AUG 4 1963

THE SYSTEMATICS OF BARYON AND MESON STATES

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Facsimile Price \$ 3.60

Microfilm Price \$ 1.16

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Contract No. AT(11-1)-264

EFINS-63-33

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CONF-131-1

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Over the last two years, there have been observed many new strongly-interacting particles, whose study forms the subject of this conference. Some of these particles are exceedingly short-lived (as short as $\approx 5 \times 10^{-24}$ sec.), others appear to be relatively long-lived (probably as long as $\approx 5 \times 10^{-18}$ sec.). Their observation has opened up a new field of nuclear physics. The study of their properties is already giving us many new clues in our quest to understand what structure must be required for the underlying theory of matter which is to give rise to their occurrence. At the moment, we are still in the exploratory phase of determining the basic quantum numbers associated with these states. We are just beginning to learn a little about their coupling schemes and about the associated parameters, which we hope will lead us to an appreciation of the new symmetries which we all expect this underlying theory to possess, in some form or other.

*This work supported by the U. S. Atomic Energy Commission.

†Invited paper presented at the Topical Conference on Recently Discovered Resonant Particles, Ohio University, Athens, Ohio, April 1963.

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Let me begin with an introductory survey of the status of our knowledge of these mesons and baryons. The meson states are shown in Fig. 1, which I have borrowed from A. H. Rosenfeld. First, there is the family of pseudoscalar mesons, with spin zero and negative parity, consisting of the three pions (mass ≈ 140 MeV), the two K-mesons (mass ≈ 495 MeV) and their two antiparticles, the $\bar{K}$ -mesons, and the η meson (mass ≈ 550 MeV). Next, we have the vector meson family, with spin one and negative parity, consisting of three ρ -mesons (mass ≈ 750 MeV), two K^* -mesons (mass ≈ 890 MeV) and their antiparticles, the $\bar{K}^*$ mesons, the ω -meson (mass ≈ 785 MeV) and the φ -meson^{1,2} (mass ≈ 1020 MeV). There appears to be another family, represented to date only by the f^0 -meson (mass 1250 MeV)^{3,4,5}, an iso-singlet state whose spin J must be even, with $J \geq 2$. Finally, there is one further meson, whose role appears to be rather a mystery at present. This is the K' or K -meson of mass ≈ 725 MeV, which has been observed in positive and neutral charge states, as well as in the corresponding antiparticle states, through its decay $K' \rightarrow K + \pi$ (or $\bar{K}' \rightarrow K + \pi$). Evidence for K' production has been found in π^- -p collisions^{6,8} (1900 - 2050 MeV/c), K^- -p collisions⁷ (1500 MeV/c) and K^+ -p collisions (1960 MeV/c), but the production appears to be quite weak, with cross-sections from 15 μ b for π^- -p collisions to 40 μ b for K^- -p collisions. The width of the K' meson is also quite small, of order ≤ 10 MeV. Despite these strange features, the K' evidence now has quite large statistics, so that it is no longer reasonable to overlook this state.

How have the spin and parity values been determined for so many of these mesons? There are really two approaches which have been successful.

(i) the study of the characteristics of their decay processes, with appeal to the selection rules for angular momentum J , parity P , and charge conjugation C . For example, an early illustration of this procedure was provided by the deduction of spin-parity $(1-)$ for the ω -meson from the study of the spectrum for its major decay mode $\omega \longrightarrow \pi^+ \pi^- + \pi^0$ on a phase space plot.^{9,10} Similarly, for the η -meson^{10,11}, the study of the decay mode $\eta \longrightarrow \pi^+ \pi^- + \pi^0$ showed that this decay mode violated isospin conservation (because the intensities of corresponding configurations $(\pi^+ \pi^- \pi^0)$, $(\pi^- \pi^0 \pi^+)$, and $(\pi^0 \pi^+ \pi^-)$, were unequal, contrary to expectation for $I = 0$, appropriate to the isosinglet η meson) and that the spin-parity was most probably $(0-)$; of course, the very observation of 3π decay requires negative parity if the η spin is zero. This conclusion has received further support from the direct observation¹² of the mode $\eta \longrightarrow \gamma + \gamma$, which necessarily excludes spin 1 for the η -meson. For the ϕ -meson, the existence of the decay mode $\phi \longrightarrow K_1^0 + K_2^0$ requires $C = -1$ and $P = -1$; since the K -mesons are spinless, the last condition requires $J = \text{odd}$ for the ϕ -meson. A decision between $J = 1$ and higher values has been possible from the study of the ratio $(K_1^0 K_2^0)/(K^+ K^-)$ for the ϕ -meson;^{1,2} since the $K^+ K^-$ and $K_1^0 K_2^0$ thresholds are quite close to the ϕ -meson mass, the momentum p_0 in the $K_1^0 K_2^0$ channel is significantly less than the momentum p_{ch} in the $K^+ K^-$ channel ($p_0/p_{ch} = 0.87$) and the effect of

