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HADRON PHYSICS*

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Is all hadronic physics ultimately describable by QCD†? Certainly, many disparate phenomena can be understood within the QCD framework. Also certainly, there are important questions which are open, both theoretically (little guidance, as yet) and experimentally, regarding confinement. Are there dibaryons, baryonium, glueballs? In addition, there are experimental results which at present do not have an explanation. This talk, after a short section on QCD successes and difficulties, will emphasize two experimental topics which have recent results--glueball spectroscopy and exclusive reactions at large momentum transfer. Both are experimentally accessible in the AGS/LAMPF II/AGS II/TRIUMF II/SIN II energy domain.

INTRODUCTION--QCD

That the ingredients of QCD exist has been substantially confirmed experimentally.† Quarks or hard regions inside protons were observed in deep inelastic e-p scattering. QCD "charge," or color, is consistent with the rate observed for $e^+e^- \rightarrow$ hadrons, which is proportional to the number of final states available, giving a color factor of 3. Three-jet events are seen for e^+e^- collisions at high energy which are interpreted as two quark jets and a gluon bremstrahlung jet. The large body of spectroscopic data is consistent with $(q\bar{q})$ mesons and (qqq) baryons in color singlets.

Magnetic moment data and radiative decay widths of vector mesons also support this picture.[1] Eight baryon moments have been measured to a few percent (many to 1%), and these should be the vector sum (SU(6)) of u-, d- and s- quark moments. These agree at a 20% level. If the quarks are point-like, they would have Dirac moments, so the experimental quark moments can be converted to confined-quark masses. These masses agree with those obtained from mass splittings.

In QCD gluons carry color and can interact, unlike QED where photons do not carry charge. Gluon interactions increase the strength of the coupling constant α_S at large distances and are responsible for confinement. For short distance interactions, large momentum transfer, α_S is small and perturbation theory may be used. Quarks are asymptotically free at short distances, with light (u,d,s) quark masses estimated to be ~5 MeV. Hadron physics then divide into two regions--a hard scattering region where perturbation theory can be used and a soft region where a complete theory is necessary. Predictions for this low energy region may be forthcoming from Monte Carlo studies of lattice QCD.

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†The theory of quantum chromodynamics and evidence for it is discussed by Walecka and Farrar at this conference.

A somewhat distressing aspect of QCD for an experimentalist is the question of the transverse momentum boundary, above which perturbative QCD may be used. There are many experimental results which indicate that an asymptotic region has been entered for $p_T > 1.5$ GeV/c or Q^2 or $|t| > 5$ GeV^2/c^2. Examples are the Q^2 dependence of the proton form factor[2] (constant for $Q^2 > 5$), that fixed-angle elastic scattering follows dimensional counting predictions for $-t > 5$,[3] and that elastic cross sections develop a flat central region at this value of momentum transfer.[4] For inclusive production, an expected power law behavior sets in for $p_T > 1.5$, however the rate dependence is p_T^{-8}. An expected asymptotic dependence of p_T^{-4} is not observed until $p_T > 10$.[5] Farrar discusses the applicability of perturbation theory in her talk at this conference.

The following experimental results either do not seem to agree with QCD, or may require a more complete theory. Inclusive hyperon polarization in $p + p \to \Lambda + X$ has been observed out to $p_T = 4.5$.[6] The large polarization observed for smaller p_T is still there. In QCD high p_T inclusives are fragments of a single quark jet. Helicity-flip is strongly suppressed leading to an unambiguous prediction that there should be no such polarization. Several large polarization effects have been seen for exclusive reactions. At the ZGS with a polarized beam incident on a polarized target, the ratio of spin parallel p-p scattering to spin-antiparallel (transverse spins) grows to a value of 4 by $p_T = 2.3$ or $-t = 10$.[7] By varying scattering angle and beam energy, it was shown that the effect depends on p_T and not angle. Such a large value in the ratio of pure spin cross sections represents a serious difficulty for QCD: a polarized proton contains only partially polarized quarks so that even if one assumes antiparallel-spin quark scattering to be zero, proton-proton scattering cannot give such a large ratio $(\uparrow\uparrow)/(\uparrow\downarrow)$. There are also two new results. Single-spin elastic scattering using a polarized proton target, $p + p^{\uparrow} \to p + p$, develops a large asymmetry (51% ±17%) by $p_T = 2.5$.[8] At large angles (90° cm), the ρ^- in the quasi-elastic process $\pi^- p \to \rho^- p$ is polarized, possibly with no helicity-0 component. This will be presented later in this talk.

There are a number of candidates for states which do not appear to be standard mesons or baryons. QCD is not yet explicit as to what states should exist, although lattice calculations indicate a ground state glueball (gg) between .7 - 1 GeV. Glueball candidates will be discussed next. Other possibilities, some having their candidates, are dibaryons (6q), hybrids ($q\bar{q}g$), ggg, baryonium ($\bar{q}\bar{q}qq$), and free quarks. Also in the "soft" sector, there are 20% disagreements for a naive quark model with magnetic moments, and with the ρ radiative decay width.

GLUEBALL SPECTROSCOPY

Since gluons carry the color charge, it is expected that they can form color singlet states such as (gg), (ggg), or a hybrid state ($q\bar{q}g$). There is little theoretical guidance on masses, with an expected range from 1 - 2 GeV. For (gg), the C-parity must be + and, because gluons are assumed massless, the total angular momentum cannot be 1. Therefore, for (gg), $J^{PC} = 0^{\pm +}, 2^{\pm +}$. One looks for resonances which are not part of a $q\bar{q}$ multiplet, and which behave like glueballs.

Glueball production would be favored for disconnected graphs where all quarks in the initial state are otherwise accounted for in the final state. Three systems which have produced candidates are J/ψ radiative decay, $\pi^- p \to Gn$, and central production $pp \to pp\pi\pi$ (Figure 1).

