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LIGHT QUARK-HADRON SPECTROSCOPY

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1. INTRODUCTION

The aim of hadron spectroscopy is not merely to catalogue the states in the quark model, but also to provide some information about basic questions such as the role of spin, orbital, and radial excitations of the quark system, the quark confinement mechanism, etc. Still, the main guiding line of this review will be to confront the experimental observations with the non-relativistic quark model, in the hope that some facts will force us to introduce new concepts, the MIT bag model, glueballs, etc.

Our plan is straightforward: we shall discuss, in turn, systems which may consist of one, two, three, four ... quarks.

2. SEARCHES FOR QUARKS

Quarks have been looked for using accelerators (and cosmic rays) or searched for in matter. The accelerator searches are limited by the mass of the free quarks, those in matter by their abundance. Therefore these two series of attempts are complementary.

Yock¹ has used a cosmic-ray telescope at the sea level. The telescope consists of six scintillator planes, two wide-gap spark chambers, and steel absorbers. The scintillators provide a time of flight over a 2 m path length, and pulse-height measurements before and after the absorber. The trigger accepts slow particles ($\beta < 0.5$) which have penetrated the absorber. Three possible examples of fractionally charged particles are given. The measured masses and charges are $m_1 > 5.3 m_p$, $m_2 > 2.8 m_p$, $m_3 > (9.3 \pm 3.0) m_p$, and $q_1 = (\pm 0.75 \pm 0.05)$, $q_2 = (\pm 0.70 \pm 0.05)$ and $q_3 = (\pm 0.89 \pm 0.06)$, respectively. Before considering these events as convincing evidence of fractionally charged particles, the multitrack efficiency of the spark chambers has to be demonstrated.

Bussire et al.² have searched for long-lived particles in 200-240 GeV/c proton-nucleon collisions. Pulse heights and times of flight of eight scintillation counters and of four erenkov counters (of which two were of the DISC type) were recorded. Advantage was taken of a superconducting RF separator to remove high-velocity particles, bringing the acceptance to more than 2×10^7 particles per burst. The time measurement accuracy of each scintillator was ± 0.15 ns. The 200 MHz RF structure of the CERN Super Proton Synchrotron (SPS) proton beam was used to give a time-of-flight resolution of ± 0.6 ns over the 210 m beam length. Several hundreds of antitritons and ^3He have been recorded. No quark candidate was detected, the upper limit at 95% confidence level for the ratio q/π for particles q with charge $\pm 2/3$ and masses $1 < m < 5$ GeV being 10^{-10} .

The CBFEB Collaboration³ has been looking for quarks in $\nu, \bar{\nu}$ interactions on lead nuclei. Candidates from an electronic pulse-height analysis were examined more closely by looking at the tracks

left in an avalanche chamber. No good candidate has yet been found. An upper limit for charged $\pm 1/3$ particles to normal secondary hadrons of 10^{-4} is achieved.

Bartel et al.⁴ have searched for free quarks in e^+e^- annihilations at PETRA in the energy range 30 to 35 GeV, using the JADE detector. The particle identification is given by 48 measurements of dE/dx in the drift chamber gas. Exclusive and inclusive quark production were both studied. There is no evidence for tracks with abnormal ionization, an upper limit for $\sigma(e^+e^- \rightarrow q\bar{q})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ being of the order of 10^{-2} and 10^{-1} for exclusive and inclusive production, respectively, with masses in the range $1 < m < 15$ GeV.

At this conference, the results of two experiments on the search for quarks in matter have been reported. Marinelli and Morpurgo⁵ have studied the levitation of small steel balls (ϕ of 0.2 and 0.3 mm) suspended magnetically between two capacitor plates. It is shown that, with a very good precision, the force acting on the balls takes the form of

$$F_x = \left(q + \alpha \frac{\partial E_x}{\partial x} + \beta \frac{\partial H_x}{\partial x} \right) E_x ,$$

where q is the electric charge to be measured, α is the polarizability of the balls $\alpha = 4\pi\epsilon_0 r^3$, E_x is the applied electric field, and H_x is the magnetic field in which the ball is levitating; $\alpha(\partial E_x/\partial x)$, known as the patch effect, is due to non-uniformities of the electric potential on the surface of the capacitor plates. This patch effect can induce large errors and must be kept under careful control during the experiment. To work at constant patch, the levitation chamber was built in such a way that several balls could be measured in succession without opening the chamber. Marinelli and Morpurgo find that the drift observed for several balls cannot be attributed to this patch effect, but to a new force, of magneto-electric nature. This is the term $\beta(\partial H_x/\partial x)$ which appears in the above formula, β being a coefficient which is ball-dependent. To isolate this effect, Marinelli and Morpurgo measure the apparent charge under two different conditions, given by

$$\frac{\partial H_x^+}{\partial x} = \left(\frac{\partial H_x}{\partial x} \right)_0 \pm \Delta \left(\frac{\partial H_x}{\partial x} \right) .$$

Then the apparent charge can be written:

$$Q_R^\pm = q + \alpha \frac{\partial E_x}{\partial x} + \beta \frac{\partial H_x^\pm}{\partial x} .$$

The results of the measurements for 23 balls with $\phi = 0.2$ mm and for 24 balls with $\phi = 0.3$ mm are shown in Figs. 1 and 2, respectively. Note that a patch effect is visible for the larger balls, at least for the run corresponding to the symbol $\odot$, but all the measurements are compatible with $Q = 0 \pm 0.05e$, i.e. no quark is found in 3.4 mg of steel.

Instead of using a ferromagnetic material, La Rue, Phillips and Fairbanks⁶ use a superconducting material, niobium. In previous

publications^{7, 8}, evidence for the existence of fractional charge was presented. The new measurements, which consist in 21 independent measurements on 5 different balls, support the previous results. During these measurements it has been found that the charge of the same ball can jump by $\frac{1}{3}e$ units, indicating that the fractional charge can be transferred either to or from the surface of the ball when it is in contact with other substances. Altogether, 39 independent measurements have been made on 13 balls. The results are shown in Fig. 3. It seems that the magneto-electric force which explains the drifts observed by Marinelli and Morpurgo cannot account for the observations made by La Rue et al., since they find charges consistent with 0 or $\pm\frac{1}{3}$ and observe no continuous drift with time.

Fig. 1

Fig. 2

Fig. 3

Should we attribute the differences in these results to the differences in the nature of the tested material? Are there solid-state physics effects that are not yet completely understood? Or, as suggested by Lackner and Zweig⁹, are there atomic chemistry effects? If electric charges of $\pm 1/3$ have effectively been observed, should they be attributed to quarks? It is now too early to answer these questions, but the measurements and investigations now in progress will hopefully shed more light on this important problem in the near future.

3. MAGNETIC MOMENTS OF THE QUARKS

Handler et al.¹⁰ have reported new accurate measurements on the magnetic moment of the Ξ^0 and Ξ^- . They are given in Table I, together with recently published results on the Λ^0 ¹¹ and Σ^+ ¹², as well as with the known values of the magnetic moments of other stable baryons.

Table I Magnetic moments of the baryons

(unit: $\mu_N = e\hbar/2m_p c$)

Baryon	Experiment	Quark model
p	+2.7928456	Input
n	-1.91304184	Input
Λ	-0.6138 $\pm$ 0.0047	Input
Σ^+	+2.33 $\pm$ 0.13	2.67
Σ^-	-1.48 $\pm$ 0.37	-1.09
Ξ^0	-1.237 $\pm$ 0.016	-1.44
Ξ^-	-0.75 $\pm$ 0.06	-0.50

Using the static quark model relations,

$$p = \frac{4}{3} u - \frac{1}{3} d ,$$

$$n = \frac{4}{3} d - \frac{1}{3} u ,$$

$$\Lambda = s ,$$

$$\Sigma^+ = \frac{4}{3} u - \frac{1}{3} s ,$$

$$\Sigma^- = \frac{4}{3} u - \frac{1}{3} s ,$$

$$\Xi^0 = \frac{4}{3} s - \frac{1}{3} u ,$$

$$\Xi^- = \frac{4}{3} s - \frac{1}{3} d ,$$

where the particle symbols stand for their magnetic moments, one can predict the magnetic moments of Σ^+ , Σ^- , Ξ^0 , Ξ^- (Table I).

We see that the static quark model gives a qualitative understanding but with the new accurate measurements of the Σ^+ , Ξ^0 , and Ξ^- , any attempt to give a good quantitative interpretation fails badly.

Non-static effects (orbital, relativistic, exchange couplings) can now be usefully studied¹³⁻¹⁷. Relativistic effects are suggested¹³ as the dominant symmetry-breaking mechanism. It will be interesting to watch the results of new measurements undertaken on the Σ^- , $\langle \Lambda | \Sigma^0 \rangle$, and Ω^- .

Nevertheless, using as first approximation the quark magnetic moments deduced from the baryon magnetic moments,

$$u = +1.85, \quad d = -0.97, \quad s = -0.61,$$

one can predict the radiative decay of the vector mesons into pseudo-scalars $V \rightarrow P\gamma$, which are pure M1 transitions (Table II).

Table II Radiative width of vector mesons (keV)

Meson	Experiment	Ref.	Quark model
ρ^-	67 ± 7	(19)	76
ω^0	789 ± 92	(20)	798
$K^{*-}(892)$	60 ± 15	(18)	83
$K^{*0}(892)$	75 ± 35	(21)	137

In Table II these predictions are compared with recent measurements^{18,19}. The new value observed for the radiative decay of the ρ^- eliminates one of the most striking disagreements encountered previously by the quark model. Kamal and Kane²² have suggested that a possible explanation of the earlier results, i.e. $\Gamma(\rho \rightarrow \pi\gamma) = 35 \pm 10$ keV obtained with 23 GeV/c pion beams, instead of the 200 GeV/c used in Ref. 18, may be found in the presence of isovector hadronic exchange (in addition to the Primakoff effect). They also note that the importance of this exchange could invalidate also the $K^{*0}(892)$ measurements.

