve Weinberg discussed this in his Richtmyer lecture four years ago. The strong, the electromagnetic, and the weak interactions have very different characteristics, such as their ranges and strengths, as studied at present laboratory energies. It has been conjectured,[16] starting with the pioneering work in 1967 of S. Weinberg and A. Salam, that the difference between the weak and electromagnetic interactions is a consequence of a partially broken symmetry for the weak processes. Due to the symmetry breaking the intermediate vector mesons of the weak interactions acquire a large mass, and only at truly high energies exceeding these masses, which are thought to be in the range of 70 GeV or higher, will the common characteristics of the weak and electromagnetic interactions be apparent. Some of the predictions of this approach to a unified theory of weak and electromagnetic processes have already been verified; in particular, neutral current effects in neutrino scattering.

A further extension of the same symmetry considerations underlying the gauge theories to the strong interactions puts the quarks in terms of which these theories are formulated on the same basis as the leptons. The difference between quarks and leptons derives from the fact that quarks carry the color quantum number which is the charge of the strong interactions whereas leptons do not and are immune to the strong forces. Hence leptons, in contrast to quarks, are not confined by the requirement that color remain Nature's secret. Such a picture is very attractive. It provides a giant step toward one of the principal goals of modern physics - i.e., a unified understanding of all the basic interactions in Nature.

Were we to achieve such a theoretical synthesis the case for quarks being admitted to the Social Register as the hadron's basic constituents would clearly be very strong. Nevertheless, referring to our earlier discussion of the neutrino, do we care or does it matter that we are now identifying as our fundamental hadronic constituents things that, in contrast to all our prior experience, cannot even in principle be isolated and observed? In other words, when <u>is</u> a particle? Are we now willing to say, as a variation of Archibald MacLeish's lines, that in contrast to a poem a particle need not be, but should mean?

The burden of proof for quarks is very different from the original argument for the neutrino. Whereas the neutrino was postulated in order to protect conservation laws through their observable space-time properties of energy, momentum, and spin, no conservation laws <u>require</u> quarks. However the quarks present very strong operational credentials - both real experimental ones and theoretical ones still in the making as I have described.

What troubles me most about accepting quarks as the fundamental hadronic constituents is quite simple and has nothing to do with their confinement and Helmholtz's dictum "*to purify physics from the last remnants of metaphysics.*" It is that we have already come up with so many quark degrees of freedom - at least five flavors in each of three colors. The social register of particles must surely be more exclusive than that if it is to be valued and honored as it was in those good old days!

Having said this, I have a sneaky suspicion that quarks may turn out to be somewhat like magnetic poles, and nothing more.[17] When broken in two, a bar magnet becomes not isolated north and south poles separated from one another, but two magnets each with its own north and south poles. As many have noted, this is very similar to what happens when a meson made of a quark and an anti-quark is smashed apart as shown in Figure 11. The debris of the shattered meson consists not of isolated quarks but of more mesons, each with its own quark and antiquark. This is not a literal analogy, of course, because the non-abelian color gauge theory also allows baryons made of three quarks to be formed in color singlet states. Nevertheless the physical analogy of quarks with magnetism is sufficiently close and accurate to be a useful guide.

Our curiosity and present plight with quarks may not be very different from that of an inquisitive mariner at sea some ten centuries or so ago. In a moment of calm on a passage he might have viewed a compass needle - hopefully a spare one - with idle bafflement or scientific curiosity and tried to break it apart in order to separate the north pole from the south pole. But to no avail, for with each breaking of the compass needle he ended up with an additional one having both a north and south pole. The understanding of this impossibility to isolate single magnetic poles came only many centuries later when, in 1820, the French physicist André Ampere first explained magnetism in terms of electrical currents. In fact a fundamental theory of magnetism at the atomic level in terms of the currents of circulating and spinning electrons was achieved only in this century on the basis of the modern quantum theory.

Like magnetic poles, which are but phenomenological manifestations of amperian currents, perhaps the quarks are not the fundamental particles of hadron dynamics. Presumably they will remain no less important for the description and understanding of subnuclear processes than are the bar magnets with their north and south poles for understanding a whole lot of the physics of magnetism. The quarks have done too much already to be forgotten or discarded. If, however, there is an underlying dynamics, the whole question of the meaning of confined constituents as elementary particles will disappear. Independent of whether the specific analogy with magnetism has any merit whatsoever, the notion of a new "elementary structure" underlying the quarks destroys the very attractive idea of a quark-lepton parallel unless we similarly modify and elaborate our picture of leptons. This hardly seems to be an attractive prospect at this time, particularly since no one has either seen or theorized creatively as to what these new "elementary structures" might be. On the other hand, it is also not very attractive to endow so many quark degrees of freedom as have already been discovered with a fundamental significance. What is more the lepton degrees of freedom have also begun to proliferate. Some were discouraged already 30 years ago with the discovery of the muon about which Rabi is quoted as remarking *"Who ordered that?"*. More recently we have apparently encountered a new third strain of leptons[13] in the tau of mass approximately 1.8 GeV. The tau is also thought to be accompanied by its own neutrino, as are the electron and muon. As we continue to raise our energy frontier, are we fated to meet proliferating families of leptons as well as quarks? Facing this dilemma, Werner Heisenberg proposed a different viewpoint in a lecture on the nature of elementary particles which he delivered in 1975 shortly before his death.[18] He raised the possibility that we are asking the wrong question in particle physics when we ask what a proton "consists of":

> *"I will now discuss that development of theoretical particle physics that, I believe, begins with the wrong questions. First of all there is the thesis that the observed particles such as the proton....consist of smaller particles: quarks....or whatever else, none of which have been observed. Apparently here the question was asked: What does a proton consist of? But the questioners appear to have forgotten that the phrase 'consist of' has a tolerably clear meaning only if the particle can be divided into pieces with a small amount of energy, much smaller than the rest mass of the particle itself."*

Heisenberg is referring here to the fact that in the realm of quarks, in contrast to atomic or even nuclear physics, we are no longer dealing with energies that are but small fractions of the rest masses of the particles themselves. The strong subnuclear forces confining the three valence quarks in the baryon also create many virtual quark pairs and gluons. Retardation effects as well as the energy/momentum content of these gluon fields that bind the quarks together will also be important. All of those effects and virtual particles - the gluons as well as the fluctuating numbers of quark pairs - must be included in a dynamical description of "life" within the hadrons. When we apply quantum mechanics in a relativistic strong interaction problem, our basic elements are no longer simply a fixed small number of particles but field amplitudes that create eigenstates of definite quantum numbers. In view of this Heisenberg suggests that our quest for simplicity and an underlying level of unification should be formulated in terms of the fundamental currents or symmetries of the theory.