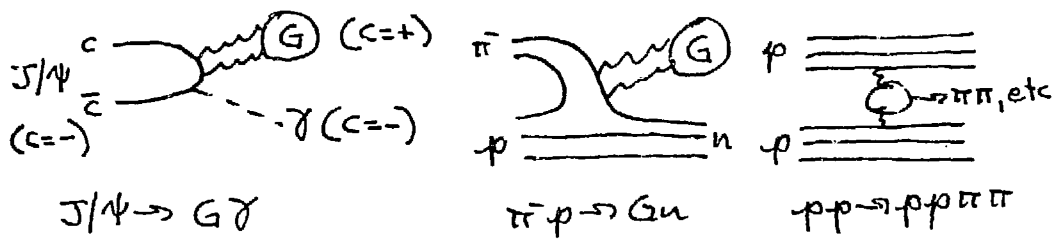


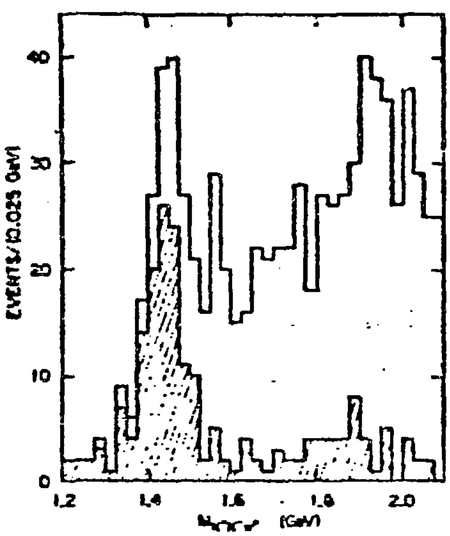
Figure 1.

Since the glueball coupling does not depend on quark flavor, there should be substantial $s\bar{s}$ in the final states. Table I shows the glueball candidates which I am aware of.

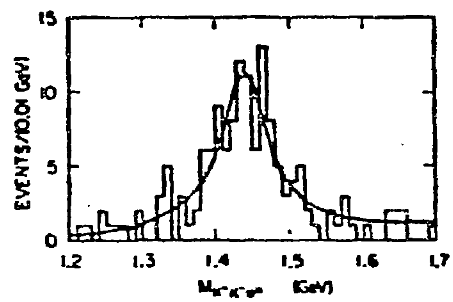
TABLE I

GLUEBALL CANDIDATES

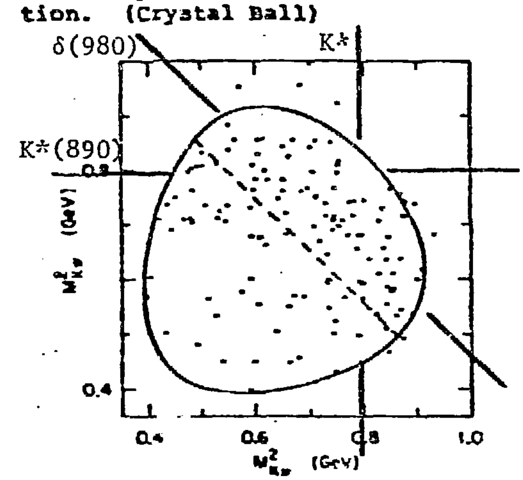
Reaction	Candidate	Final States	J^{PC}	Γ (MeV)
$J/\psi \to G + \gamma$	E/i(1440)	$K\bar{K}\pi$[9]	0^{-+} $(J/\psi, \bar{p}p)$ 1^{++} (πp)	$\sim 50 \pm 30$
	$\theta(1640)$	$\eta\eta, \bar{K}K$[10]	2^{++} favored	160 ± 80
	$\xi(2220)$	$\bar{K}K$[11]	--	< 40
$\pi^- p \to Gn$	$g_1(2120)$	$\phi\phi$[12]	2^{++}	300^{+150}_{-50}
	$g_2(2220)$	$\phi\phi$[12]	2^{++}	200 ± 50
	$g_3(2360)$	$\phi\phi$[12]	2^{++}	150^{+150}_{-50}
	G(1590)	$\eta\eta$[13]	0^{++}	210 ± 40
$pp \to pp\pi\pi$	~ 1400	drop in $\pi\pi$ cross section[14]	0	--



$K^+K^-\pi^0$ invariant mass distribution for events consistent with the hypothesis $J/\psi \to \gamma K^+K^-\pi^0$. Shaded region has the requirement $M_{K\bar{K}} < 1125$ MeV. (Crystal Ball)



$K^+K^-\pi^0$ invariant mass distribution with $M_{K\bar{K}} < 1125$ MeV. Curve represents fit to distribution. (Crystal Ball)



$K^+K^-\pi^0$ Dalitz plot for events with $1400 \leq M_{K\bar{K}\pi} < 1500$ MeV. Solid curve shows boundary for $M_{K\bar{K}\pi} = 1450$ MeV. Dashed line shows $M_{K\bar{K}} = 1125$ MeV. (Crystal Ball)

Figure 2. $J/\psi \to \gamma K^+K^-\pi^0$. Data are from ref. 9 C. Edwards et al.