the centrifugal barrier $(p_o/p_{ch})^{2\ell+1}$ on the branching ratio is sufficiently large to give a rather clear discrimination between $\ell = 1$ and higher ℓ -values, the observed ratio being compatible with the expectation (p_o/p_{ch}) for $\ell = 1$. We should remark that we appear to have been rather fortunate in the physical circumstances which have held in these situations; the momenta involved in the final states are frequently quite high, yet there generally appears relatively little indication of structure. Apart from the η decay spectrum, where its dependence on the π^0 energy may be regarded as a structure effect, the simplest possible matrix-elements, appropriate to point interactions, appear to provide a fairly good approximation to the distributions observed. This is particularly striking in the case of the ω -meson, where the energy release is so large.

(ii) the observation of two-body scattering angular distributions in which the particle of interest appears as a resonant state. This situation is not available for the real scattering of two mesonic particles, of course; rather, we are referring to the scattering of mesons by a pion within the target nucleon, the process of peripheral collision involving one-pion exchange whose importance was stressed by Chew and Low. The characteristics of this peripheral process are rather striking, so that it can generally be recognized when this process gives the dominant contribution to the observed distributions; when this is established to be the case, $\sigma(\pi M)$ or $\frac{d\sigma}{d\Omega}(\pi M)$ can then be deduced as function of the (final) π -M c.m. energy rather directly from the

physical data. This procedure has successfully established spin-parity (1-) for the ρ -meson,³ from the form $\cos^2\theta_{\pi\pi}$ observed for the resonant angular distribution in π - π scattering. The π -K scattering cross-section has similarly been established as $\cos^2\theta^*$ at resonance, indicating spin-parity (1-) for the K^* meson, with particular clarity in recent observations⁴ on the reactions $K^+ + p \rightarrow K^* + N^*$. The indications on the f^0 -spin have come from quite similar evidence, although less complete.⁵ It is by no means the case that the one-pion exchange process is necessarily the dominant mechanism in particle production processes. Even when the one-pion exchange process is allowed, there is always a strong possibility that competing mechanisms which lead to the same final state may interfere with this term and distort these final distributions from the characteristic forms expected. In the study of the ρ - and K^* mesons, especially, we have really been rather fortunate in finding circumstances in which the one-pion exchange mechanism stands out strongly, with little interference from background processes.

There are other quantum numbers needed to characterize each particle state, of course, such as the isotopic spin I and hypercharge Y which are rather readily determined. For mesonic states of zero hypercharge, there is also the G -parity, which is conserved only through the strong interactions. It is a useful mnemonic, and perhaps of no more significance than this, that the G -parity for the known mesons is always equal to the G -parity,

$$G = (-1)^{l+S+I}, \quad (1)$$

of the nucleon-antinucleon system which has the same J , with $\underline{J} = \underline{L} + \underline{S}$, the same isospin I , and the same parity $P = (-1)^{\underline{L}+1}$. For neutral mesons, the charge conjugation parity C is a particularly useful quantum number, since it is conserved also through electromagnetic interactions (with $C = -1$ for a photon). The G -parity is then related to C by the relation $G = C(-1)^I$. In Fig. 1, each particle state is labeled by the quantum numbers (JPG), and these states have been collected into columns according to their I and Y . For neutral meson states, the charge conjugation parity may be deduced from these entries as $G(-1)^I$.