4. MESON SPECTROSCOPY

If a simple hadronic oscillator potential is assumed for the $q\bar{q}$ model of the mesons, their spectroscopy can be reduced to a two-parameter classification of nonets,

$$M \sim (2n + L)M_0 = N \cdot M_0,$$

where n is the radial degree of excitation, L the internal orbital angular momentum.

For $N = 0$ we have the two well-known nonets of pseudoscalar and vector mesons ($J^{PC} = 0^{-+}, 1^{--}$).

For $N = 1$ we expect four nonets, with $J^{PC} = 0^{++}, 1^{+-}, 1^{++}, 2^{++}$. The 2^{++} nonet is well identified. This is not yet the case for the other $N = L = 1$ nonets.

4.1 The 0^{++} mesons

The $J^{PC} = 0^{++}$ mesons are exceptionally important for testing our ideas on hadron structure. In addition to the conventional 3P_0 -wave $q\bar{q}$ nonet, a low-lying $q^2\bar{q}^2$ nonet has been proposed²³. The 0^{++} states built from gluons have also been proposed^{24,25}. Inspired by the MIT bag model, Aerts et al.²⁶ have calculated the $q\bar{q}$ spectrum and have found a 0^{++} nonet with masses ~ 1285 MeV for $I = 0$ and $I = 1$, ~ 1475 MeV for the $s\bar{s}$ isovector, and ~ 1380 MeV for $I = 1/2$.

The experimental situation has been clarified by a series of new results. The existence of an $I = 0$ $J^{PC} = 0^{++}$ resonance in the 1300-1400 MeV mass range, mainly coupled to $\pi\pi$, is now firmly established. Not only has it been shown²⁷ that the $\pi^+\pi^-$ S-wave has a resonant behaviour with an intensity peaking ~ 1300 MeV, but Cason et al.²⁸ have produced $\pi^0\pi^0$ data, i.e. $\pi^+p \rightarrow \Delta^{++}\pi^0\pi^0$, which show unambiguously a large S-wave contribution in the broad $\epsilon(700)$ and $\epsilon(1300)$ mass regions, with substantial S- and D-wave interferences (Fig. 4).

Moreover, independent evidence for an $I = 0$ $\epsilon(1300)$ comes from the study of the $K\bar{K}$ system. Görlich et al.²⁹ observe a K^+K^- S-wave enhancement in the 1100-1500 MeV mass region which they tend to attribute to $I = 0$. Loverre et al.³⁰ show that the $K_S^0K_S^0$ S-wave has production properties similar to those of the D-wave at small t and for $M \sim 1300$ MeV (Fig. 5), suggesting that it is produced by π exchange in the reaction $\pi^-p \rightarrow K_S^0K_S^0n$ and therefore must be $I = 0$. Cohen et al.³¹ have now carried out a complete amplitude analysis of the K^+K^- system produced in $\pi^-p \rightarrow K^+K^-n$ and $\pi^+n \rightarrow K^+K^-p$. Having large statistics for both channels, they can separate the $I = 0$ from the $I = 1$ K^+K^- contributions. The analysis leads to several ambiguous solutions, but only one exhibits t dependences consistent with the expected production mechanisms (Fig. 6). This solution presents a large $I = 0$ enhancement at 1300 MeV. Figure 7 shows the $\pi\pi \rightarrow K\bar{K}$ scattering amplitude. The speed variations indicate a resonance at ~ 1425 MeV with $\Gamma \sim 160$ MeV. The Argand plot also shows that the resonance couples asymmetrically to the two channels, $\pi\pi$ being the dominant one, $0.28 < (x_\pi x_K)^{1/2} < 0.40$. The OZI rule predicts $(x_\pi x_K)^{1/2} \sim 0.40$, while a pure SU(3) singlet such as a glueball would have $(x_\pi x_K)^{1/2} \sim 0.50$.

A complete coupled-channel analysis of the $I = 0$ $J^{PC} = 0^{++}$ scattering amplitudes $\pi\pi \rightarrow \pi\pi$, $\pi\pi \rightarrow K\bar{K}$, and $K\bar{K} \rightarrow K\bar{K}$ is still necessary in order to fully understand the scalar mesons. It has been shown³², in particular, how some experimental information on $K\bar{K} \rightarrow K\bar{K}$ could constrain the solutions. Nevertheless, the new data and analyses of Cohen et al.³¹ provide convincing evidence for an $I = 0$ $J^{PC} = 0^{++}$ resonance with $M = 1425 \pm 15$ MeV, $\Gamma = 160 \pm 30$ MeV, the $\pi\pi$ coupling^{27,33} being dominant. In addition, a large background below 1000 MeV and the $S^*(980)$ are both necessary for interpreting the data.

Aston et al.³⁴, using the LASS spectrometer at SLAC, have made a partial-wave analysis of the $K^-\pi^+$ system. The interaction analysed is

$$K^-p \rightarrow K^-\pi^+n \text{ at } 11 \text{ GeV}/c.$$

The $K\pi$ S-wave shows a clear elastic loop on the Argand plot (Fig. 8), which can be interpreted as a resonance with $M \sim 1500$ MeV, $\Gamma \sim 250$ MeV.

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

In conclusion, it seems possible that a 0^{++} nonet emerges in the 1300-1600 MeV mass region. Of course it remains to identify the $I = 1$ and $I = 0$ ($s\bar{s}$) constituents. The simplest decay mode for the $I = 1$ scalar would be $\eta\pi$, a two-body system not yet well known. In this picture, the $\delta(980)$ and $S^*(980)$ could be the $q^2\bar{q}^2$ states $s\bar{s}$ ($u\bar{u} \pm d\bar{d}$) advocated by Jaffé²³. The quark configuration of the $\delta(980)$ and $S^*(980)$ is, however, still open to debate^{35,36}.

4.2 The 1^+ mesons

Our experimental knowledge of the $J^{PC} = 1^{+\pm}$ mesons has recently made important progress; but this is not to say that everything is clear for the two expected nonets.

It is now well established that two resonances are observed in the $K\pi\pi$ system with $J^P = 1^+$: the Q_1 with $M \sim 1270$ MeV, $\Gamma \sim 80$ MeV decaying mainly into $K\rho$; the Q_2 , with $M \sim 1400$ MeV, $\Gamma \sim 200$ MeV, decaying mainly into $K^*\pi$. These results come mainly from the diffractively produced $K\pi\pi$ system^{37,38}. In fact, the Q_1 was first observed in $\bar{p}p$ annihilations at rest³⁹, and called at that time the $C(1240)$ meson. The Q_1 is also observed in non-diffractive reactions, such as

$$\pi^- p \rightarrow (K\pi\pi)^0 \Lambda^0.$$

New results are available on this reaction at 3.9 GeV/c⁴⁰. A Q_1 is clearly observed (Fig. 9) with $M = 1294 \pm 10$, $\Gamma = 66 \pm 15$ MeV, and a partial-wave analysis shows that it is mainly a $J^P = 1^+$ $K\rho$ S-wave. The peak observed at 1435 MeV is attributed as a whole to the $K^*(1435)$. The same collaboration gives an upper limit for the ratio $K\omega/K\rho$ of 30%, to be contrasted with the observation of a $K\omega$ peak in the diffraction data which is claimed³⁸ to be mainly associated with the Q_1 . This uncertainty on the $K\omega$ partial width of the Q_1 must be kept in mind when discussing the $1^\pm$ nonets' characteristics. For the first time, the ACCMOR Collaboration³⁸ sees the $K^*\pi$ D-wave contribution to the Q_1 - Q_2 resonances, which fits nicely with the absence of $\rho\pi$ D-wave in the $A_1(1100-1300)$ meson and the D/S ratio of 30% observed for the $\omega\pi$ decay of the $B(1235)$ meson.

Recently, the ACCMOR Collaboration⁴¹ has published evidence showing that the diffractively produced 1^+ $\rho\pi$ S-wave in the reaction $\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$ at 63 and 94 GeV/c incident momenta contains a resonant component with a mass of 1280 ± 30 MeV and a width of 300 ± 30 MeV. It is well known that the production of A_1 in diffractive reactions is confused by the presence of Deck processes. The mass and width quoted above have been reached with the use of a formulation proposed by Bowler⁴². New results on the A_1 have been presented at this conference⁴³, using large statistics on the neutral ($\pi^+ \pi^- \pi^0$) spectrum produced in forward exchange at 8.45 GeV/c,

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

This analysis is particularly interesting since it can separate four incoherent contributions having natural or unnatural parity exchange and nuclear helicity flip or non-flip. Both partial waves

with $I = 1$ and $I = 0$, $J^P = 1^+$ $\rho\pi$ S-waves, have a significant contribution and both peak at ~ 1130 MeV in the 3π mass spectrum (Fig. 10a and 10c) for the natural parity exchange, nuclear helicity flip sample. Figure 10 also shows the exotic $I = 2$ $J^P = 1^+$ $\rho\pi$ S-waves: the $M = 1$ (Fig. 10b) is barely detectable, but the $M = 0$ component (Fig. 10d) is sufficiently robust to serve as a phase reference. Figure 10e shows the $A_2(1310)$ meson. The phases of the $I = 0$ and $I = 1$ $J^P = 1^+$ $\rho\pi$ partial waves, relative to the exotic $I = 2$ or to the $A_2(1310)$, show a large forward motion of $\sim 150^\circ$, establishing the resonant character of these $J^P = 1^+$ waves. This is the first convincing evidence for the existence of the isoscalar $H(1190)$ $J^P = 1^+$ $\rho\pi$ resonance.