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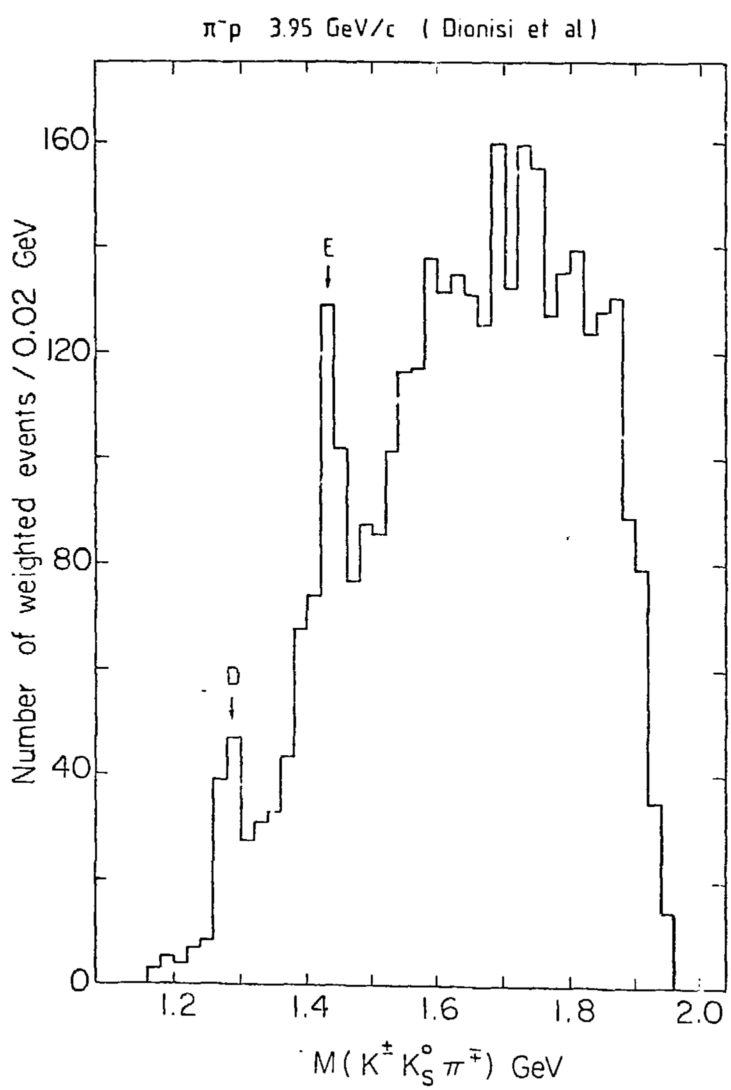

Figure 3. Mass of $KK\pi$ for $\pi^- p \to KK\pi n$, C. Dionisi et al., ref. 9.

There are several reviews which discuss most of these states.[15] I will show data here from a recent AGS experiment[16] which was designed to study the iota (1440) region where states of the same mass were identified with different J^{PC}. The iota was first identified as a candidate glueball when observed decaying to $K^+K^-\pi^\circ$ in the radiative J/ψ decay in the Crystal Ball detector,[9] as shown in Figure 2. The Dalitz plot shows a strong $\delta(980)$ component, with a considerably sharper signal observed for $KK\pi$ events with $m_{K^+K^-} < 1125$ MeV. A state at 1420MeV had been identified for $\pi^- p \rightarrow E(1420) + n$ at 4 GeV/c,[9] with $J^P = 1^+$ (Figure 3). The Dalitz plot showed K* lines.

New data, first presented at Moriond by Protopopescu this year (40% of the data sample analyzed), indicates that there may, indeed, be two states in this mass region. The experiment used the Multiparticle Spectrometer to observe $KK\pi$ final states, produced both by a pion beam and by an antiproton beam:

$\pi^- p \rightarrow K^+ K_S \pi^- n$ at 8 GeV/c and

$\bar{p}p \rightarrow K^+ K_S \pi^- X^\circ$ at 6 GeV/c.

The $K_S \rightarrow \pi^+\pi^-$ effective mass width was 6.5 MeV further with few percent background. The (missing mass)^2 histogram for the π^- data, shown in Figure 4, shows a clear exclusive neutron peak, also with little background.

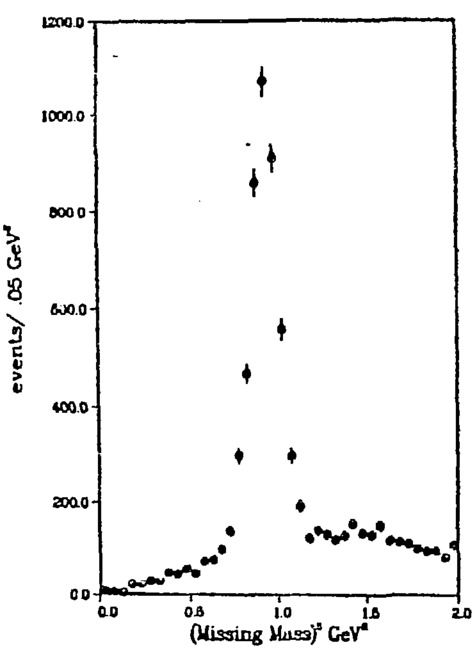

Figure 4. Missing mass-squared for X in $\pi^- p \rightarrow K^+ K_S \pi^- n$. Ref. 16.

Figure 5a gives the $KK\pi$ mass for the pion exclusive data and 5b gives the effective mass for the antiproton data. Clear signals are seen in the E/iota mass region. If events are kept with $M_{KK} < 1.05$ GeV to select for events with a $\delta\pi$ channel, the peak in the E/iota region becomes much more prominent for the pion data. For the $\bar{p}$ data the E/i peak is almost lost in the background (Figure 6). A partial-wave analysis of the data is in progress.