Heisenberg's emphasis on symmetries is reminiscent of the ideas of Pythagoras and Plato. Pythagoras first explicitly emphasized the importance of symmetry 25 centuries ago and insisted that ultimately all order is capable of being understood and expressed in terms of number. Plato provided a specific form for this idea by identifying the fundamental symmetries as the basic atoms in his scheme. Transforming his idea to modern garb, rather than focusing on the problem of the many quark degrees of freedom we should seek the aesthetic grail of simplicity in the underlying group structure of the fundamental equations. Or, following the lead of Einstein, perhaps we should seek simplicity by incorporating the sources and forces of a unified field theory in the physical geometry of space-time.

The fate of the idea of hidden building blocks can be settled only by experiments, including the very fundamental and difficult quark searches already in progress. Whatever their future fate, the concept of confined quarks already has a distinguished history, as I learned in preparing this lecture - a history which dates back to the classical Greek and Roman times and includes the writings of Leucippus, Democritus, Epicurus, and Lucretius. Modern historians of science still debate intensely whether the atoms of Democritus and Leucippus are physically indivisible, because they are solid and impenetrable, or whether they are logically and mathematically indivisible, because they have no parts. Some suggest that both kinds of atoms are to be found in their writings. Apparently a full development of the idea of indivisible elementary atoms that consist of minimal parts which are permanently confined and cannot be pulled apart from one another dates to Epicurus around 300 B.C. In a charming article that recently appeared in the American Journal of Physics,[19] J. H. Gaisser and T. K. Gaisser refer to the elaboration of this idea by Lucretius who refers to the *minimae partes* of the indivisible atoms in his great poem "De Rerum Natura." Clearly these were the early versions of quarks - or partons as we sometimes refer to the minimal parts of the hadrons.

I was so intrigued by these references to confined quarks, or minimae partes, in Greek philosophy that I found myself also wondering whether Greek mythology couldn't provide some roots - perhaps even a name - for these hidden basic things. What I came up with after anything but a scholarly, thorough search[20] was the nymph goddess Calypso, referred to as the hidden one, who kept Odysseus confined to her island of Ortygia for seven years after his shipwreck en route home from the Trojan wars. Indeed, Calypso offered him immortality if he would share eternal, blissful confinement with her. However, when the gods called on Odysseus to resume his human destiny and hazardous journey home, he rejected her offer.

Whether quarks will remain mysterious as hidden elementary calypsons, or will be understood as phenomenological manifestations of an underlying dynamics, or will reveal themselves directly to experiment remains for the future. So does the fate of those theorists among us who concern ourselves with QCD, asymptotic freedom and quark confinement. Those theorists who have said that it is impossible to liberate quarks should perhaps look again to Epicurus, the metaphysical father of confined quarks, for a second message which is frequently, and erroneously, attributed to him: *eat, drink, and be merry for tomorrow an isolated quark may actually be found.*

It is a pleasure to thank Drs. Maurice Goldhaber and Peter Pesic for the valuable discussions during the preparation of this lecture.

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Figure Captions

Fig. 1 Quantum numbers and flavor labels of the three original quarks. Q is their electric charge, I_3 is the third component of their isotopic spin, and S is their strangeness number.

Fig. 2 Quantum numbers of the four quark scheme including charm, C.

Fig. 3 Identified baryons multiplets.

Fig. 4 Energy levels of charmonium labelled by their quantum numbers.

Fig. 5 Masses and decay processes of charmonium levels.

Fig. 6 Energy levels of positronium.

Fig. 7 Charmed meson (D's and D*'s) spectroscopy.

Fig. 8 Schematic picture showing that R, the ratio of the annihilation cross section to hadrons to the cross section to produce a $\mu^+\mu^-$ pair, is given by the sum of the squares of the quark charges.

Fig. 9 Experimental measurement of R.

Fig. 10 Shapes of binding potentials in QCD, with asymptotic freedom and confinement, and in QED.

Fig. 11 Comparison of how magnets and mesons break.

Quarks and their Quantum Numbers [SU(3)]

(q) Quark Flavor	Q/|e|	I_3	S
u (up)	2/3	1/2	0
d (down)	−1/3	−1/2	0
s (strange)	−1/3	0	−1