To obtain the resonance parameters of the H and A_1 , Dankowych et al.⁴³ have applied, as did the ACCMOR Collaboration, the formulation of Bowler which treats the Deck-like background in a coherent way. As in the purely diffractive case, a consequence of this formulation is to shift the mass from ~ 1100 MeV, where the peaks are observed, to ~ 1200 MeV. More precisely, Dankowych quotes the following masses and widths:

$$\begin{array}{llll} I = 1 & A_1 & M = 1240 \pm 80 \text{ MeV} & \Gamma = 280-480 \text{ MeV} \\ I = 0 & H & M = 1190 \pm 60 \text{ MeV} & \Gamma = 270-370 \text{ MeV} . \end{array}$$

Other observations of the $I = 1$ $J^{PC} = 1^{++}$ (A_1) come from baryon-exchange reactions, which are free from Deck processes (but of course may have other kinds of background).

In particular, Gavillet et al.⁴⁴ observe a peak in the $\pi^+\pi^-\pi^-$ mass spectrum of the reaction

$$K^-p \rightarrow \Sigma^- \pi^+ \pi^- \pi^- \quad \text{at } 4.2 \text{ GeV}/c .$$

This collaboration has now achieved a new partial-wave analysis of the 3π system, and finds a phase variation of the 1^+ $\rho\pi$ S-wave which supports the resonance hypothesis for the peak observed at 1050 MeV with a width of 200 MeV. Although this resonance has all the quantum numbers and decay properties observed in diffractive and charge-exchange processes, the mass (1050 compared to more than 1200 MeV) are not compatible. It is possible that the diffractive (and to some extent the charge-exchange) data, although strongly

Fig. 9

Fig. 10

indicating the presence of a resonant contribution to the A_1 enhancement, do not give a precise determination of the mass, since the presence of Deck contributions makes it necessary to solve this problem in a model-dependent way. It is also possible that baryon exchange mechanisms have their own complexities which would require much larger statistics in order to be fully appreciated. A more attractive hypothesis may be that both results are correct, and that the A_1 observed with $M \sim 1240$ MeV is the $q\bar{q}$ partner of the 1^{++} nonet, whereas the A_1 observed with $M \sim 1050$ MeV is of a more exotic nature, a $2q2\bar{q}$ object being more naturally expected in these reactions if the t -exchange is non-exotic. Note finally that Aerts et al.²⁶ predict a mass of 1285 MeV for the $J^{PC} = 1^{++}$ isovector $q\bar{q}$ (non-strange) meson.

To complete the 1^+ meson review, we must now discuss the status of the E meson. In "classical" hadron interactions, (π^-p , K^-p , $\bar{p}p$ annihilations in flight), one observes two relatively narrow peaks in the $K\bar{K}\pi$ mass spectrum: the $D(1285)$ and the $E(1420)$. See, for instance, the new results of Dionisi et al.⁴⁵ and of Bromberg et al.⁴⁶ (Figs. 11 and 12).

The quantum numbers of the D are well established: $I^G J^P = 0^+ 1^+$. Those of the E have been uncertain for several years. A new analysis⁴⁵ now gives convincing evidence that, for the E also, $I^G J^P = 0^+ 1^+$.

The D has not enough phase space to decay into K^*K . Most authors attribute its $K\bar{K}\pi$ decay to $D \rightarrow \delta\pi$, $\delta \rightarrow K\bar{K}$. Since the $\delta(980)$ has a large $\eta\pi$ decay mode, the D should also be observed in the $\eta\pi\pi$ system -- and it is. This is not the case for the E , the K^*K decay mode being dominant (86% according to Ref. 45, 76% according to Ref. 46). Note that, in the $K_S^0 K^\pm \pi^\mp$ Dalitz plot of the E , the two K^* interfere constructively ($C = +1$) and therefore create a large accumulation near the $K\bar{K}$ threshold. Therefore a δ cut is an efficient selection for enhancing the E (and the D) over the $K_S^0 K^\pm \pi^\mp$ background (Fig. 12).

Fig. 11

Fig. 12

With these observations it makes sense to attribute the D and the E to the $J^{PC} = 1^{++}$ nonet, the E being a " ϕ -like" object made primarily of $s\bar{s}$ quarks, with the following new determinations of its mass and width:

$$\text{Ref. 45: } M = 1426 \pm 6 \text{ MeV} \quad \Gamma = 40 \pm 15 \text{ MeV} ,$$

$$\text{Ref. 46: } M = 1440 \pm 5 \text{ MeV} \quad \Gamma = 62 \pm 14 \text{ MeV} .$$

However, $\bar{p}p$ annihilation at rest⁴⁷ and the radiative decay modes of the J/ψ ^{48,49} also show a $K\bar{K}\pi$ enhancement at 1425 MeV with a width which may be slightly larger than the one observed in classical hadronic interactions, i.e. $\Gamma \sim 80 \text{ MeV}$, but which is not accompanied by the D(1285) (Figs. 13 and 14). This is particularly remarkable for annihilations at rest, where the 1425 MeV $K\bar{K}\pi$ enhancement was indeed originally observed with no visible D(1285), whereas for $\bar{p}p$ annihilations in flight, i.e. at 700–750 MeV/c⁵⁰, both D(1285) and E(1425) are clearly observed. Moreover, this E seems to have a larger branching ratio into $\delta\pi$ than the one observed in π^-p and $\bar{p}p$ annihilations in flight: the $\eta\pi^+\pi^-$ mode is observed (Fig. 15) and a branching ratio $E \rightarrow \delta\pi$ as large as 50% is given⁴⁷. A spin-parity determination of this E favours 0^{-+} over 1^{++} .

It may not be a surprise that $\bar{p}p$ annihilations at rest show some similarities to the J/ψ decays, since the dominant $\bar{p}p$ initial state is 3S_1 , a state which has the quantum numbers of the J/ψ .

Fig. 13

Fig. 14

Fig. 15

An attractive interpretation of these observations is to assume that in $\bar{p}p$ annihilations at rest and in the radiative decay of J/ψ one produces a resonance which is not the $I = 0$ $s\bar{s}$ $J^{PC} = 1^{++}$ of the quark model, but may be a $2q2\bar{q}$ or a glueball object.

4.3 Higher-L excitations

The partial-wave analysis of high statistics experiments performed at high energy have succeeded in establishing the existence of several higher-spin states schematically represented in Fig. 16.

Of the four $q\bar{q}$ nonets corresponding to $L = 2$ (3^{--} , 2^{--} , 2^{-+} , 1^{--}), only one (3^{--}) is relatively well known. The ACCMOR Collaboration⁵¹ has presented conclusive evidence for the existence of an $A_3(1670)$ meson, with $\Gamma \sim 210$ MeV, $J^{PC} = 2^{-+}$, a peak and corresponding phase variation being observed in three partial waves: $2^{-}S(f\pi)$, $2^{-}P(\rho\pi)$, and $2^{-}D(\epsilon\pi)$. The same collaboration has also shown that the $K\pi\pi$ diffractive system contains at least one resonant component, at $M \sim 1820$ MeV, $\Gamma \sim 200$ MeV, with $J^P = 2^{-}$, peaks and phase variations again being observed in three partial waves, i.e. $2^{-}S(K^{*}\pi)$, $2^{-}P(K^{*}\pi)$ and $2^{-}D(Kf)$. However, even with the large statistics available in this experiment, it is not yet possible to disentangle the two resonant states (2^{--} , 2^{-+}) which are expected in this mass region.

The $F_1(1540)$ has been considered for some time as a possible 2^{-} candidate. It has now been shown⁵⁰ that this $K\bar{K}\pi$ enhancement is not a genuine resonance.

For the $L = 3$ nonets, we now have to add three recently observed resonances to the $I^G J^P = 0^{+}4^{+}$ $h(2040)$. The ACCMOR Collaboration³⁸ observes a peak and a phase variation for the $2^{+}P(f\pi)$ partial wave with $M \sim 1700$ MeV and $\Gamma \sim 200$ MeV, which may be interpreted as the $I = 1$ member of the 3F_2 $q\bar{q}$ nonet (Fig. 17). Cleland et al.⁵² observe a peak and phase variation for the $I^G J^P = 1^{-}4^{+}$ ($K_S^0 K^{\pm}$) partial wave with $M \sim 2000$, $\Gamma \sim 250$ MeV, and for the $I^G J^P = 1^{-}6^{+}$ ($K_S^0 K^{\pm}$) partial wave with $M \sim 2515$, $\Gamma \sim 450$ MeV (Fig. 18). The same collaboration, analysing the $K_S^0 \pi^{\pm}$ system produced at small t in the reactions

$$K^{\pm} p \rightarrow (K_S^0 \pi^{\pm}) p$$

at 50 GeV/c, finds also a peak and a phase variation for the $J^P = 4^{+}$ partial wave with $M \sim 2060$ MeV, $\Gamma \sim 150$ MeV, in addition to the tail of the $K^{*}(1425)$ and to the $J^P = 3^{-}K^{*}(1780)$ resonance (Fig. 19).

Finally, the ACCMOR Collaboration⁵³ observes a bump in the $K^{+}K^{-}$ system produced at small t in the reaction

$$\pi^{-} p \rightarrow K^{+} K^{-} n$$

at 60 GeV/c, the decay angular distribution indicating the dominance of a $J^P = 5^{-}$ wave at $M \sim 2300$, $\Gamma \sim 260$ MeV to which it seems reasonable to assign $I^G = 1^{+}$ (Fig. 20).

All these new resonances fall nicely on linear spin-mass squared meson trajectories (Fig. 16).