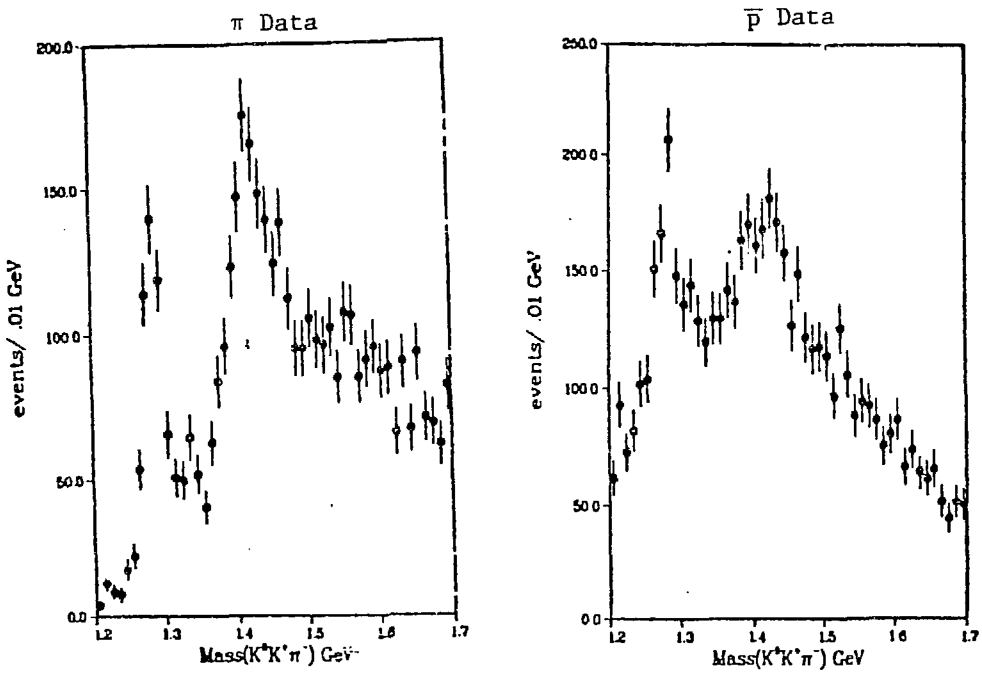

Figure 5. Mass (KKπ) for $\pi^- p \to K^o K^+ \pi^- n$ and for $\bar{p}p \to K^o K^+ \pi^- X$, ref. 16.

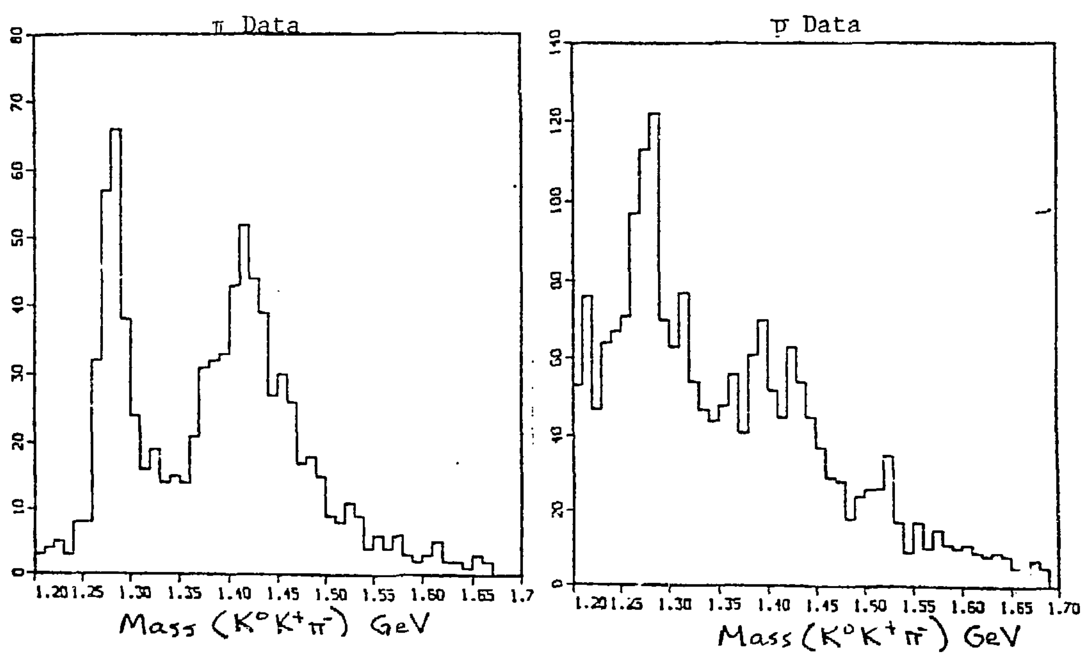

Figure 6. Mass (KKπ) for π and $\bar{p}$ data, for events with $M(K^+ K_S) < 1.05$ GeV.

The E/i system has other puzzles. The decay $i \to \delta\pi$ is seen in the J/ψ data, but not $i \to \eta\pi\pi$, expected if $\delta \to \eta\pi$. K^- production of E/i is not seen, while the D-meson is produced. There is also data on π^+p and pp central production of the E/i at 85 GeV/c with the Ω spectrometer, where they see the K*K decay mode, but not $\eta\pi^+\pi^-$. The E/i system is not yet sorted out, but there are strong indications that more than one state may be there, with one possibly a (gg) state.

Other candidates listed in Table I also represent clearly seen states which are observed in systems which favor glueball production. For example, Figure 7 shows the K^+K^- mass in $\pi^-p \to K^+K^-\phi n$ where one $\phi \to K^+K^-$ decay has been identified.[12] The experiment observes

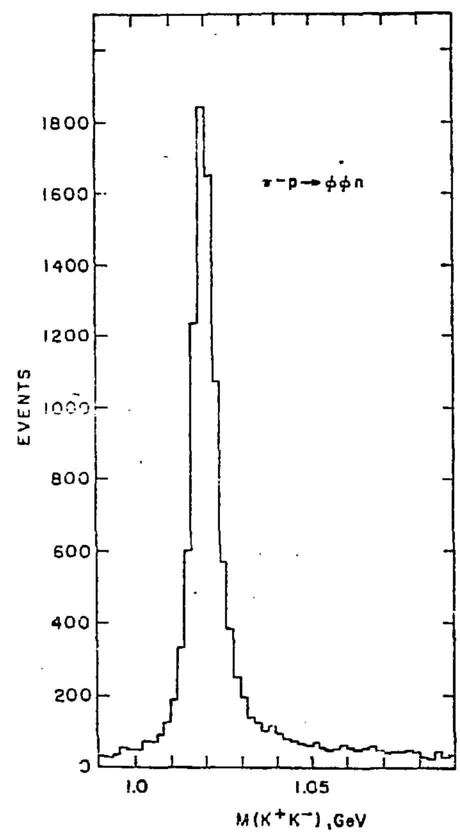

Figure 7. The effective mass of each K^+K^- pair for which the other pair was in the ϕ mass band.