Baryon = qqq

Meson = $q\bar{q}$

1−18
3343A1

Fig. 1

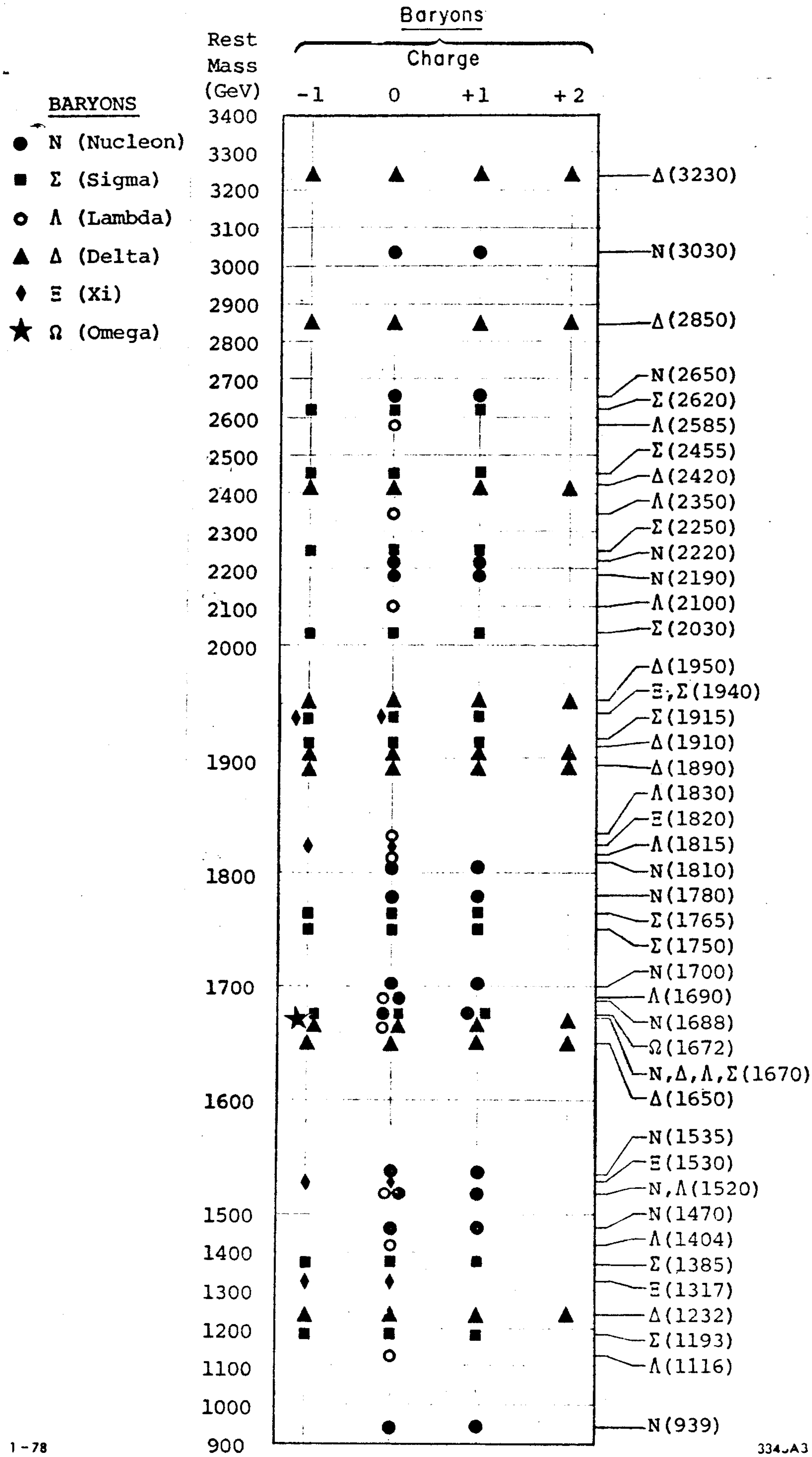
Four Quark Scheme [SU(4)]

Quark Flavor	$Q/\|e\|$	I_3	S	C
u	2/3	1/2	0	0
d	−1/3	−1/2	0	0
s	−1/3	0	−1	0
c	2/3	0	0	1