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

4.4 Heavy vector mesons

Recent results from photoproduction and e^+e^- experiments have very much increased our information on heavy vector mesons. Note that the quark model predicts the existence of two nonets of $J^{PC} = 1^{--}$ in the 1200-1800 MeV mass region, the $n = 0$, $L = 2$ 3D_1 and the $n = 1$, $L = 0$ 3P_1 nonet.

It has been known for some time that the annihilation

$$e^+e^- \rightarrow 2\pi^+2\pi^-$$

presents a maximum around 1600 MeV, with $\Gamma \sim 500$ MeV, called the $\rho'(1600)$. Bizot et al.⁵⁴ have combined their measurements, made between 1.4 and 2.2 GeV, with those of Novosibirsk⁵⁵ (Fig. 21), and get a mass which varies from 1580 to 1630 MeV with Γ varying from 465 to 540 MeV, depending on the model used for the $4\pi^\pm$ dynamics. This is in good agreement with the results presented by d'Almagne⁵⁶ on the reaction

$$\gamma p \rightarrow 2\pi^+2\pi^-p.$$

The $\rho\pi$ decay mode is presumably dominant. However, d'Almagne claims that he needs a contribution from the $A_1\pi$ channel to interpret his data. The $\rho\pi$ decay mode produces a bump in the reaction

$$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0, \quad \text{with } \sigma_{+-00} \sim \frac{1}{2} \sigma_{++--},$$

but, in addition, one observes for this reaction a maximum around 1300 MeV which is attributed to another ρ' , the $\rho'(1250) \rightarrow \omega^0\pi^0$, with

Fig. 21

$M \sim 1250$ MeV, $\Gamma \sim 250$ MeV (Fig. 21). This $\rho'(1250)$ is also clearly observed in the photoproduction data⁵⁶, the decay angular distributions supporting the hypothesis $J^P = 1^-$, and not 1^+ as expected for the $B(1235) \rightarrow \omega^0 \pi$ meson. However, the resonant character of this $\rho'(1250)$ is not yet firmly established.

The problem raised by the $\pi^+\pi^-$, $K_S^0 K_L^0$, K^+K^- possible decay modes of these ρ 's is not easy to solve. In photoproduction experiments^{56, 57} a $\rho' \rightarrow \pi^+\pi^-$ is observed, but with a width which is much smaller than the one in the 4π decays: $\Gamma \sim 250$ MeV, suggesting that simple fits adding Breit-Wigners incoherently on a "smooth" background are misleading. In these conditions, it is difficult to quote a branching ratio for the $\rho'(1600)$. Photoproduction experiments tend to favour a relatively small branching ratio $2\pi^\pm/4\pi^\pm \sim 10-20\%$, which is in agreement with the inelasticity measured for the 1^- partial wave observed in the phase-shift analyses of the $\pi^-p \rightarrow \pi^+\pi^-n$ reaction.

Bizot et al.⁵⁴ note that one cannot interpret simultaneously the annihilations

$$e^+e^- \rightarrow K_S^0 K_L^0 \quad \text{and} \quad e^+e^- \rightarrow K^+K^-$$

without the introduction not only of a $\rho'(1600)$ but also of an isoscalar resonance which interferes constructively with the ρ' in the K^+K^- channel and destructively in the $K_S^0 K_L^0$ one. A fit for this isoscalar gives $M = 1674 \pm 6$ MeV, $\Gamma = 94 \pm 30$ MeV. These numbers are similar to those obtained for the enhancement observed in the annihilations

$$e^+e^- \rightarrow \omega^0 \pi^+\pi^-$$

(Fig. 22), ($M = 1634 \pm 9$ MeV and $\Gamma = 89 \pm 32$ MeV)⁵⁴. The same structure is observed by d'Almagne⁵⁶ in photoproduction.

This isoscalar is probably the ϕ' partner (and not the ω') of the $\rho'(1600)$: its width is relatively narrow [compared to the $\rho'(1600)$], and it has a significant coupling to $K\bar{K}$ and an even larger coupling to $K_S^0 K^\pm \pi^\mp$, where an enhancement is observed (Fig. 23), with

Fig. 22

Fig. 23

$K^{*0}K^0 - K^{*-}K^+$ interference effects which require a large $I = 0$ contribution. All these observations are made with e^+e^- annihilations⁵⁴ as well as with photoproduction⁵⁶. In this last case, the 5π structure observed at 1600 MeV with $\Gamma \sim 100$ MeV is superimposed on a large $\omega^0\pi^+\pi^-$ threshold enhancement which extends from 1500 to 2000 MeV: one may speculate that the ω' partner of the $\rho'(1600)$ is hidden in this enhancement.

To complete this short review on heavy vector mesons, one may add the information which comes from two experiments, both of them studying the K^+K^- final state. Amirzadeh et al.⁵⁸ have analysed the reaction $K^-p \rightarrow \Lambda^0 K^+K^-$ at 8 GeV/c, and see two peaks in the K^+K^- mass spectrum above 1200 MeV, the $f'(1515)$ and a second peak at 1851 MeV (Fig. 24). This is supported by the observations made by Frame et al.⁵⁹, who have analysed the reaction $K^+p \rightarrow K^+K^-K^+p$ at 13 GeV/c, and see also two enhancements, the $f'(1515)$ and a peak at 1830 ± 9 MeV, $\Gamma = 72 \pm 3$ MeV. Although we present these results in the context of heavy vector mesons, the spin parity of this new resonance has not been determined: it could be, indeed, the $J^P = 3^-$ state which is still missing in the 3D_3 nonet.

Finally, the partial-wave analysis performed by Aston et al.³⁴ on the $K^-\pi^+$ system produced in

$$K^-p \rightarrow K^-\pi^+n \quad \text{at 11 GeV/c}$$

shows two loops in the Argand plot of the P-wave, a large elastic loop corresponding to the $K^*(892)$ and an inelastic one, with maximum speed around 1650 MeV (Fig. 25).

Conclusions: The heavy vector mesons exist. With the $\rho'(1600)$ one may associate a $\phi'(1670)$ and a $K^{*'}(1650)$. In addition, hints of an $\omega' \rightarrow \omega\pi\pi\pi$ and of another ρ' , with $M \sim 1250$ MeV and $\omega^0\pi^+$ as a dominant decay mode, come from e^+e^- annihilations, photoproduction, and $\bar{p}p$ annihilations at rest⁶⁰.

Fig. 24

Fig. 25

5. BARYON SPECTROSCOPY

The experimental information on baryons being much more complete than for other hadrons, the baryons have been considered as the best field for testing our ideas on the quark model, although they are made of three quarks and therefore require, in principle, the solution of a three-body problem.

The usual non-relativistic quark model for baryons starts from the wave function

$$|3\rangle = \underbrace{|\text{Flavour}\rangle|\text{Spin}\rangle|\text{Space}\rangle}_{\text{SU}(6) \otimes \text{O}(3)} |\text{Colour}\rangle$$

$\otimes 1_c$

and approximates the quark binding forces with a two-body harmonic interaction which leads to the famous harmonic oscillator shell model with radial and orbital excitation⁶¹. Using the notation $[\text{SU}(6), L^P]$, L being the orbital excitation and P the parity of the states, we get, for the first three levels:

$$\begin{array}{l|l} N = 2 & [56, 2^+], [70, 2^+], [56, 0^+], [70, 0^+], [20, 1^+] \\ N = 1 & [70, 1^-] \\ N = 0 & [56, 0^+] \end{array}$$

This model works remarkably well. Not only have we been able to identify all the members of the $N = 0$ level (one octet with $J^P = \frac{1}{2}^+$ and one decuplet with $J^P = \frac{3}{2}^+$), but 18 out of the 21 $N^* + \Delta + \Lambda + \Sigma$ predicted for the second level (negative parity) are observed and a number of good candidates have been identified for the third level. However, this simple model encounters serious difficulties when interpreting the mass spectra and decay properties simultaneously. It predicts too many states.

Starting from this framework and adding some prejudices about quark dynamics,

- confinement of the quarks in a flavour- and spin-independent long-range potential,
- introduction of a perturbative term at short distances represented by one-gluon exchange,
- flavour symmetry-breaking entirely due to the constituent quark mass differences,
- non-relativistic approach to the decays, assuming that they proceed through a single quark transition with photon or meson emission,

Isgur, Karl and Koniuk⁶² have shown that it is possible to go a long way inside a detailed interpretation of the mass spectra and decay

Fig. 26

modes of the baryons with a non-relativistic quark model. Figure 26 shows schematically some of the achievements of this model for the $S = 0$ baryons with positive and negative parity. The predictions are represented by thick lines of length proportional to the coupling to the initial state. The experimental results are represented by boxes giving the regions in which the masses of the resonances should most likely lie. Most predicted resonances with a large coupling fall inside or close to a box. Those which have a small coupling to the initial state are not, as expected, observed.

5.1 The $S = 0$ sector

For the $S = 0$ sector, most of our experimental information comes from $\pi^\pm p$ partial-wave analyses made by the CMU-LBL Collaboration⁶³, the Helsinki-Karlsruhe Collaboration⁶⁴, and the recent analysis of Chew⁶⁵. Although these analyses use different approaches, their conclusions, as shown for example in Fig. 27 for the Δ 's and Fig. 28 for N^* 's, are generally in good agreement. The CMU-LBL partial-wave analysis concentrates on the energy region above the $\Delta(1232)$, combines data from various experiments, and performs energy-independent fits, using a parametrization which incorporates t - and u -channel analyticity. Several minima are then combined into clusters characterized

Fig. 27

Fig. 28

by a correlated set of partial-wave amplitudes. The results on individual partial-wave amplitudes are then fitted with a coupled channel plus background parametrization. The Karlsruhe-Helsinki analysis extends to 10 GeV/c. Energy-independent fits are performed. Analyticity and dispersion relation constraints are introduced for fixed s , fixed t , and fixed ϕ amplitudes. Chew has analysed the π^+p elastic scattering data between 0.6 and 2.3 GeV/c, using the method of Barrelet's zeros. Transversity amplitudes at fixed energy are parametrized in terms of polynomials in $w = e^{i\phi}$. The most recent results of this analysis suggest that four S_{31} and four P_{31} resonances coexist in the 1700-2200 MeV mass range. The exact status of the $S_{31}(1620)$ resonances is important since, in the harmonic oscillator quark model, it degenerates with the $D_{33}(1700)$. The CMU-LBL analysis suggests that these two states have a definite mass difference.