This information on the meson states has been collected together in families on Fig. 2. At present, the most attractive scheme which provides some logical organization of this information is that of unitary symmetry, based on the hypothesis that the strong interactions are invariant with respect to transformations of the unitary group $SU(3)$. With this hypothesis, the particle states are naturally arrayed as unitary multiplets, consisting of multiplets of isospin multiplets, since $SU(2)$, the group to which the transformations of isospin belong, is a subgroup of the unitary group $SU(3)$. Of course, it is clear that this unitary symmetry is far from exact, for the isospin multiplets within a given unitary multiplet are not degenerate but differ rather appreciably in their mass values. Gell-Mann¹⁵ originally suggested that these mass deviations should have a rather definite origin within a particular model, for which the $SU(3)$ symmetry appeared rather natural, namely the Sakata model. This hypothesis was equivalent to the statement

that the mass deviations should transform under $SU(3)$ like the component T_3^3 of a unitary tensor $T_\nu^\mu(\mu, \nu = 1, 2, 3)$, where the axis 3 is that associated with hypercharge. From this, Gell-Mann derived the relation

$$m^2(M_1) + 3m^2(M_0) = 2(m^2(M_{\frac{1}{2}}) + m^2(\bar{M}_{\frac{1}{2}})) \quad (2)$$

between these mass deviations, for an eightfold unitary multiplet (which consists of an isovector multiplet, an isosinglet, and two isospinor multiplets, and forms a basis for the regular representation of $SU(3)$), where $m(M_I)$ denotes the mass for the multiplet of isospin I . Okubo¹⁶ has recently derived a general mass formula^{for bosons} on the basis of the same physical assumptions, with the result

$$m^2(I, Y) = m_0^2 \left\{ 1 + aY + b(I(I+1) - \frac{1}{4}Y^2) \right\} \quad (3)$$

We now know that the simple Sakata model cannot be valid, so that the proper basis for the derivation of these formulae, which do appear to fit the empirical mass deviations rather well, has become something of a mystery.

The pseudoscalar mesons do appear to form a unitary octet, and their mass values fit rather well with the relation (2). However there are nine vector mesons, the isovector ρ , the two isospinors K^* and $\bar{K}^*$, and two isoscalars ω and φ (called ω' in Rosenfeld's slide (Fig. 2)). Presumably these form an 8-fold and a 1-fold unitary multiplet; but which of the ω and φ mesons is the unitary singlet state? Neither ω nor φ masses satisfy the relation (2); however their mean square value $(\frac{1}{2}(m^2(\omega) + m^2(\varphi)) = (910)^2)$

almost satisfies this relation. Probably the situation is that, since ω and φ have the same quantum numbers except for those associated with unitary symmetry itself, the strong interactions which violate unitary symmetry couple the unitary-pure ω_0 and ρ_0 states and mix them rather strongly, so that possibly neither the physical ω nor the physical φ are particularly pure states with respect to the quantum numbers of unitary symmetry. The experimental determination of the couplings of the physical ω and φ states to baryons and mesons may finally establish their relationship for us. For example, the observation that the ω meson is produced very strongly in the reaction $K^- + p \rightarrow \Lambda + \omega$ (with cross-section $\approx$ mb at 1500 MeV/c, for example), whereas the φ and ρ mesons are produced rather weakly (cross-sections $\approx$ 100 μ b at 2000 MeV/c, for example) in the corresponding K^-p reactions to $\Lambda + \rho$ and $\Lambda + \varphi$, suggests that the ω has much stronger couplings than φ and ρ . This suggests, in turn, that it may be the φ -meson which belongs to the vector meson octet, that the ω -meson is a unitary singlet, and that the ω - φ mixing may not be a large effect. However more extensive and more detailed data on the $\omega, \varphi, \rho, K^*$ production reactions will be needed to settle the question of the precise relationship between the vector mesons.

The f^0 -meson may well be a unitary singlet, or it may be a member of a larger multiplet not yet explored. The relationship of the K^1 meson to the scheme of unitary symmetry is quite unclear at this stage. Nambu and Sakurai¹⁷ have recently proposed an interpretation which relates the existence of the K^1 meson to the existence of symmetry-breaking interactions; in this case, the K^1 meson would not

be expected to belong to a unitary multiplet and its existence would not necessarily imply the existence of related pionic resonance states.

The known baryon states are shown on Fig. 3. The lowest states are the baryons themselves, with parity $\frac{1}{2}+$ (by convention, for the Λ particle; the parity of the Ξ particle has not yet been established empirically, although its spin is definitely $\frac{1}{2}$). The baryon masses satisfy the Okubo formula (linear in the masses, as is appropriate for fermions),

$$m(I, Y) = m_0 \left(1 + a' Y + b' \left(I(I+1) - \frac{1}{4} Y^2 \right) \right), \quad (4)$$

and appear to form a unitary octet. Rosenfeld¹⁸ has proposed that this family be labeled by the subscript α , thus $N_\alpha, \Lambda_\alpha, \Sigma_\alpha$ and Ξ_α .