$J/\psi = c\bar{c}$

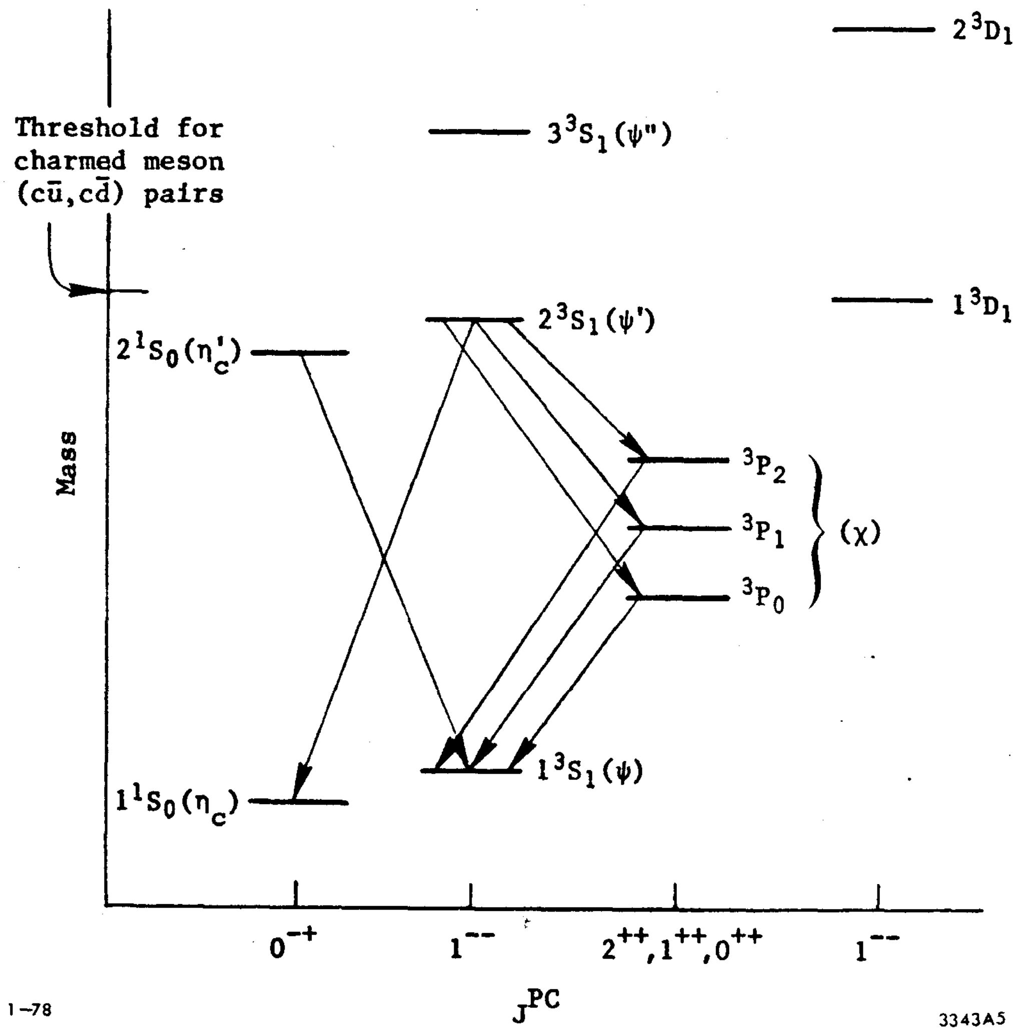
1−18
3343A2

Fig. 2



BARYONS
N (Nucleon)
Σ (Sigma)
Λ (Lambda)
Δ (Delta)
Ξ (Xi)
Ω (Omega)
Rest Mass (GeV)
Baryons
Charge
-1
0
+1
+2
3400
3300
3200
3100
3000
2900
2800
2700
2600
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
Δ(3230)
N(3030)
Δ(2850)
N(2650)
Σ(2620)
Λ(2585)
Σ(2455)
Δ(2420)
Λ(2350)
Σ(2250)
N(2220)
N(2190)
Λ(2100)
Σ(2030)
Δ(1950)
Ξ,Σ(1940)
Σ(1915)
Δ(1910)
Δ(1890)
Λ(1830)
Ξ(1820)
Λ(1815)
N(1810)
N(1780)
Σ(1765)
Σ(1750)
N(1700)
Λ(1690)
N(1688)
Ω(1672)
N,Δ,Λ,Σ(1670)
Δ(1650)
N(1535)
Ξ(1530)
N,Λ(1520)
N(1470)
Λ(1404)
Σ(1385)
Ξ(1317)
Δ(1232)
Σ(1193)
Λ(1116)
N(939)
1-78
334JA3

Fig. 3



Threshold for charmed meson ($c\bar{u}$,$c\bar{d}$) pairs
Mass
2^3D_1
$3^3S_1(\psi'')$
1^3D_1
$2^3S_1(\psi')$
$2^1S_0(\eta_c')$
$^3P_2$
$^3P_1$
$^3P_0$
(χ)
$1^3S_1(\psi)$
$1^1S_0(\eta_c)$
0^{-+}
1^{--}
$2^{++},1^{++},0^{++}$
1^{--}
J^{PC}
1-78
3343A5