$\pi^-p \to \phi\phi n / K^+K^-\phi n \approx 1/5$. The leading graph for the $KK\phi n$ system is not disconnected, as shown in Figure 8a, the leading graph for $\phi\phi n$ is shown in Figure 8b, and is disconnected. A large suppression would be expected, for example in the rates for $\pi^-p \to \phi n / K^-p \to \phi\Lambda \approx 1/60$. A different experiment measured the ratio of rates for $K^-p \to \phi\phi\Lambda / K^+K^-\phi\Lambda$ which is also 1/5. For this case, neither diagram is disconnected (Figure 8c shows the $\phi\phi\Lambda$ diagram.) It is argued that the lack of suppression for $\pi^-p \to \phi\phi n$ may indicate that the resonances found in the system couple strongly to gluons and are candidate glueballs.

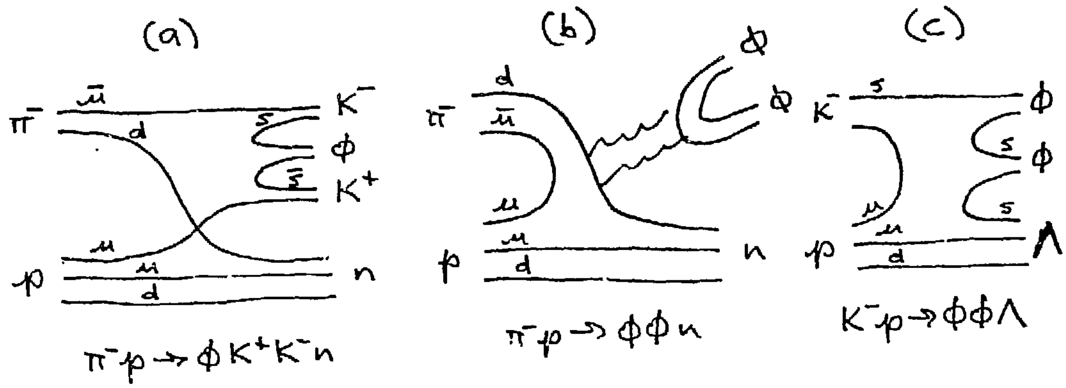

Figure 8. Quark diagrams of three reactions. Only (b) must be disconnected.

The spectra of these odd states in the low mass region--(gg), (ggg), ($q\bar{q}g$), (6q), ($q\bar{q}q\bar{q}$), (q)--will represent a fundamental test of theory. Many possible candidates have been discovered quite recently, due to many factors including improved apparatus which can accept higher luminosities, an accumulation of J/ψ events, and the stimulation of the field by theoretical developments. Areas of spectroscopy which are still virtually untouched are resonances with neutral final states and those which can be made with K^- beams. A good neutral detector capable of taking high rates in a pion or kaon beam and a 10^6 to 10^7/second separated K^- beam above 10 GeV/c (requiring high proton intensity) would open up a new and potentially exciting area of spectroscopy.

INCLUSIVE EXPERIMENTS--POLARIZATION

As mentioned in the introduction, single particles produced at high p_T are seen in QCD as fragments of single quark jets. Indeed, quark jet signatures have been unmistakable in data for high energy e^+e^- and $\bar{p}p$ collisions. Because of the expected suppression of helicity-flip amplitudes, single particles should not be polarized at high transverse momenta. But hyperons are. Figure 9 shows data for the polarization of Λ hyperons produced inclusively versus p_T for several energies.[17] At the ISR, polarization reached 50%. The effect has been shown to depend on both p_T and $x \approx p_\Lambda/p_{beam}$, increasing linearly in x or p_T, and flat for $p_T > 1$, fixed x. When the data are matched in x and p_T, the polarization is seen to be independent of energy from $\sqrt{s}$ = 5 to 56 GeV. An experiment at Fermilab[6] measured the Λ polarization out to p_T = 4.5. The polarization remained constant, when compared at fixed x, from p_T = 1 to 4.5. Other experiments have

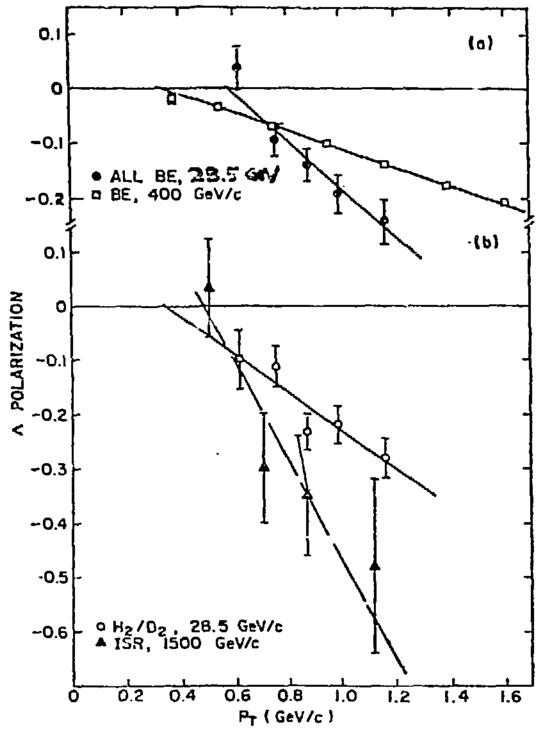

Figure 9. Λ polarization for $p + Be \rightarrow \Lambda + X$ and for $p + p \rightarrow \Lambda + X$. References are in ref. 17.

measured large polarizations for inclusively produced $\Sigma^{\pm}, \Xi^{0}$ which have led to precise magnetic moment results.[18] Inclusively produced protons and $\bar{\Lambda}$s (incident protons) have not been found polarized.[19]

Theoretical models for the effect have been proposed.[20] A major difficulty has been to include all hyperons, for example Ξ where two strange quarks must emerge and Λ which requires just one s-quark. A tantalizing result is that the Σs have the opposite polarization from Λs and Ξs. The strange quark spin in the Σ is antiparallel to the Σ spin, while for the Λ and Ξ the s-quark and hyperon spins are parallel.