The next baryon family consists of the $Y_0^*(1405 \text{ MeV})$ state. In Rosenfeld's notation, the family with spin $\frac{1}{2}-$ is labeled β ; since the isospin and hypercharge of the Y_0^* state are the same as for the Λ -particle, Rosenfeld suggests the notation $\Lambda_\beta(1405 \text{ MeV})$. However, in fact, the spin and parity of this state are not yet established. The location and width of this resonance are quite consistent with the assignment $\frac{1}{2}-$, and with our knowledge of the $I = 0$ s-wave $\bar{K}$ -N scattering amplitudes in the low-energy region. However, the extrapolation from the $\bar{K}$ -N threshold through negative energies to reach this resonant state is quite long, and there is a good deal of uncertainty in the values of the $\bar{K}N$ scattering amplitudes, so that it cannot be said that this interpretation of the $Y_0^*(1405)$ resonance is definitely required. There is another interpretation available for the Y_0^* state, as a $p_{\frac{3}{2}}$ unitary

singlet, which is not at all ruled out empirically. It should be possible to settle this question before long by angular correlation and polarization studies on $Y_0^*(1405)$ decay, when sufficient data has been accumulated in a situation where the $Y_0^* \rightarrow \Sigma + \pi$ decay occurs relatively free of background $\Sigma + \pi$ production.

At this point, we should remark briefly on the unitary multiplets which are accessible to a meson-baryon system. Since the PS mesons and the baryons belong to the unitary representations $[8]$, a meson-baryon system belongs to the product representation $[8] \times [8]$, which reduces to

$$[8] \times [8] = [1] + [8^a] + [8^s] + [10] + [\bar{10}] + [27], \quad (5)$$

where $[n]$ denotes an n -fold representation of $SU(3)$. The isospin content of the $[10]$ representation is given by $(I, Y) = (\frac{3}{2}, +1), (1, 0), (\frac{1}{2}, -1), (0, -2)$; whereas the isospin content of the $[\bar{10}]$ representation is given by $(I, Y) = (0, 2), (\frac{1}{2}, 1), (1, 0), (\frac{3}{2}, -1)$. The $[27]$ representation consists of the ^{multiplets} $(I, Y) = (1, \pm 2), (\frac{3}{2}, \pm 1), (\frac{1}{2}, \pm 1), (2, 0), (1, 0)$ and $(0, 0)$.

The third baryon family is listed in Fig. 4 under spin-parity $\frac{3}{2}^+$. For the well-known $(3, 3)$ resonance, $N_{\frac{3}{2}}^*$ (1238 MeV), the notation of Rosenfeld requires a new symbol to characterize $I = \frac{3}{2}$, taken as Δ . This family has been labeled the δ -family, so we have $N_{\frac{3}{2}}^* (1238) \equiv \Delta_\delta$. The other members of this family are the π - Λ resonance $Y_1^* (1385 \text{ MeV}) \equiv \Sigma_\delta$, the π - Ξ resonance $\Xi_{\frac{1}{2}}^* (1530) \equiv \Xi_\delta$. In view of its isospin content, it is natural to identify this multi-

plet with the [10] representation; this requires the existence of one further state, the Ω^- state with $I = 0$, $Y = -2$, not yet known^{empirically}. For a 10-fold multiplet, Okubo's formula (4) reduces to a rule of equal spacing as Y decreases in unit steps. This rule is well obeyed for these $N_{\frac{3}{2}}^*$, Y_1^* and $\Xi_{\frac{1}{2}}^*$ states, and it predicts 1676 MeV for the Ω^- mass. With this mass value, the Ω^- particle would actually be semi-stable, decaying to $\Xi + \pi$ or $\Lambda + K^-$ through weak interactions only. For Ω^- -production, the simplest reactions are

and a number of bubble chamber groups are already searching for K^-p ~~events~~ ^{of type (6b)}. Possibly the Eisenberg event,¹⁹ reported from emulsion work at about the point when research into elementary particles by cosmic ray physicists effectively came to a halt,^{may} represent an example of Ω^- decay. This event represented the decay of a baryon to a K^- meson and one or more neutral particles; as pointed out by Glashow and Sakurai,²⁰ the identification of this decay with the mode $\Sigma^0 + K^-$ leads to a mass 1690 MeV for the Eisenberg baryon, not far from the predicted value for the Ω^- particle.