Fig. 4

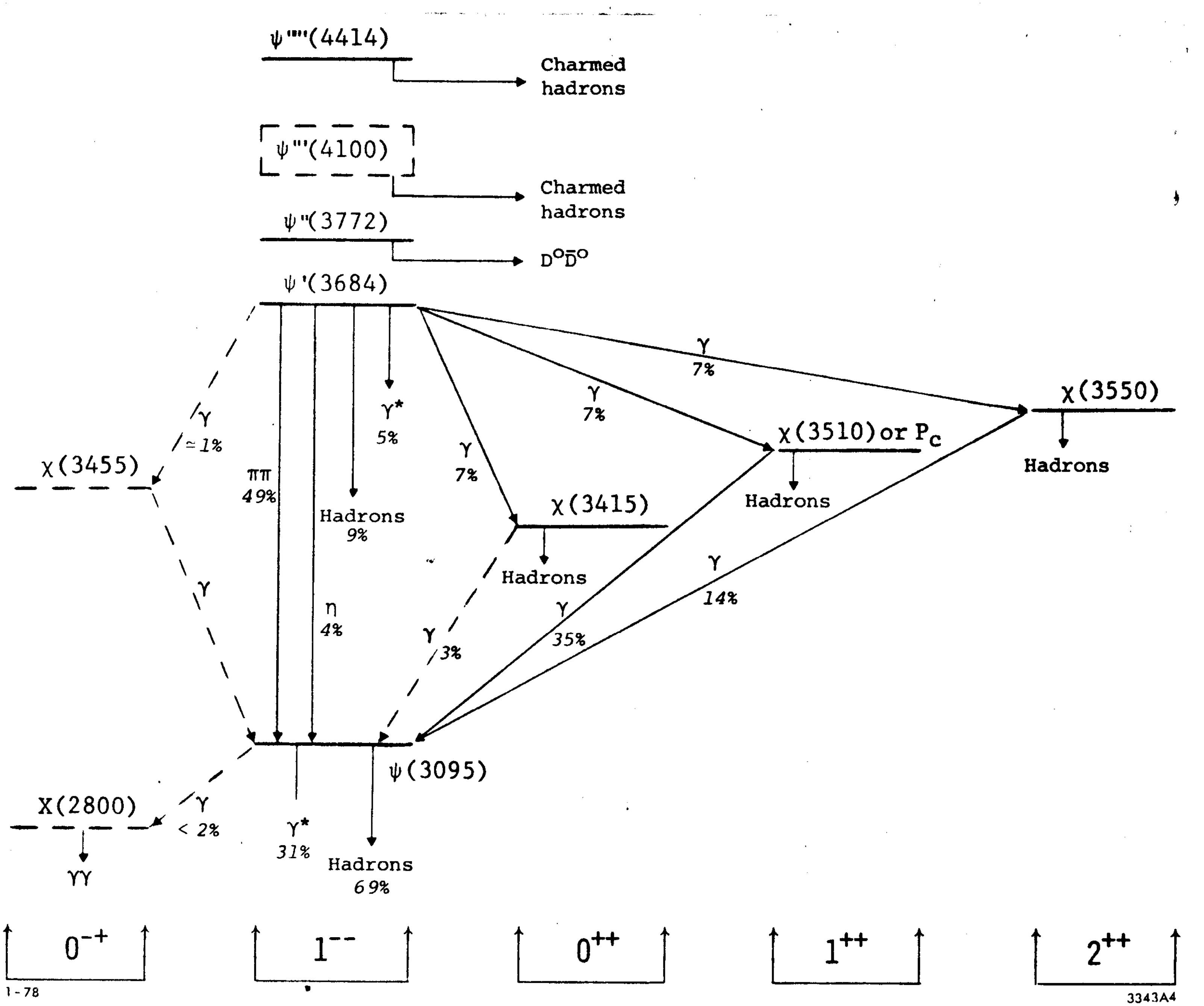
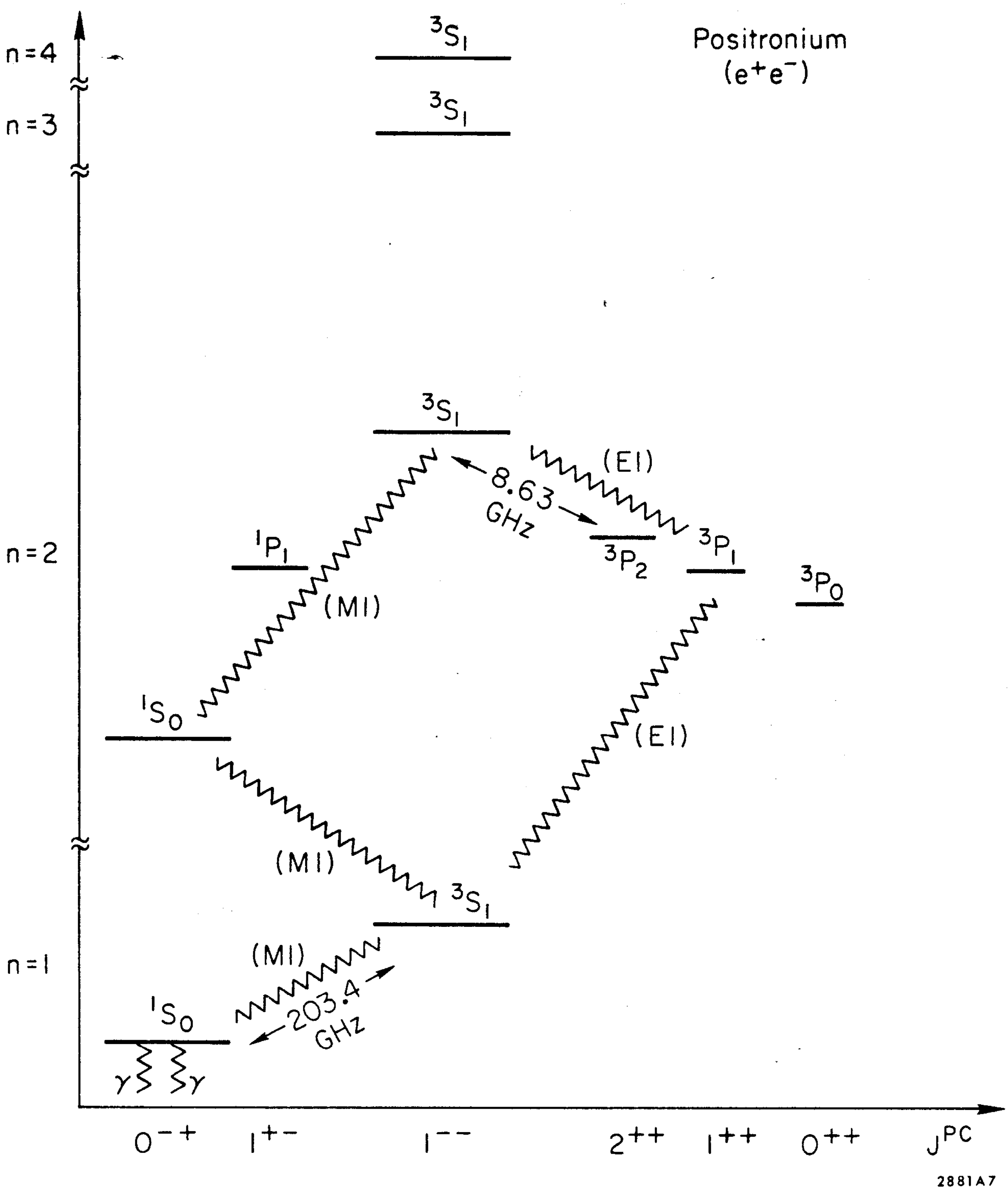
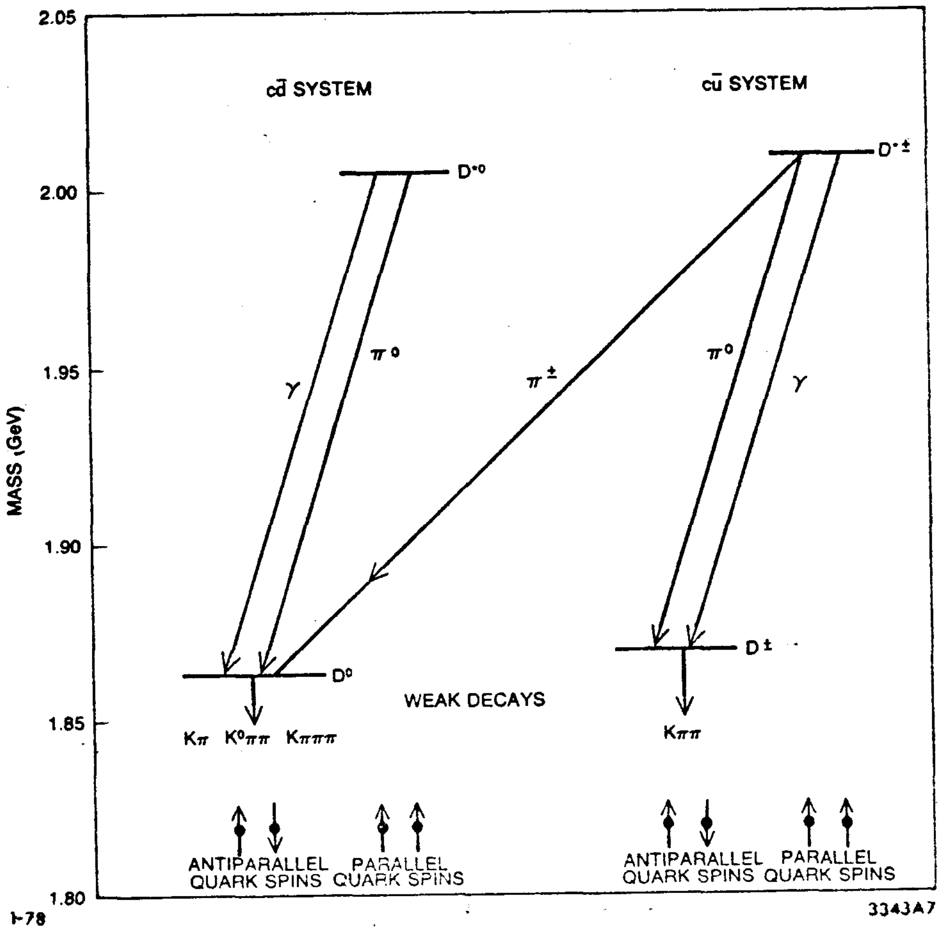