EXCLUSIVE EXPERIMENTS

Theoretically, exclusive reactions at high p_T are much more difficult to treat than inclusives. Every quark must be accounted for and wave functions are required. Exclusives may represent the next step between hard inclusive scattering and the soft domain where perturbation theory cannot be used. There are, however, very large spin effects that have been discovered. This would seem to argue that a simplification should be possible.

Figure 10 shows results from an elastic scattering experiment with a polarized proton beam incident on a polarized proton target

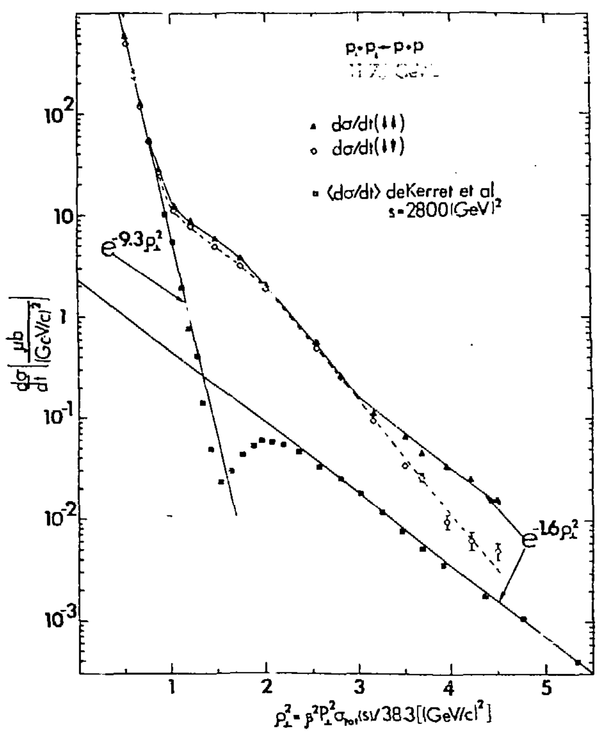

Figure 10. The proton-proton differential elastic cross-section in pure initial spin states is plotted against the scaled $P_\perp^2$ variable. Unpolarized ISR data is shown for comparison.

(transverse polarization).[7] A ratio of 4 is observed between the rates for spin parallel and spin anti-parallel scattering at p_T = 2.3. A new result, presented at this conference by Raymond, gives a single-spin asymmetry of 51% $\pm$ 17%. Again, the asymmetry only becomes large at high-p_T, just where it is expected to be small.

There are also new results from a large angle two-body exlusive scattering experiment which observes a large spin effect for hard scattering. These first results from the experiment[21] are preliminary.

Several types of quark diagrams may contribute to meson-baryon two body exclusive scattering, as shown in Figure 11. Elastic scattering may proceed via any or all of the graphs, as can $\pi^- p \rightarrow \rho^- p$. A reaction such as $\pi^- p \rightarrow K^\circ \Lambda$ cannot occur via pure gluon exchange or quark interchange. And others, such as $\pi^- p \rightarrow \pi^+ \Delta^-$ or $K^+ \Sigma^-$, require both annihilation and quark interchange. The purpose of the experiment was to compare these and other two body reactions at the highest possible p_T. Each reaction is sensitive to different mixtures of the graphs shown in Figure 11. If the quark graphs are flavor-independent, as expected for hard scattering where the asymptotic quark masses are small on the scale of the momentum transferred in the interaction, the amplitudes for the two body exclusive reactions can be written in terms of the same quark scattering amplitudes, with corresponding relationships between the reaction cross sections.[22]

The experiment was performed at the AGS with an intense 10 GeV/c π^- beam incident on a hydrogen target. Results on elastic scattering and on the $\rho^- p$ final state will be presented here. The apparatus consisted of a single-arm spectrometer which selected events with a positive particle with momentum close to the elastic limit of 5.6 GeV/c near 22° in the laboratory or near 90° in the $\pi^- p$ elastic center of mass system. The absence of a signal in each of two threshold cerenkov counters with $\gamma_{threshold}$ = 22 and with $\gamma_{threshold}$ = 10 tagged protons in the arm. The incident beam momentum was measured to $\Delta p/p \simeq \pm 1\%$ (rms) and the scattered proton momentum resolution was $\Delta p/p = \pm 0.5\%$. Charged particles recoiling to the other side of the spectrometer arm were detected by three wide-aperture proportional wire chambers with no magnet.

Figure 12a shows the (missing mass)^2 for $\pi^- + p \rightarrow p + X$ where we require only one track to the recoil side, a clear proton track in the spectrometer arm, a good reconstructed vertex, and with coplanarity and opening angle cuts to select elastic events. The width is large, due to the poor beam momentum resolution. The 500 events observed give a cross section for elastics of approximately $d\sigma/dt \approx 1$ nb/GeV^2/c^2.

Figure 12b shows the missing mass distribution for 1-track recoil events, with the elastics removed. The cuts used to select $\pi^- p \rightarrow \rho^- p$, $\rho^- \rightarrow \pi^- \pi^\circ$ are indicated. The apparent width of the ρ mass is consistent with the resolution. If we assume a linearly falling background extrapolated from higher masses, the ratio of events with a $\rho^- p$ to a $\pi^- p$ final state is approximately half.