Hendry⁶⁶ has analysed the 2 to 4 GeV mass region. He finds numerous candidates with spins going from $G_{3,9}$ to $N_{3,21}$. These results are in fair agreement with K-H⁶⁴ up to $K_{3,15}$. These resonances do not lie on a linear Regge trajectory (Fig. 29) but if drawn, instead, on a spin- k (the c.m. momentum of the coupled pion-nucleon channel) plot, they do lie on a straight line (for N^* as well as for Δ), suggesting that centrifugal barrier effects are important (Fig. 30). It seems difficult⁶⁶ to reconcile the large widths observed for these high-spin states with estimates based on the quark model.

Fig. 29

Fig. 30

Fig. 31

Fig. 32

The agreement between the partial-wave analysis and the remarkable success of the non-relativistic model of Isgur-Karl-Koniuk should not distract our attention from the weaknesses which need to be cured.

New measurements on π^-p elastic scattering and charge-exchange measurements between 2 and 4 GeV/c made at KEK⁶⁷ have revealed the weaknesses of the partial-wave analysis predictions, which are not even qualitatively good for the new polarization data (Fig. 31).

Some measurements of the π^+p elastic scattering at large angles in the 2-6 GeV/c momentum range observe narrow structures which seem qualitatively consistent with the Ericson fluctuation mechanism⁶⁸. Other very accurate measurements of the same reactions in the 6-14 GeV/c momentum range do not show these narrow structures⁶⁹. Narrow baryon resonances seem to be observed in the diffraction processes. Fukunaga et al.⁷⁰, who have compiled the πN and $\pi\pi N$ data observed in diffraction dissociation (Fig. 32), show that these data do not match very well with the partial-wave resonances $P_{11}(1470)$ and $F_{15}(1690)$ with which they are usually associated. A detailed analysis of the diffractive dissociation processes

$$\pi^+p \rightarrow \pi^+(\pi^+n)$$

$$\text{and } \pi^+p \rightarrow \pi^+(\pi^0p)$$

at 16 GeV/c⁷¹, with a mass resolution of ~ 10 MeV, shows that the πN diffractive enhancement is best interpreted, at $t < 0.1$ GeV², in terms of two narrow peaks, with $M = 1344 \pm 5$, $\Gamma = 66 \pm 14$, and $M = 1451 \pm 7$, $\Gamma = 132 \pm 22$ MeV (Fig. 33), whereas, at $t > 0.2$ GeV², a two-peak structure shows up with $M = 1450$, $\Gamma = 130$ MeV and $M = 1639 \pm 7$, $\Gamma = 96 \pm 20$ MeV. (Fig. 34).

Fig. 33

Fig. 34

A re-examination of the world data on the πN diffractive system leads these authors to the observation of two peaks, $M = 1471 \pm 3$, $\Gamma = 86 \pm 8$ MeV, and $M = 1655 \pm 5$, $\Gamma = 110 \pm 11$ MeV. A similar analysis of the $\pi\pi N$ diffractive system gives also two peaks, with $M = 1450 \pm 3$, $\Gamma = 98 \pm 7$ MeV, and $M = 1705 \pm 2$, $\Gamma = 84 \pm 4$ MeV. It should be noted that interference effects may take place between the Deck mechanism and the direct production of resonances. In general, they shift the mass determinations and enlarge the widths, so that the broad resonances observed in formation cannot become narrower with Deck interference effects. Moreover, the three peaks (1.34, 1.46, and 1.70 GeV) do not move with t' , whereas Deck effects would. One is led to the conclusions that $N^*(1.34)$ with $\Gamma = 66 \pm 14$ MeV has no analogue in formation experiments, and that $N^*(1.46)$ with $\Gamma \sim 90$ MeV cannot be $P_{11}(1470)$, which has a width between 180-240 MeV, nor $D_{13}(1520)$, which has a mass between 1510 and 1530 MeV. If the difference in mass between $N^*(1.66) \rightarrow \pi N$ and $N^*(1.71) \rightarrow \pi\pi N$ is statistically significant, it becomes unrealistic to consider both of them as being due to a single resonance $F_{15}(1890)$. The $N^*(1.71) \rightarrow \pi\pi N$ could be associated with $D_{13}''(1700)$, 90% of its decay being $\pi\pi N$.

These results open up the interesting speculation that Pomeron exchange creates a new type of resonance⁷². It may also be appropriate to underline that such low-mass N^* resonances would not fit easily into the simple quark model, but may find a less difficult interpretation within the framework of the MIT bag model⁷³.

Extensive measurements of $\pi^- p$ inelastic reactions have been made at RHEL⁷⁴, and the isobar model has been applied to the channel $\pi N \rightarrow \pi\pi N$ ^{75,76}, bringing us new information on the P_{11} , S_{31} , P_{31} , P_{33} , and D_{33} waves. One of the most interesting results of these analyses is the claim that there is a narrow P_{31} state around 1525 MeV, $\Gamma \sim 40$ MeV, again rather difficult to accommodate in the simple quark model. A more detailed discussion of these results may be found elsewhere^{77,78}.

One of the most significant threshold enhancements which may be interpreted as an inelastic $N^*(1810)$ resonance is the ωp threshold peak observed by Arenton et al.⁷⁹, using the polarized proton beam of the ZGS:

$$p \uparrow p \rightarrow p \omega p .$$

The t-distribution suggests ω -exchange, and the ωp angular distributions are qualitatively consistent with $J^P = \frac{3}{2}^-$ for an N^* which would have a mass of 1810 ± 25 and a width of 140 ± 40 MeV. As is often the case for threshold enhancements, the resonance nature of the peak is difficult to establish with confidence.

5.2 The $S = -1$ sector

We have already underlined the general good agreement between the experimental observations and the simple non-relativistic quark model⁶² for the $S = 0$ sector. The same agreement applies for the $S = 1$ sector (Fig. 35). The model does not reproduce the mass splitting of the $\Lambda(1405)$ and $\Lambda(1520)$. However, it should be noted that the model ignores spin-orbit forces. Another apparent difficulty is that the model does not predict large enough widths. This, however, may be partially due to the experimental methods, the widths generally quoted being those observed in the partial-wave analyses of formation experiments, notably larger than those observed in production experiments. In addition, several production experiments report the observation of generally narrow Y^* 's which have no obvious counterparts in the Y^* spectroscopy deduced from formation experiments.

The ACNO Collaboration has reported three such Y^* 's: i) A $\Sigma(1550)$ produced in a rather complex final state: $K^- p \rightarrow \Sigma^\pm(1550) K_S^0 K^\mp$ at 4.2 GeV/c incident momentum⁸⁰, the $\Sigma^+(1550)$ being produced mostly backward, the $\Sigma^-(1550)$ mostly forward. The mass and width are 1553 ± 7 and 80 ± 30 MeV, respectively. The main decay modes seem to be $\Lambda\pi^\pm$ and $\Sigma^0\pi^\pm$. ii) A $\Sigma(2230)$, observed⁸¹ in the reactions $K^- p \rightarrow \Sigma^\pm\omega^0\pi^\mp$, $\Sigma^\pm(2230) \rightarrow \Sigma^\pm\omega^0$, the $\Sigma^+(2230)$ again being produced mostly backward, the $\Sigma^-(2230)$ mainly forward. The mass and width are 2230 ± 30 and 60 ± 20 MeV, respectively. iii) A $Y^*(2580)$, observed⁸² in the reaction $K^- p \rightarrow Y^*(2580)\pi^0$, with a rather complex decay mode, involving three strange particles,

$$Y^*(2580) \rightarrow \Sigma^\pm K^\pm K_S^0.$$

The mass and width of this peak are 2576 ± 10 and 37 ± 11 MeV (Fig. 36). No charge decay is observed, suggesting that this $Y^*(2580)$ is a Λ^0 .

Fig. 35

Fig. 36

The CCMS Collaboration⁸³ has presented evidence for a low-mass Y^* , the $\Sigma(1460)$, observed at the K^-n threshold of the reaction

$$\pi^- p \rightarrow (K^- n) K_S^0 \pi^+ \quad \text{at } 3.9 \text{ GeV/c},$$

with also some evidence for a $(\Sigma^0 \pi^0)$ decay mode (Fig. 37). The mass and width of this peak are 1464 ± 8 and 44 ± 24 MeV, respectively. This resonance may have been observed previously by Yu-Li Pan⁸⁴ in the reactions

$$\pi^+ p \rightarrow (\Lambda \pi)^+ K^+, \quad (\Sigma \pi)^+ K^+ \quad \text{at } 1.7 \text{ GeV/c},$$

but in this case, it seems that the predominant decay mode was $\Lambda \pi^+$, which is not observed by CCMS.

None of these four Y^* having an obvious candidate among the Y^* 's observed in formation experiments, and most of them being produced in complex reactions or having complex decay modes, they may be seriously considered as candidates for more complex objects than those predicted by the three-quark model.