ψ''''(4414)
Charmed hadrons
ψ'''(4100)
Charmed hadrons
ψ''(3772)
D⁰D̄⁰
ψ'(3684)
γ 7%
γ 7%
χ(3550)
Hadrons
χ(3510) or Pc
Hadrons
γ ≈1%
γ* 5%
γ 7%
χ(3455)
ππ 49%
Hadrons 9%
χ(3415)
Hadrons
γ
η 4%
γ 3%
γ 35%
γ 14%
ψ(3095)
X(2800)
γ < 2%
γY
γ* 31%
Hadrons 69%
0⁻⁺
1⁻⁻
0⁺⁺
1⁺⁺
2⁺⁺
1-78
3343A4

Fig. 5



Positronium
(e+e−)
n=4
n=3
n=2
n=1
3S1
3S1
3S1
1P1
(M1)
8.63
GHz
(E1)
3P2
3P1
3P0
1S0
(E1)
(M1)
3S1
(M1)
203.4
GHz
1S0
γ
γ
0−+
1+−
1−−
2++
1++
0++
JPC
2881A7

Fig. 6



2.05
2.00
1.95
1.90
1.85
1.80
MASS (GeV)
cd̄ SYSTEM
cū SYSTEM
D*0
D*±
γ
π0
π±
π0
γ
D0
D±
WEAK DECAYS
Kπ K0ππ Kπππ
Kππ
ANTIPARALLEL QUARK SPINS
PARALLEL QUARK SPINS
ANTIPARALLEL QUARK SPINS
PARALLEL QUARK SPINS
1-78
3343A7

Fig. 7

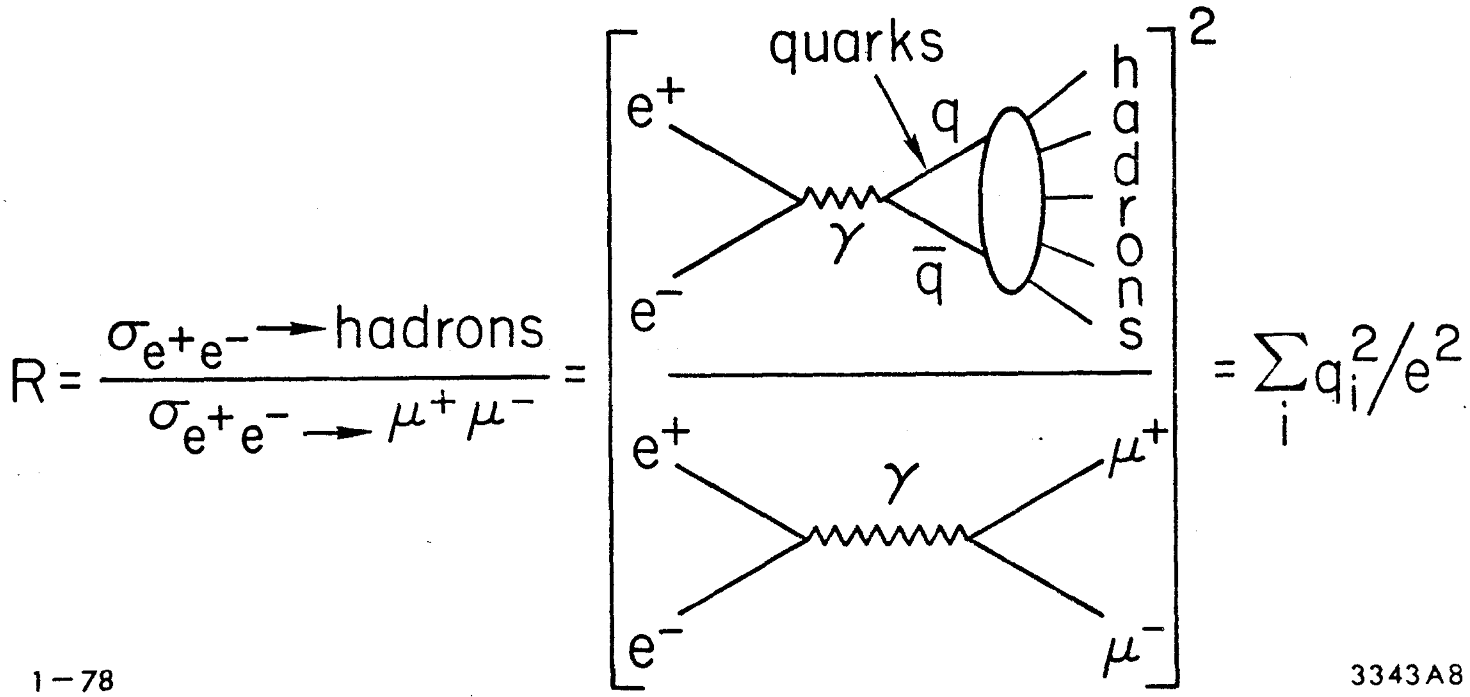

R =
σe+e- → hadrons
σe+e- → μ+μ-
quarks
q
q̄
γ
e+
e-
hadrons
μ+
μ-
2
= Σi qi²/e²
1-78
3343A8