The angular distribution of the π^- from ρ^- decay analyses the helicity of the ρ^-. In the Gottfried-Jackson frame, the distribution of the π^- is given by

$$W(\theta,\phi) = \frac{3}{4}\pi\,[\rho_{00}\cos^2\theta + (\rho_{11} - \rho_{1-1})\sin^2\theta\,\cos^2\phi + (\rho_{11} + \rho_{1-1})\sin^2\theta\,\sin^2\phi - 2\,\rho_{10}\sin 2\theta\,\sin\phi]$$

where θ is the polar angle from the incident π^- direction in this frame and ϕ is the azimuthal angle. ρ_{ij} is a spin-density matrix element for helicity i, j ρ^- amplitudes. A non-resonant S-wave $\pi^-\pi^\circ$ background would have an isotropic angular distribution.

In Figure 13a we show the angular distribution of events within the -cut, plotting events versus cos θ and ϕ. Our acceptance can be seen in Figure 13b which shows the scatter plot for an isotropic Monte Carlo distribution, filtered by our apparatus and event selection criteria. There are two regions where the acceptance is poor--near cos θ = +1 where the elastics have been cut out, and near cos θ = -1, $\phi = 0°$ where backward decays toward the beam line miss our side chambers. A $\sin^2\theta\,\sin^2\phi$ Monte Carlo distribution is shown in Figure 13c and a $\cos^2\theta$ distribution is displayed in Figure 13d. The data appear to have little $\cos^2\theta$, and show qualitativity the two lobes of the $\sin^2\theta\,\sin^2\phi$ distribution, indicating the presence of helicity ± 1 and absence of helicity ϕ ρ^-. The higher mass data are consistent with isotropy, or non-resonant S-wave $\pi^-\pi^\circ$ background.

If the pure gluon exchange graph (Figure 11a) were to dominate this reaction, helicity conservation at the quark level, a QCD prediction, would require that the ρ^- helicity be the same as the incident π^-, or zero. Helicity-flip amplitudes are expected to be suppressed by a factor $m_q/\sqrt{s} \approx 10^{-3}$ for our case where we assume the asymptotically free quark mass of about 5 MeV. Thus, the gluon exchange graphs appear to be small.

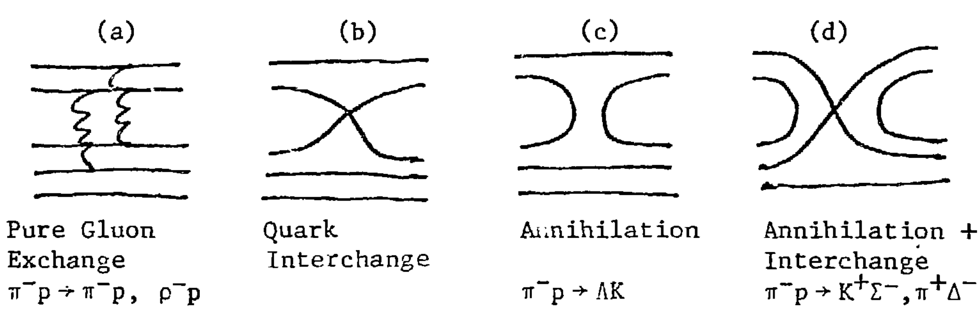

Figure 11. Quark diagrams for meson-baryon exclusive scattering. Example reactions for the diagrams are shown. The reactions listed in (a) can proceed via diagrams (b), (c), (d). Similarly, $\pi^-p \to K\Lambda$ can proceed via (d).

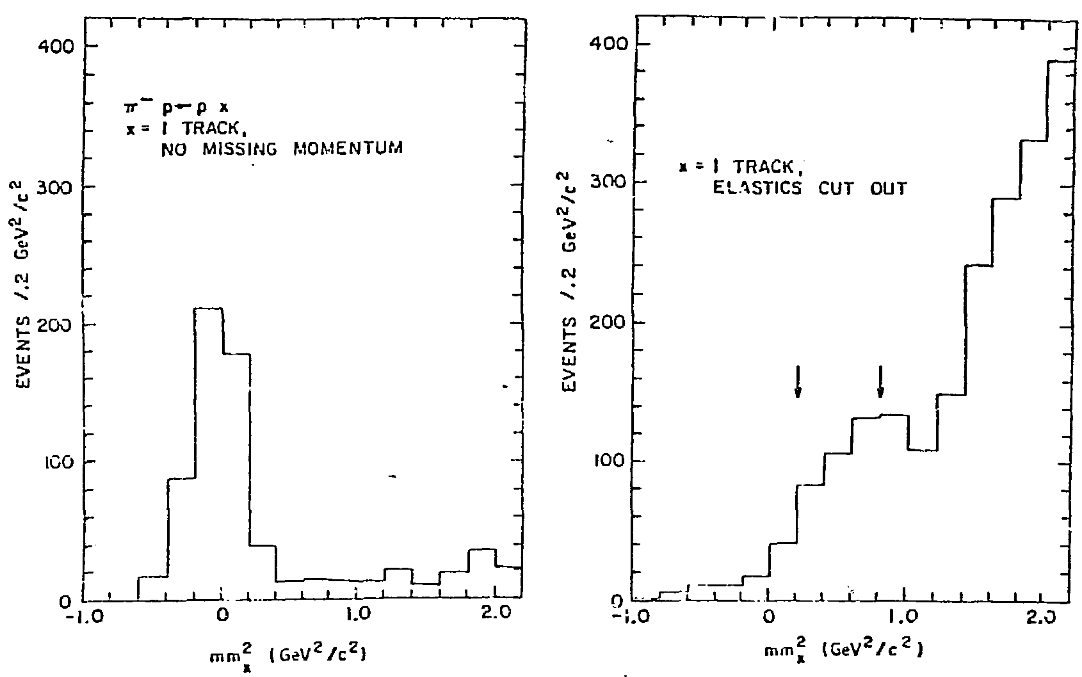

Figure 12. Mass^2(X) for $\pi^- p \rightarrow p + X$ at 90^o CMS, for cuts selecting elastics, and for elastics removed. Ref. 21.