The spins and parities of the $Y_1^*(1385)$ and $\Xi_{\frac{1}{2}}^*(1530)$ have not yet been finally established, but the indications that they are $\frac{3}{2}^+$ particles are now becoming quite strong. In the early experiments at lower energies, there appeared to be many difficulties hindering the determination of these spins, especially for the broad Y_1^* resonance ($\Gamma \approx 50$ MeV):

- (i) Distortions in the decay distributions for these

short-lived states could occur at low energies because the decaying particle does not have time to travel clear of the other particles before its decay and the decay products may then interact with these other particles,

(ii) Frequently, the same final configuration of particles can be reached through several different intermediate steps involving resonant states, for example:

$$K^+ + p \longrightarrow K^0 + N^{*++} \longrightarrow K^0 + \pi^+ + p, \quad (7a)$$

$$\longrightarrow K^{*+} + p \longrightarrow K^0 + \pi^+ + p. \quad (7b)$$

In this situation, the amplitudes describing the production of the various overlapping resonances can interfere, giving rise to severe distortions of the decay distributions,

(iii) There always appeared the problem of non-resonant background; for example, with Y_1^* production, there can also be $\pi\text{-}\Lambda$ production amplitudes for $\pi\text{-}\Lambda$ angular momentum different from that for the resonant state, which can interfere with the resonant amplitudes and can produce quite strong distortions of the angular distributions for quite small total intensity.

It has turned out that there is a great advantage in going to higher energies and seeking situations which avoid the first two difficulties. It also appears that the effect of non-resonant background is not always important. In other words, if one keeps looking at different reactions and different energy values, there is a good chance of finding circumstances in which production through the resonant state is particularly strong relative to the background production. Under these circumstances, there are systematic methods

available for establishing the spin and parity of the resonant state, which were first pointed out by Gatto and Stapp²¹, and which have been clarified and extended by Byers and Fenster²². Apart from the unlikely event that the resonant state is produced with an isotropic spin distribution, these methods will necessarily give definite statements ruling out the lower spin values or giving the parity for an assumed spin value consistent with the angular and polarization distributions, at least if the background interference is sufficiently weak or sufficiently random, and if sufficiently large statistics are available. Recently, the Berkeley experiments on K^- -p collisions at 1500 MeV/c have given data with unusually good statistics on Y_1^* (1385) production and on the angular and polarization distributions in the subsequent decay, from which J. Button-Shafer et al.²³ have given strong arguments for spin-parity $\frac{3}{2}^+$, at least of the possibilities for $J < \frac{5}{2}$. At 2400 MeV/c, a recent Brookhaven-Syracuse study²⁴ of K^- -p collisions has shown that the Y_1^* (1385) production has all the general characteristics associated with K^* exchange; in particular, the production angular distribution has the form characteristic of such a peripheral collision, and, whereas the $Y_1^{*+} + \pi^-$ reaction is strong, the $Y_1^{*-} + \pi^+$ reaction is absent (in the K^* exchange process, the transfer of two units of charge is not possible). In these circumstances, it is reassuring to find that the Y_1^{*+} decay angular distribution relative to the normal to the production plane is $(1 + 4(\pm 1.0)\cos^2\theta)$, to be compared with the expectation²⁵ (pointed out by Sakurai and Stodolsky) of $(1 + 3\cos^2\theta)$ for K^* exchange to a

²⁵This expectation is based on the assumption that the $K^* + N \rightarrow Y_1^*$

absorption occurs through an "M1" rather than an "E2" interaction. That this should be so, is suggested by the fact that the electromagnetic excitation of the $N_{\frac{3}{2}}^*$ resonance occurs dominantly through the magnetic dipole interaction, and is determined by the isovector part of the nucleon magnetic moment, which is mediated by the ρ -meson. It is consistent with the $N_{\frac{3}{2}}^*$ decay data for other excitation processes such as $\pi + N \rightarrow \pi + N_{\frac{3}{2}}^*$ which may be mediated by vector meson exchange.