The most remarkable Y^* observed in production experiments may be the $R(3170)$, reported by the BCGMP⁸⁵ Collaboration, the data coming from two experiments, both studying the reaction

$$K^- p \rightarrow \pi^- R^+ \quad \text{at } 6.5 \text{ and } 8.25 \text{ GeV/c}.$$

The $R^+(3170)$ is a relatively narrow peak observed in five- and six-body combinations containing several strange particles (Fig. 38). The $R^+(3170)$ is produced forward, implying $I = \frac{3}{2}$ baryon exchange in the t -channel. $I = 1$ is consistent with the observation of a small R^0 signal. Its mass and width are 3170 ± 5 MeV and $\Gamma < 20$ MeV, respectively. With these characteristics, the $R(3170)$ could be a new type of hadron: H. Lipkin has suggested that it could be a bound $BB\bar{B}$ state.

Fig. 37

Fig. 38

5.3 The $S = -2$ sector

It is well known that many Ξ^* are still missing in the SU(6) classification. Apart from the $\Xi^-(1321)$ and $\Xi^*(1530)$, which are the two members of the $[56, 0^+]$ $N = 0$ level, two Ξ^* are reasonably well established, although we do not know the parity of the $\Xi^*(1820)$, which however has a spin $J \geq 3/2$, and do not know the spin and parity of the $\Xi^*(2030)$. Claims have been made for two other Ξ^* , the $\Xi^*(1630) \rightarrow \Xi\pi$ and the $\Xi^*(1940) \rightarrow \Xi\pi$, $\Xi(1530)\pi$, but, strangely enough, no new information has come from recent high-statistics experiments on these two evasive resonances.

Two other Ξ^* have recently been observed. The ACNO Collaboration⁸⁶ has presented evidence for an enhancement at the $\Sigma\bar{K}$ threshold, which appears both in the neutral and negative charge states. Weak evidence for a corresponding $\Lambda\bar{K}$ enhancement is also presented, and a $(\Sigma\bar{K})-(\Lambda\bar{K})$ coupled channel analysis gives results compatible with the existence of a $\Xi^*(1680)$: $M = (1684 \pm 5) \text{ MeV}$, $\Gamma = (20 \pm 4) \text{ MeV}$. Its closeness to the $\Sigma\bar{K}$ threshold favours qualitatively the $J^P = 1/2^-$ assignment. The other new Ξ^* comes from the observation made by the BCGMP Collaboration⁸⁵ of $\Xi^*(2370)$, which has the remarkable feature of having a dominant three-body decay, $Y\bar{K}\pi$ (Fig. 39). However, 48% of its observed decay modes can be attributed to quasi-two-body decays, including 24% of $\Lambda\bar{K}^*(892)$, 15% of $\Sigma^*(1385) K^0$, and $9 \pm 4\%$ of $\Omega^- K^0$. This $\Xi^*(2370)$, with $M = (2373 \pm 7) \text{ MeV}$ and $\Gamma = (85 \pm 20) \text{ MeV}$, seems to be produced by $I = 0$ exchange (Λ exchange), so that $I = 1/2$ is preferred.

As we see, the Ξ^* spectroscopy is still at an embryonic stage. New techniques are certainly necessary to change this situation: this may be the case with the advent of good hyperon beams at Fermilab and CERN.

Fig. 39

Fig. 40

Fig. 41

5.4 The $S = -3$ sector

If the last two years have been very successful for the Ω^- (lifetime, decay modes, weak decay parameters, etc.), no Ω^+ have yet been observed. In contrast, five Δ 's are well known [in SU(3), we expect to observe as many Ω^* 's as Δ 's]. The most significant work on Ω^* has been presented by the BCGMP Collaboration⁸⁵ (Fig. 40). The Ω^* have been searched for in $\Omega^- \pi^+ \pi^-$, $\Xi \bar{K}$, $\Xi \bar{K} \pi$ mass spectra. There may be a hint of an accumulation around 2180 MeV (11 ± 4 events) in the $\Omega^- \pi^+ \pi^-$, but no really convincing effect.

It seems that the $\Omega^- \pi^\pm$ mass spectrum (Ω^* forbidden by I-spin) presents a threshold enhancement (Fig. 41).

6. BARYONIA

In the past years, the baryonia have represented one of the most favoured fields in the search for new states which would not fit with the simple $(q\bar{q}, 3q)$ model. One usually means by "baryonium" a state which has a relatively large coupling to the baryon-antibaryon system. Experimentally, one conventionally classes the baryonia into two categories, according to their widths: the broad ones and the narrow ones. Theoretically, this separation is fundamental since the narrow baryonia could be taken as a beautiful confirmation of QCD⁸⁷.

The broad baryonium field is still flourishing. The narrow baryonium field is dead. One previously narrow baryonium [the S(1936)] has become broad. A recent theoretical and experimental review has been published elsewhere⁸⁸.

It is well known that, in total, elastic, and $\bar{p}p$ annihilation cross-sections, broad bumps have been observed in the 2100-2400 MeV mass region. Three broad enhancements have been identified with the following properties:

$T_1(2190)$	$M = (2185 \pm 5) \text{ MeV}$	$\Gamma = (130 \pm 30) \text{ MeV}$	$I = 1$
$U_1(2350)$	$M = (2350 \pm 5) \text{ MeV}$	$\Gamma = (185 \pm 20) \text{ MeV}$	$I = 1$
$U_0(2390)$	$M = (2385 \pm 10) \text{ MeV}$	$\Gamma = (80 \pm 30) \text{ MeV}$	$I = 0$

Partial-wave analyses of the two-body annihilations $\bar{p}p \rightarrow \pi^+\pi^-$ and $\bar{p}p \rightarrow \pi^0\pi^0$ have shown that nearly all the partial waves, from 3D_1 to 3G_5 , have a resonant behaviour in this mass range, with an indication that the total spin increases with the mass^{89,90}. However, these resonances contribute to only a small fraction (10 to 20%) of the bumps observed in the total cross-section. In other words, these resonances could have relatively large elasticity, giving some support to the baryonium interpretation. In Fig. 42 we sketch what may happen in the T-U region.

The S(1936) seems to present a similar situation. New high-statistics measurements on the total, charge-exchange, and annihilation $\bar{p}p$, $\bar{p}n$ cross-sections^{91,92} conclude that an enhancement is present in the total and annihilation cross-sections, with the following features (Fig. 43):

$$\begin{aligned}\sigma_{\text{tot}} &= 3.0 \pm 0.7 \text{ mb} & M &= (1939 \pm 2) \text{ MeV} & \Gamma &= (22 \pm 6) \text{ MeV} \\ \sigma_{\text{ann}} &= 2.5 \pm 0.8 \text{ mb} & M &= (1937 \pm 2) \text{ MeV} & \Gamma &= (21 \pm 10) \text{ MeV} .\end{aligned}$$

Most of the recent experiments have concentrated their efforts on a search for a resonance with $\Gamma < 10 \text{ MeV}$ but have failed to find it. This is, of course, not in contradiction with the results of Hamilton et al.⁹¹. Lowenstein et al.⁹³ measure the $\bar{p}p$ annihilation cross-section between 1925 and 1955 MeV with an r.m.s. resolution of $\pm 2.5 \text{ MeV}$, and have set an upper limit of 9 mb MeV (2 standard deviations) for any resonance with $\Gamma \leq 4 \text{ MeV}$ (Fig. 44). Jastrzemski et al.⁹⁴ also measure the $\bar{p}p$ annihilation cross-section in the mass range 1932-1942 MeV and set an upper limit of 12 mb MeV for any resonance with $\Gamma \sim 4 \text{ MeV}$ (Fig. 45). Cresti et al.⁹⁵ have repeated the measurements of Chaloupka et al.⁹⁶, using a hydrogen bubble chamber as a spectrometer but with initial $\bar{p}$ momenta slightly different from those used in the original experiment. They do not see a resonance with $\Gamma \lesssim 10 \text{ MeV}$ in the total cross-section (Fig. 46); and the reinterpretation of the original data, leaving aside a few data points at the entrance of the bubble chamber, and without merging the data with others (to avoid normalization problems), gives the numbers: $M = (1935 \pm 3)$, $\Gamma = (16 \pm 11) \text{ MeV}$, $\sigma_{\text{tot}} = (5.2 \pm 1.5) \text{ mb}$, in agreement with Hamilton et al.⁹¹. Several experimental results indicate that the S(1936) may be, like the T and U bumps, of a complex nature: absence of a peak in charge-exchange cross-section⁹¹, angular distribution of the $K_S K_L$ annihilation channel⁵⁰, and the enhancement observed in 5π annihilations by Defoix et al.⁹⁷, who assign to this enhancement

Fig. 40

Fig. 41

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The S(1936) seems to present a similar situation. New high-statistics measurements on the total, charge-exchange, and annihilation $\bar{p}p$, $\bar{p}n$ cross-sections^{91,92} conclude that an enhancement is present in the total and annihilation cross-sections, with the following features (Fig. 43):

$$\begin{aligned}\sigma_{\text{tot}} &= 3.0 \pm 0.7 \text{ mb} & M &= (1939 \pm 2) \text{ MeV} & \Gamma &= (22 \pm 6) \text{ MeV} \\ \sigma_{\text{ann}} &= 2.5 \pm 0.8 \text{ mb} & M &= (1937 \pm 2) \text{ MeV} & \Gamma &= (21 \pm 10) \text{ MeV} .\end{aligned}$$