Fig. 8

$$R \simeq 3\left[\left(\frac{2}{3}\right)^2+\left(\frac{1}{3}\right)^2+\left(\frac{1}{3}\right)^2\right]=2 \qquad R \simeq 2+3\left(\frac{2}{3}\right)^2+1=4\frac{1}{3}$$

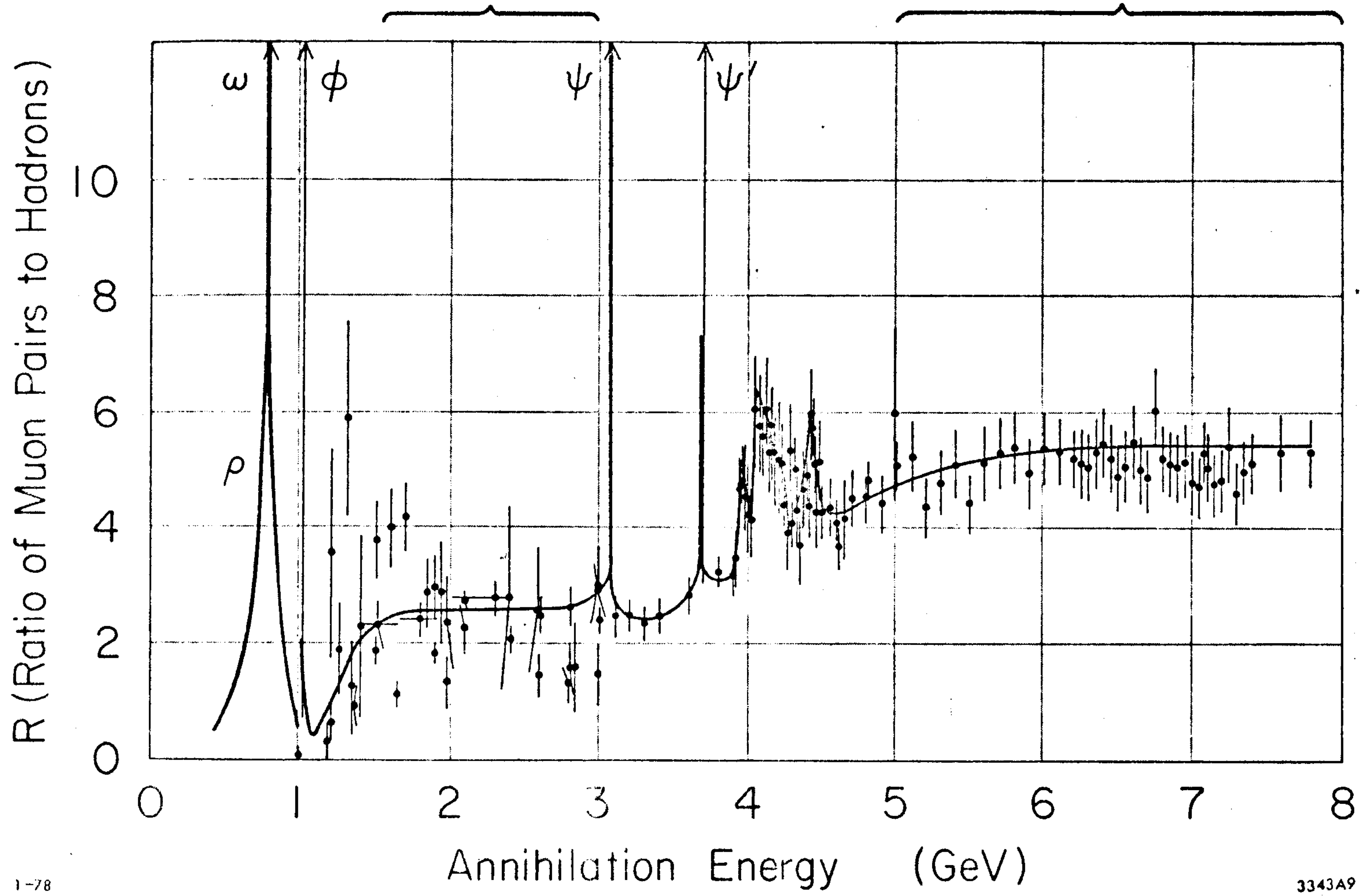