Y_1^* with spin-parity $\frac{3}{2}^+$. For the $\Xi_\delta \equiv \Xi_{\frac{1}{2}}^*(1530)$ state, the angular distributions of the direction and polarization of the particles from Ξ_δ decay have been analyzed, following the general Gatto-Stapp procedure; despite the limited statistics, the analysis favors $\frac{3}{2}^+$ for Ξ_δ and gives no indication for higher spin values.²⁶

The next family of resonances are those with $\frac{3}{2}^-$, consisting of $N_\gamma = N_{\frac{1}{2}}^*(1510 \text{ MeV})$, $\Lambda_\gamma = Y_0^*(1520 \text{ MeV})$ and possibly the recently-discovered state $\Sigma_\gamma = Y_1^*(1660 \text{ MeV})$. This assignment is well established for both N_γ and Λ_γ , the latter being the narrow resonance ($\Gamma \approx 16 \text{ MeV}$) investigated by Tripp et al.,²⁷ which represents a classic example of a simple Breit-Wigner resonance. It appears likely that $Y_1^*(1650 \text{ MeV})$ has spin $J = \frac{3}{2}$, but its parity is not yet established.^{28,29} If this $Y_1^*(1650 \text{ MeV})$ resonance does have $\frac{3}{2}^-$ and belong to the γ -octet, then the Okubo formula would predict the existence of a further state $\Xi_{\frac{1}{2}}^*$ at about 1600 MeV. Although this mass value is within the range which has been explored already (with somewhat limited statistics), there has been no evidence to indicate the existence of this resonance yet. However, there have been many experiments in the past where known resonances have not turned up prominently, so that this negative evidence need not be taken very seriously at this stage. It is of obvious importance to settle this

question as soon as possible.

The next π - N resonance known is the $N_{\frac{1}{2}}^*$ (1690 MeV), with spin $\frac{5}{2}$. There is no firm evidence on its parity yet, to my knowledge. The Y_0^* (1815 MeV) resonance established in K^- -p scattering also appears to have spin $\frac{5}{2}$, to judge by the elastic and charge-exchange angular distributions in the neighborhood of this resonance;^{30,31} again, there is no evidence on the parity of this state. These two states may possibly be members of a further octet, in which case corresponding Y_1^* and $\Xi_{\frac{1}{2}}^*$ states are to be expected in this mass region. No evidence has been seen for an $I = 1$ $\bar{K}N$ resonance in this region, but the data available is rather incomplete.³² Further measurements of K^- -p and K^- -n total cross-sections as function of energy in this region would be very desirable, as well as bubble chamber studies of K^- -d interactions at these higher energies.

The resonance $N_{\frac{3}{2}}^*$ (1920 MeV) appears to have spin $\frac{7}{2}$, according to the π^+ -p elastic scattering angular distribution observed at this energy.³³ This is presumably a member of another 10-fold unitary multiplet (of type $[10]$), which implies the existence of further corresponding Y_1^* , $\Xi_{\frac{1}{2}}^*$ and Ω^* resonances, yet to be established. Very recently, higher pion-nucleon resonances have been established,³⁴ $N_{\frac{1}{2}}^*$ (2200 MeV) and $N_{\frac{3}{2}}^*$ (2350 MeV), of which little is yet known, but which are expected to have their counterparts in the Y^* , Ξ^* and Ω^* systems. It is reasonable to expect that there are many resonant states still to be discovered, especially in the baryonic systems with non-zero strangeness.

Clearly, what we are beginning to see is the emergence of a series of families of resonances. The determination of the structure of each family, of its isospin content, of the mass values of the isospin multiplets, and of their decay processes and their partial widths, all of these quantities will be of crucial importance for testing the interpretations proposed for these resonances in terms of higher symmetries for the strong interactions. Here we will also mention briefly several of the many other questions which are of importance in this connection:

(i) the existence of $I = 2 \pi - \Sigma$ resonance states? These states have been sought in a number of experiments now, with no positive indications for such a resonant state below about 1700 MeV.³⁵ Their absence is interesting for unitary symmetry, since such resonances only occur in the 27-fold representation. In the detailed calculations on π -Y scattering which have been made in the past, it has been found that a ^{low-lying} $I = 2 p_{3/2} \pi - \Sigma$ resonance would necessarily be predicted if there were a $\pi \Sigma \Sigma$ coupling comparable in strength with the πNN coupling. In this view, the absence of a $p_{3/2}$ resonant state means that the $\pi \Sigma \Sigma$ coupling is actually relatively small, and this conclusion is consistent with the interpretation of Λ -N forces in terms of π -Y interactions and with the $\pi \Sigma \Sigma$ coupling strength ($f_{\Sigma \Sigma} \approx \frac{1}{2} f_{NN}$) required by the condition that the unitary multiplet [10] lie lowest in the $p_{3/2}$ state

(ii) the existence of KN resonant states is a related question, since a K^+p resonance can also belong only to a unitary multiplet [27]. The K^+p system has been rather well explored,

with no indication of resonant states. On the other hand, rather little is known of the properties of the $I = 0$ KN system. From the viewpoint of unitary symmetry, the observation of an $I = 0$ resonance would require the existence of a $[10]$ unitary multiplet, with corresponding resonances $N_{\frac{1}{2}}^*$, Y_1^* and $\Xi_{\frac{3}{2}}^*$.