Most of the recent experiments have concentrated their efforts on a search for a resonance with $\Gamma < 10 \text{ MeV}$ but have failed to find it. This is, of course, not in contradiction with the results of Hamilton et al.⁹¹. Lowenstein et al.⁹³ measure the $\bar{p}p$ annihilation cross-section between 1925 and 1955 MeV with an r.m.s. resolution of $\pm 2.5 \text{ MeV}$, and have set an upper limit of 9 mb MeV (2 standard deviations) for any resonance with $\Gamma \leq 4 \text{ MeV}$ (Fig. 44). Jastrzemski et al.⁹⁴ also measure the $\bar{p}p$ annihilation cross-section in the mass range 1932-1942 MeV and set an upper limit of 12 mb MeV for any resonance with $\Gamma \sim 4 \text{ MeV}$ (Fig. 45). Cresti et al.⁹⁵ have repeated the measurements of Chaloupka et al.⁹⁶, using a hydrogen bubble chamber as a spectrometer but with initial $\bar{p}$ momenta slightly different from those used in the original experiment. They do not see a resonance with $\Gamma \lesssim 10 \text{ MeV}$ in the total cross-section (Fig. 46); and the reinterpretation of the original data, leaving aside a few data points at the entrance of the bubble chamber, and without merging the data with others (to avoid normalization problems), gives the numbers: $M = (1935 \pm 3)$, $\Gamma = (16 \pm 11) \text{ MeV}$, $\sigma_{\text{tot}} = (5.2 \pm 1.5) \text{ mb}$, in agreement with Hamilton et al.⁹¹. Several experimental results indicate that the S(1936) may be, like the T and U bumps, of a complex nature: absence of a peak₀₀ in charge-exchange cross-section⁹¹, angular distribution of the $K_S^0 K_L^0$ annihilation channel⁵⁰, and the enhancement observed in 5π annihilations by Defoix et al.⁹⁷, who assign to this enhancement

Fig. 42

Fig. 43

Fig. 44

Fig. 45

Fig. 46

a mass of (1949 ± 10) MeV, a width $\Gamma = (80 \pm 20)$ MeV, and $\sigma \sim 5$ mb ($I = 1$). Note that Igi⁹⁸ favours a width of 20 to 30 MeV for the S(1936) in a model based on duality and t-channel vector meson exchange.

A recent result on the observation of the S(1936) in a production experiment⁹⁹ is not confirmed by its authors. Finally, the S(1936) may have been observed in photoproduction¹⁰⁰, but the mass and width quoted agree only marginally with the values observed in $\bar{p}p$ formation experiments (Fig. 47). Photoproduction may involve complex threshold behaviour which makes difficult the interpretation of the $\bar{p}p$ mass spectrum.

Broad resonances have also been observed in the $(\bar{\Lambda}p)$ and $(\Lambda\bar{p})$ system, with no presently known counterpart in purely mesonic channels, suggesting a baryonium nature. Cleland et al.⁵² have made a partial-wave analysis of the Λp system produced diffractively in the reactions

$$K^+p \rightarrow (\bar{\Lambda}p)p \quad \text{and} \quad K^-p \rightarrow (\Lambda\bar{p})p \text{ at } 50 \text{ GeV/c},$$

with $0.05 < -t < 1 \text{ GeV}^2$, and produce evidence for three broad states with $J^P = 2^-, 3^+$, and 4^- at (2260 ± 20) , (2320 ± 30) , and (2490 ± 20) MeV, respectively. The widths are of the order of 250 MeV (Fig. 48). On a Chew-Frautschi plot, these resonances fall significantly below the dominant Regge trajectories.

None of the previous claims for the observation of narrow baryonium resonances have survived a variety of high-statistics and precise experiments. The M(2020) and M(2200), originally observed in π^-p reactions at 9 and 12 GeV/c, produced in association with Δ^0 or $N^{*0}(1520)$, and having cross-sections of the order of 10 to 30 nb¹⁰¹, have not been observed in a similar experiment performed at BNL¹⁰² with 16 GeV/c incident π^- (Fig. 49). An upper limit for the cross-sections is set at 3 nb and would correspond, to be compatible with

Fig. 47

Fig. 48

Fig. 49

Benkheiri et al., to a laboratory momentum dependence of the order of p^{-10} . Using a π^+ beam and looking for the M's in the reaction $\pi^+ p \rightarrow \Delta^{++} \bar{p} p$ at 10 GeV/c, with a forward Δ^{++} , Bionta et al.¹⁰³ set an upper limit of 15 nb, although the production of M's was expected to be enhanced, in this reaction, with respect to π^- -induced reactions, since the t-channel exchange seems to be dominated by $I = 1/2$ ¹⁰¹. The M's have also been looked for in $\bar{p}$ -induced reactions, which are *a priori* more favourable and can be performed at relatively low incident momenta. Chung¹⁰⁴, using a 5 GeV/c $\bar{p}$ beam, sets an upper limit of 100 nb, whereas Armstrong et al.¹⁰⁵, using a 12 GeV/c $\bar{p}$ beam at CERN, set an upper limit of 40 nb. Frame et al.¹⁰⁶, studying the reaction

$$K^+ p \rightarrow \bar{p}_f p K^+ p \text{ at } 13 \text{ GeV/c},$$

give an upper limit of 30 nb. Finally, Kooijman et al.¹⁰⁷ have searched for baryonium states in the reaction

$$pp \rightarrow pp\bar{p}p \text{ at } 12 \text{ GeV/c}$$

and set an upper limit of 10 nb for $\bar{p}p$ states with $M < 2200$ MeV, $\Gamma < 10$ MeV, and for $pp\bar{p}$ states with $M < 3400$ MeV.

This laconic enumeration of negative results does not of course, "explain" the original results of Benkheiri et al.¹⁰¹. More work is indeed continuing at the Omega spectrometer, at CERN, with 20 GeV/c incident π^+ and 12 GeV/c incident π^- , in an attempt to reproduce the original claims. Perrin¹⁰⁸ has given a recent review of the status of these experiments.

Another narrow baryonium had previously been reported, in the exotic channel $\Lambda p \pi^+$, with $M = 2460$ MeV¹⁰⁹. This experiment, studying $K^+ p \rightarrow \bar{\Lambda} p \pi^+ n$ at 13 GeV, has now been repeated by the same collaboration¹¹⁰, using the same technique but with more than 10 times the original statistics. No peak is observed at a level of ~ 150 nb. Bar Yam et al.¹¹¹, using a 16 GeV/c π^- beam and looking for a narrow resonance in the $\bar{\Lambda} p \pi^-$ system, set an upper limit of 20 nb for such a narrow state.

No new information has been presented on the bound states observed in radiative transitions from $\bar{p}p$ annihilations at rest¹¹²: three lines have been observed in the γ spectrum, at (183 ± 7) MeV, (216 ± 9) MeV, and (420 ± 17) MeV, with widths smaller than the experimental resolution (~ 20 MeV). It is obviously important to repeat this experiment with better statistics and an improved signal-to-background ratio before considering these candidates as firmly established.

We are therefore left, for the time being, with a few broad states observed in $\bar{p}p$ annihilations and $(\bar{\Lambda} p)$, $(\Lambda \bar{p})$ systems, and the S-T-U enhancements in the total $\bar{p}p$ cross-section. Although some characteristics (the spin-mass relation) suggest that these broad resonances do not follow the general trend of the $\bar{q}q$ mesons, we are still far from being able to demonstrate that they correspond to $2q2\bar{q}$ objects and are not, for example, $3q-3\bar{q}$ systems. Interest in this last hypothesis has revived with the discovery of dibaryon resonances.

7. FIVE-QUARK RESONANCES?

We summarize here the experimental observations which may be related to the existence of $(q^4\bar{q})$ systems. Most of these observations have already been mentioned in the baryon spectroscopy section. Strottman¹¹³ has worked out a $q^4\bar{q}$ spectrum which predicts a $J^P = \frac{1}{2}^-$, $I = 0$ resonance with $M = 1420$ MeV, whereas the simple quark model of Isgur and Karl⁶² predicts degenerated $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$ at $M = 1490$ MeV. Experimentally, the $J^P = \frac{1}{2}^-$ object has a mass of 1405 MeV, the $J^P = \frac{3}{2}^-$ a mass of 1520 MeV. The $q^4\bar{q}$ model predicts also a $J^P = \frac{1}{2}^-$, $I = 1$ resonance at 1420 MeV, which may be compared to the $\Sigma(1460)$ observed by the CCMS Collaboration⁸³. No such low-mass state is predicted in the simple quark model.

On the other hand, Högaasen and Sorba¹¹⁴, starting from a $(3q)_8 - (q\bar{q})_8$ model and using as input the $\Lambda(2130)$ observed in proton-proton interactions at the CERN ISR¹¹⁵ and the $\Sigma(2230) \rightarrow \Sigma\omega$ observed by the ACNO Collaboration⁸¹, predict a $\Lambda(2550)$ which contains three strange quarks and could therefore be the $Y^*(2580)$ discussed above⁸². The same model predicts a $\Xi(2375)$ which should have a dominant three-body decay, as observed for the $\Xi(2370)$ ⁸⁵.

Before considering these states as solid evidence for multiquark states, much more experimental and theoretical work must be done. It is interesting, however, to see how well some predictions agree with recent experimental results which do not easily find a natural interpretation in the classic hadron spectroscopy.

8. DIBARYONS

Yokosawa¹¹⁶ has reviewed here the new experimental data related to the existence of dibaryon states. A striking energy dependence has been observed in the difference between the nucleon-nucleon total cross-sections for pure spin states:

$$\Delta\sigma_L = \sigma_{\text{tot}}(\uparrow\downarrow) - \sigma_{\text{tot}}(\uparrow\uparrow)$$

and

$$\Delta\sigma_T = \sigma_{\text{tot}}(\uparrow\downarrow) - \sigma_{\text{tot}}(\uparrow\uparrow) .$$

Several other observables have been measured, giving information on the spin-spin correlation parameters, polarization data in elastic scattering, etc. The interpretation of these data leads to the conclusions that three dibaryons are necessary in order to fit the data, and five more candidates may be present. The three best established dibaryons have the following properties:

$B_2^1(2140)$: $I = 1$, $J^P = 2^+$, $2140 < M < 2170$ MeV, $50 < \Gamma < 100$ MeV (1D_2)

$B_2^1(2220)$: $I = 1$, $J^P = 3^-$, $2200 < M < 2250$ MeV, $100 < \Gamma < 200$ MeV (3F_3)

$B_2^0(2220)$: $I = 0$, $J^P = 3^-$, $2200 < M < 2260$ MeV, $100 < \Gamma < 200$ MeV (1F_3).