Fig. 9

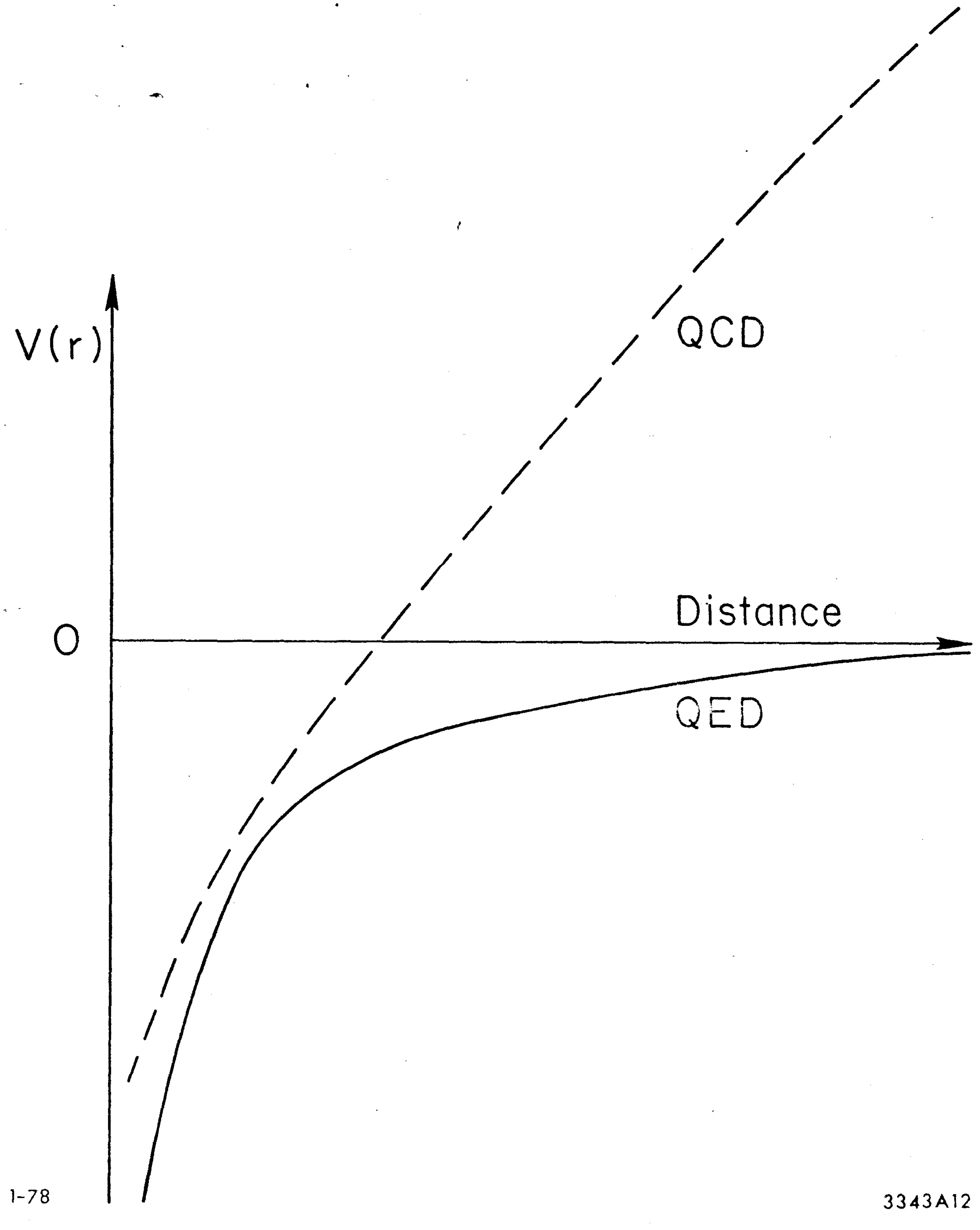


Fig. 10

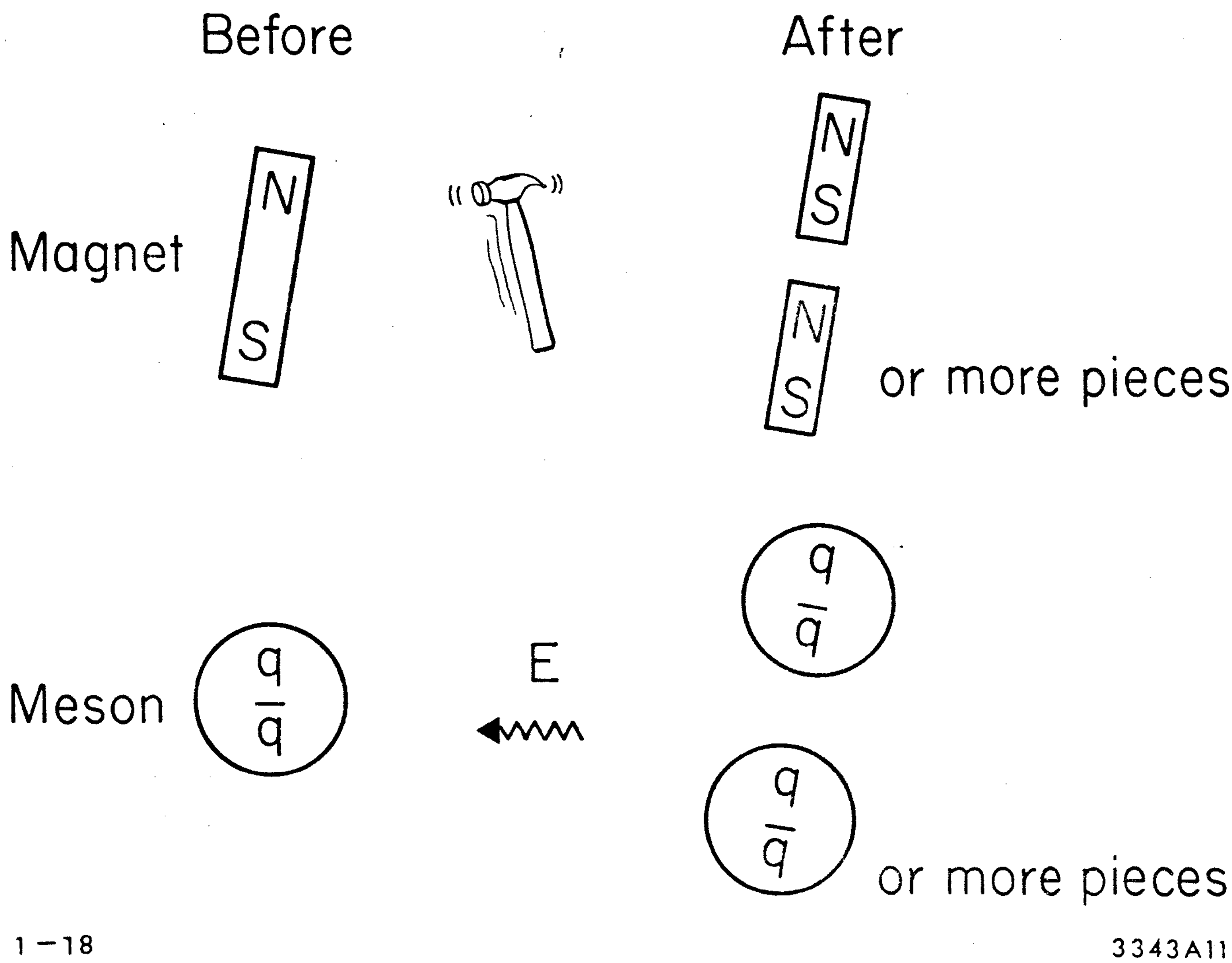

Before
After
Magnet
N
S
N
S
N
S
or more pieces
Meson
q
$\bar{q}$
E
q
$\bar{q}$
q
$\bar{q}$
or more pieces
1 — 18
3343A11

Fig. 11