(iii) Multiparticle Baryonic Resonance States. The first prediction of a strong $(\frac{3}{2}, \frac{3}{2})$ interaction in the pion-nucleon system was that given by the strong-coupling theory of pseudoscalar mesons. This theory actually predicted a sequence of "isobar states" with $j = I = N + \frac{1}{2}$, for integral N , starting with the nucleon $(\frac{1}{2}, \frac{1}{2})$, the $(\frac{3}{2}, \frac{3}{2})$ isobar, and continuing on above, the excitation energy of the N -th isobar being given by $E_N^* = CN(N+2)$. Although the validity of these predictions really requires such strong coupling that all of these isobar states would be bound, the qualitative agreement found between these predictions and the character of the lowest pion-nucleon resonance suggests that the existence of an $I = \frac{5}{2}$, $j = \frac{5}{2}$ resonance state should be regarded as a serious possibility. This $(\frac{5}{2}, \frac{5}{2})$ state $N_{\frac{5}{2}}^*$ would appear most strongly in the $\pi^+\pi^+p$ system; there are no two-particle channels of decay available to $N_{\frac{5}{2}}^*$, except for the mode $\pi + N_{\frac{3}{2}}^*$ (1238) which would be expected to be the dominant mode. This multiparticle resonant state has been sought in several reactions, for example,

$$p + p \longrightarrow (p + \pi^+ + \pi^+) + \pi^- + n, \quad (8)$$

$$\pi^+ + p \longrightarrow \pi^- + (\pi^+ + \pi^+ + p), \quad (9)$$

but there has been no clear indication yet for such a state. It

is quite possible that the strong production of $N_{\frac{5}{2}}^*$ may require more complicated processes than these. For example, the process (9) requires the transfer of two units of charge to the nucleon to reach $N_{\frac{5}{2}}^*$, as shown in Fig. 5a, and is therefore likely to be rather unfavored. To illustrate this point further, Fig. 5b shows a more complicated process which can proceed via a one-pion exchange mechanism, for which all of the vertices are expected to have large matrix-elements.

It is a matter of interest to consider this $N_{\frac{5}{2}}^*$ resonance within the scheme of unitary symmetry. This state must allow a strong decay to $\pi + N_{\frac{3}{2}}^*$, and this latter state belongs to the product representation $[8] \times [10]$, which reduces to

$$[8] \times [10] = [35] + [27] + [10] + [8]. \quad (10)$$

Since the $[8]$, $[10]$ and $[27]$ representations do not include an $I = \frac{5}{2}$ state, the $N_{\frac{5}{2}}^*$ resonance must belong to the $[35]$ representation. This representation includes a large number of isospin multiplets, as follows: $(I, Y) = (2, 2), (\frac{5}{2}, 1), (\frac{3}{2}, 1), (2, 0), (1, 0), (\frac{1}{2}, -1), (\frac{1}{2}, -1), (1, -2), (0, -2), \text{ and } (\frac{1}{2}, -3)$. For all of these states, decay to the systems $\underbrace{(\text{meson} + \text{baryon})}_{\text{two-particle}}$ is forbidden by unitary symmetry. For the states $(2, -2), (\frac{5}{2}, 1)$ and $(\frac{1}{2}, -3)$, these two-particle decays are forbidden by charge independence. For the remaining isospin multiplets, decay to (meson + baryon) is allowed by charge independence; the existence of strong interactions violating unitary symmetry will ensure that some of these two-particle decay processes will *actually take place*, although with correspondingly reduced partial widths. For example, the state $(\frac{3}{2}, 1)$ could decay to πN and $K \Sigma$ through

the symmetry-breaking interactions, as well as to $\pi + N^*$ and $K + Y_1^*$ through unitary interactions. This $j = \frac{5}{2}+$ state would then be excited only relatively weakly in π^+p collisions and would contribute a resonance bump of magnitude only $12\pi\lambda^2(\Gamma(\pi N)/\Gamma_{\text{tot}})$ to the π^+p total cross section. Similarly, the state (1,0) could be weakly excited in K^-p collisions; in final state Q -value distributions, it would appear strongly for the $\Lambda\pi\pi$ systems of zero or unit charge, but weakly for the $\bar{K}N$, $\pi\Lambda$ and $\pi\Sigma$ systems.