Data on the photodissociation of the deuteron are accumulating rapidly, with polarized beams, targets, or recoils. The consistency

Fig. 50

between these data, coming from Tokyo, Kharkov, Stanford and Bonn, is good¹¹⁷, but the "old" Tokyo analysis¹¹⁸, which suggested the presence of two dibaryons, $B_2(2260)$ with $I(J^P) = 1(3^-)$ and $B_2(2380)$ with $0(1^+)$ (solution "A") or $B_2(2260)$ with $1(3^-)$ and $B_2(2380)$ with $0(3^+)$ (solution "B") is ruled out by the new extended high-precision data (see, for example, Fig. 50). A new analysis is therefore necessary to give a good interpretation, not only of $d\sigma/d\Omega$ and $P(\theta)$ data but also of $\Sigma(\theta)$ and $T(\theta)$ (new polarized beam and target data). A detailed review of the problems raised by the use of deuteron targets to study the dibaryon resonances induced by pion beams has been prepared for this conference¹¹⁹. It is found that the elastic π -deuteron scattering can

Fig. 51

be very well described by the Glauber model, introducing three different dibaryons with the following characteristics: $B_2(2130)$ with $J^P = 2^+$, $B_2(2260)$ with $J^P = 3^-$, and $B_2(2510)$ with $J^P = 0^+$ or 4^+ (Fig. 51).

It is of fundamental interest to study the high-energy behaviour of the deuteron in order to learn about the transition of a weakly bound N-N system into a many-quark state. In this respect, Arnold et al.¹²⁰ have measured the reaction

$$e + D \rightarrow e' + X$$

near $M_X^2 = M_0^2$ and at $Q^2 = 8 \text{ GeV}^2$. These data continue the approximate scaling observed at lower Q^2 , and their confrontation with various models shows factor of 10 discrepancies, underlying the need for further theoretical developments.

Dibaryons with $S = -1$ have been looked for in reactions of the type

$$K^- d \rightarrow \pi^\pm (B_2)^\mp,$$

$$B_2 \rightarrow \Lambda p, \Sigma n \dots$$

Braun et al.¹²¹ and others have observed a $B_2 \rightarrow \Lambda p$ with $M = 2129.0 \pm 0.4 \text{ MeV}$, $\Gamma < 6 \text{ MeV}$. This peak is observed with larger statistics in a new experiment¹²² which is designed to look not only for B_2 's with $S = -1$ but also for B_2 with $S = -2$ ($K^- d \rightarrow K^+ B_2^-$). Ströbele et al.¹²³ have submitted results on the reaction

$$K^- d \rightarrow \pi^+ d_\Sigma^-$$

d_Σ^- being a hyperdeuteron with a mass below the Σ^- threshold. Although the signal is significant, the interpretation of events which do not fit the dominant channel $K^- d \rightarrow \pi^+ \Sigma^0 n$ is a delicate matter. Confirmation of these results by experiments now in progress¹²² would be most useful.

9. CONCLUSIONS

This bird's-eye view of light quark-hadron spectroscopy shows that the non-relativistic quark model works amazingly well. The work of Isgur-Karl-Koniuk⁶² should certainly be extended to mesons, Ξ^* and Ω^* .

Remarkable experimental results [$E(1420)$, $Y^*(2580)$, $\Sigma(1460)$, $R(3170)$, $\Xi^*(2370)$] may call for new interpretations which differ from the classical $q\bar{q}$, $3q$ model. The MIT bag model and its extensions is a good candidate, but it predicts, in its present formulation, too many states to have a real predicting power.

One is still unable to produce any real "exotic" (double charged, $I = 5/2 \dots$) state, but new approaches (the P-matrix) may reveal exotics which do not appear in the usual S-matrix analysis.

The light quark-hadron spectroscopy is such a lively field that it is impossible to summarize it within 40 pages!

There are so many of my colleagues whom I would like to thank for help, advice, and information that I cannot list all their names here. Let me, however, mention P. Eastabrooke and I. Gaines, my scientific secretaries, who did their best during the Conference to ease my way.

* * *

DISCUSSION (M5 -- L. Montanet)

- QL: *Sorenson*, Argonne National Laboratory: You reported on various meson resonances with high mass and high spin. Is it possible to extract from the data any information about S-waves for masses between, say, 1.7 GeV and 2.0 GeV? If so, this could be relevant to various puzzles associated with the decay of (charmed) D-mesons.
- Al: *Montanet*: I have perhaps been very brief on the S-wave. I think we still have a lot to understand about the S-wave; for instance, the apparently narrow S^* and δ peaks near $K\bar{K}$ threshold may, in fact, be very wide objects. I think we come to the conclusion that we have at least isosinglet and $I = 1/2$ resonances around 1300 MeV -- that is rather well established now.
- Q2: *Gago*, IST-Lisbon and WA56 Omega Collaboration: This is a comment about the so-called "death" of the narrow baryonium states. The $p\bar{p}$ peaks at 2020 and 2200 MeV that have been formed in $\pi^- p \rightarrow \Delta_f^0(p\bar{p})$ some years ago at Omega are still the most convincing evidence for narrow $p\bar{p}$ peaks. It seems premature to

affirm that they do not exist. In fact, the results that have been presented either do not look at the $p\bar{p}$ system backwards produced or they do not have a fast Δ^0/N^* associated.

We have made a high statistics experiment at Omega this year looking for baryonium exotic states in π^+p at 20 GeV/c and we also repeated the old π^+p experiment at 12 GeV/c. As the analysis is in progress, we expect results by the beginning of 1981.

- A2: *Montanet*: It is true that, strictly speaking, nobody has reproduced an experiment at 9 or 12 GeV/c with π^- and looked for the backward produced $\bar{p}p$ system. However, we have seen a result which I had no time to present in detail -- results obtained in 16 GeV/c π^-p , for instance, at Brookhaven, using exactly the same technique -- the same kind of trigger, the same experimental conditions, with good resolution and convincing statistics; they find an upper limit of 3 nb. Of course, we do not know the momentum dependence of these effects, so we cannot extract from this upper limit what one could have expected if one had done the experiment at 12 GeV/c.

They have an N^* and a Δ , as well as the Omega group. [Figure comparing N^* , Δ at 16 GeV/c (BNL) with 9 and 12 GeV].

- Q3: *Lindenbaum*, BNL/CCNY: The question is whether there is any doubt in the experiment. There is always doubt in every experiment, but much less doubt in ours.

- Q4: *Weiner*, Marburg: Recent theoretical arguments^{*)} suggest that the hadronic mass spectrum cannot increase exponentially at large m , as was assumed so far. What is the present experimental situation? and what are the prospects of clarifying this problem?

- A4: *Montanet*: I do not know. The diffractive peak observed in pp at 400 GeV at Fermilab (Francini et al.) may tell us something. The authors tried to extract the diffractive inelastic part, and they see that that can interpret this diffractive peak of the proton using the 12 N^* known in this mass range up to 10 GeV.

- Q5: *Roy*, TIFR: Narrow states had been reported in the radiative decay of $\bar{p}p$ at rest. Could you comment on the current status of these states?

- A5: *Montanet*: There is no new information -- for the time being I think we just have to wait for the complete analysis of the new data. You refer to the peaks observed in the photon spectrum when you study $\bar{p}p$ annihilation at rest -- they could correspond to bound states of the $\bar{p}p$ system. The experiment has been repeated with better conditions, better statistics; but the group, for the time being, refuses to say anything on the new experiment.

^{*)} G. Fowler and R. Weiner, Physics Letters, January 1980.

- Q6: *Weiss*, SLAC: Is there any understanding of why some of the high-mass Y^* 's have large branching ratios into two- and three-body modes while charmed objects of similar masses do not?
- A6: *Montanet*: There are, of course, models or interpretations. For instance, Högaasen and Sorba have proposed that, using the bag model, you could easily explain some of these observations. In fact, they have predicted some of the states which are now observed. Using this five-quark bag model they are able to understand why they have exotic decays.
- Q7: *O'Donnell*, Toronto: If we take the width of the ρ' to be ~ 250 MeV as measured in $\gamma N \rightarrow \pi\pi N$, then the cross-section for 2π production in the colliding beam experiments is predicted to be much larger than that which is presently observed (although the statistics are, admittedly, poor).
- A7: *Montanet*: There are two experiments which see the same effect. The experimental observation cannot be disregarded. The interpretation, however, is difficult. There may be not one ρ' but several ρ' 's, and you may have to build up a rather complex amplitude with interference effects to understand these effects. In e^+e^- it is completely clear that you really need to have isovector and isoscalar to interpret the set of data presented at this conference by Bizot.
- Q8: *Lindenbaum*, BNL/CCNY: In response to the comment from the audience that the original CERN experiment that discovered the 2020 and 2200 MeV narrow baryonium resonances had not been repeated, Montanet correctly pointed out that the 16 GeV/c $\pi^- + p$ experiment was not in effect a good BNL repetition and contradicted it. In response to the further statement -- could there still be doubt in this repeated result? I would say in any experiment there is some doubt, but the doubt in our BNL experiment and its conclusion is quite small -- certainly there is much less doubt in our experiment than the original CERN experiments it contradicted.

* * *

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