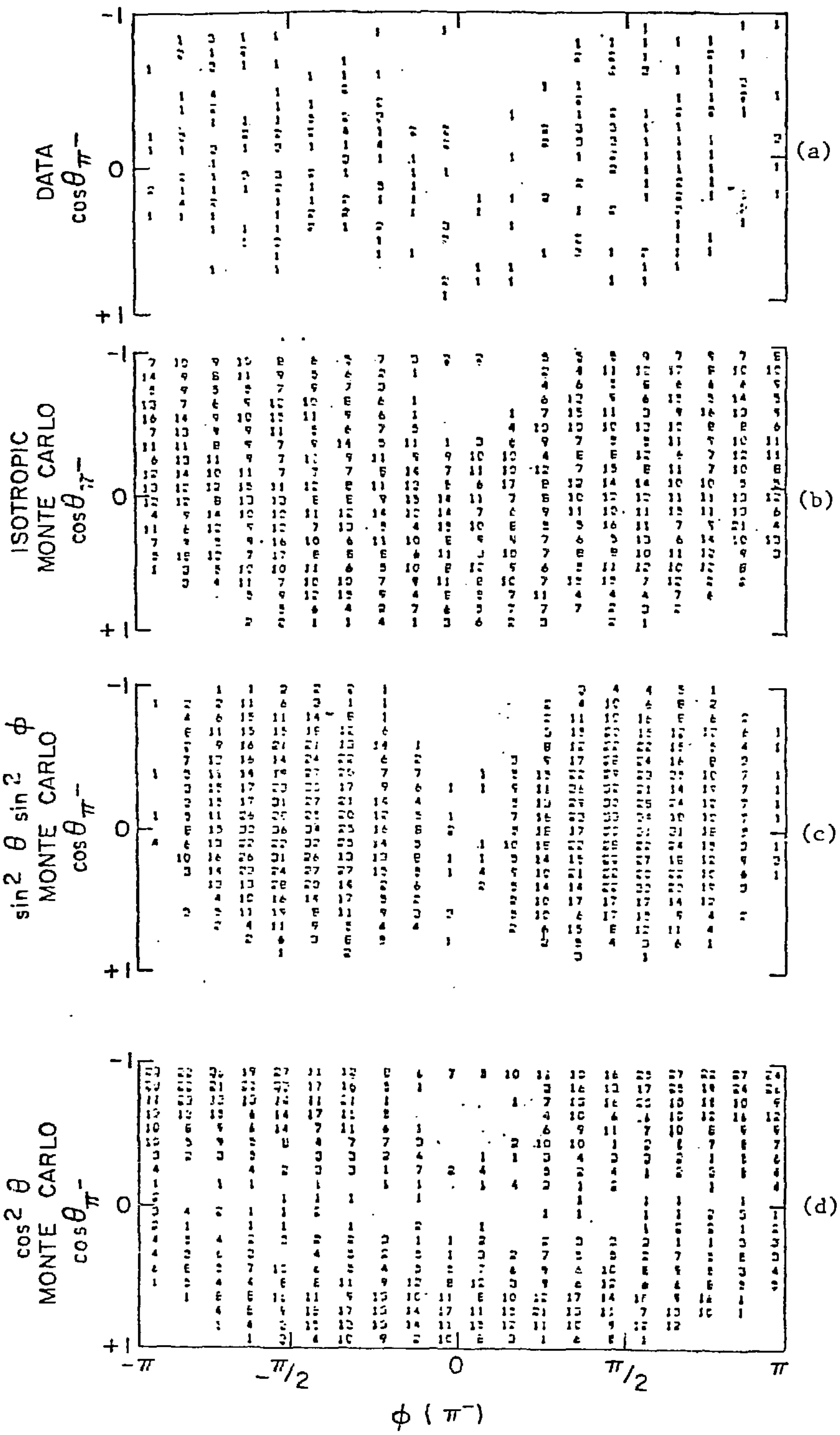

Figure 13. Scatterplots vs. cos θ and φ, the decay angles of the π^- in $\rho^- \to \pi^-\pi^0$ decay, for data and three Monte Carlo distributions.

Quark annihilation or exchange, however, is not excluded by helicity conservation. These graphs, Figures 11b, c, d, may give helicity ± 1 and 0. Why are the helicity amplitudes absent? It may be that just one mechanism dominates and that a cancellation suppresses the helicity 0 amplitudes. If so, then a relatively small number of two body exclusive reactions can over-determine these amplitudes, leading to quite stringent tests of QCD.

SOME CONCLUSIONS

QCD may be the correct description of hadronic physics, but there are puzzling results. Many have to with spin--it is not only not true that spin effects die off at high p_T, but strong spin effects [illegible]ear there! Experiments should measure spin effects at large trans[illegible]e momentum where possible. The high energy polarized proton beams [illegible] the AGS (Ratner, this conference), at FNAL from Λ decay, and poss[illegible] in the $S\bar{p}pS$ could yield new and striking phenomena.

The mechanism of confinement is fundamental to our understanding of hadronic physics. There are many new glueball, dibaryon and baryonium candidates (note the LEAR results presented at this conference by Walcher). With higher intensity available in the future, intense K^- beams will be possible. Spectroscopy with neutral final states and with strange quarks is virtually uncharted. Spectroscopy at high p_T may also be attractive, where little penalty is paid to produce exotic states (Farrar, this conference). It is hoped that high energy collisions of heavy ions will probe confinement in a new way, possibly producing a form of quark-gluon soup.

There is clearly a lot to do, and it is encouraging to an experimentalist that whenever experiments look into a new region, via higher luminosity, new probes or higher energy, new and exciting physics is uncovered.

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