(iv) Finally, there is the possibility of Regge relationships *connecting* resonances of different J -values. In Fig. 6, the $(\text{mass})^2$ for the known baryons is plotted as function of their spin J . It is remarkable that the positions of the lowest resonance for each J appear to lie on a line rising rather uniformly with increasing J .

The definition of Regge states represents a rather natural generalization of the usual definition of a resonant state. The most natural definition of a resonance state imposes the boundary condition that, for allowed real J (integral or half-integral), there are only outgoing waves in all energetically available channels. This condition represents an eigenvalue problem for the resonance energy E^* , and probability conservation requires that this eigenvalue be complex. The Regge states are eigenstates defined by the same asymptotic boundary condition, but for complex eigenvalue $J^*(E)$, the energy E being kept real. In this case the Regge state is interpreted as a particle state when E reaches a value such that $\text{Re}J^*(E)$ is half-integral (for baryon states; read integral, for mesonic states). For a narrow resonance, the resonance state as usually

defined and the Regge state are very closely related. For broad resonances, the relationship between them is far less clear. Quite apart from ^{the question of} their relevance to high-energy scattering phenomena, the Regge states are of interest to the theoretician in that they allow the possibility of establishing a continuous connection between resonance states of different J values. This connection would be such as to relate the states of spins $J, J+2, J+4, \dots$ and ^{with} the same parity, ^{hypercharge, isotopic spin, etc.;} with unitary symmetry (or any other higher symmetry), the same patterns of resonance multiplets would then repeat at intervals of two units in the spin J , with the same parity. This is an intriguing possibility which provides one more strong motivation for determining the spins and parities of the higher resonance states, as well as the complete isospin structure of each of the higher families, at the earliest possible time.

On the other hand, it is also quite possible that the observed resonance families actually correspond to Regge states on quite different trajectories (for example, with different unitary quantum numbers, ^{or differing in other quantum numbers}), so that it is not at all necessary that the patterns should repeat in the manner described above. In the data available to date, there is really no pair of families known which definitely have the same isospin structure and for which their spins and parities have been established to be such that they could be considered to lie on the same Regge trajectory.

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Figure Captions

- Fig. 1 Table of the established or possible baryon states, prepared by A. H. Rosenfeld in March, 1963. The states shown with dashed lines are hypothetical, at present. Ω_δ and Ξ_γ are predicted from established states using the Gell-Mann - Okubo mass formula, the states labeled Σ_α^{II} and Ξ_α^{II} are entirely speculative, and the possible state labeled $\Delta_{\alpha\beta}(1640)$ refers to a shoulder observed in the $\pi^+ - p$ total cross section. Each state has been placed in the column appropriate to its isospin I and hypercharge Y , at a level corresponding to its mass.
- Fig. 2 Table of Baryon Unitary Multiplets (taken from S. Glashow and A. H. Rosenfeld, Phys. Rev. Letters 10, 192 (1963)).
- Fig. 3 Table of the established meson states, prepared by A. H. Rosenfeld in March, 1963. The states are arranged in columns according to their isospin I and hypercharge Y .
- Fig. 4 Table of Mesonic Unitary Multiplets, and of the other particles without strong interactions, taken from S. Glashow and A. H. Rosenfeld, Phys. Rev. Letters 10, 192 (1963).
- Fig. 5 Graphs illustrating the production of a $(\frac{5}{2}, \frac{5}{2}) \pi^+ \pi^+ p$ resonance state.
- Fig. 6 A plot of $(\text{mass})^2$ for the baryon states, against their spin (or probable spin) value J .

POSSIBLE BARYON QUANTUM NUMBERS, MARCH 1963

Fig.1

Baryon supermultiplets

Fig.2

POSSIBLE MESON QUANTUM NUMBERS, MARCH 1963

Fig.3

Fig. 5 Graphs illustrating the production of a $(\frac{5}{2}, \frac{5}{2})$ $\pi^+ \pi^+ p$ resonance state.

Fig. 6