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RECENT PROGRESS IN MESON AND BARYON SPECTROSCOPE

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Arthur H. Rosenfeld

May 1966

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LECTURE I: RECENTLY ESTABLISHED BARYON RESONANCES

In the past year the most notable advances in information on baryons seem to me to have been the following two:

1. A much more complete understanding of the πp system, including the discovery that under or near the familiar I-spin 1/2 bumps at 1512 and 1688 MeV there are not one but two or three resonances. This advance came about because of the accumulation of an enormous amount of data both by conventional means, [1,2] and by exploiting the newly developed targets with polarized protons. [3] This flood of data has been carefully analyzed by several groups[4,5] of phenomenologists and theoreticians, I want to display their results for you in the form of partial-wave amplitudes plotted in the complex plane (known as Argand diagrams); and I want to take some time to remind you how to recognize the characteristic behavior of a resonance.

2. The discovery or assignment of three states with spin 7/2.

a. Two different experimental techniques suggest that the known $N(2190)$ bump has spin and parity $7/2^-$, making it a candidate for N_γ^{II}, i.e., the recurrence of $N(1512, 3/2^-)$.

b. Analysis of K^-p interactions in the Berkeley 72-inch hydrogen bubble chamber has uncovered $\Sigma(2040), 7/2^+)$, which I shall call Σ_δ^{II}, and a negative-parity counterpart $\Lambda(2120, 7/2^-)$, which I would

tentatively like to call Λ_γ^{II}.

A. Resonances as Argand Circles: Theory

I want to remind you about the complex trajectories of Fig. 5, where I have plotted the elastic scattering amplitude as computed by Bareyre et al.[5] for πp scattering in seven different partial waves, all of which exhibit resonant behavior. I shall follow the treatment that my colleague R. D. Tripp used in his 1964 Varenna Lectures.[6] These lectures are extremely useful, and Tripp has added an up-to-date appendix on the results obtained with polarized targets. Another useful reference is that of Dalitz.[8]

We derive the Breit-Wigner formula as follows. Consider a resonance of energy E_R (frequency ω_R) decaying slowly with mean life τ.

$$A(t) = e^{-t/2\tau} \, e^{-i\omega_R t} .$$

Its Fourier transform is called the scattering amplitude T,

$$T(\omega) = \int A(t) \, e^{i\omega t} = \frac{1/2\tau}{(\omega_R - \omega) - i/2\tau} = \frac{\Gamma/2}{(E_R - E) - i\Gamma/2}, \qquad (1)$$

where I have set

$$\Gamma = \frac{\hbar}{\tau} = \frac{\hbar c}{\tau c} = \frac{197 \text{ MeV fermi}}{\tau c} .$$

Tripp divides numerator and denominator by $\Gamma/2$, and defines

$$\epsilon = \frac{E_R - E}{\Gamma/2} ,$$

so   (2)

$$T = \frac{1}{\epsilon - i} .$$

He shows that T describes a circle of diameter 1, centered at $(0, i/2)$, called the unitary circle; see Fig. 1. We can also show that as
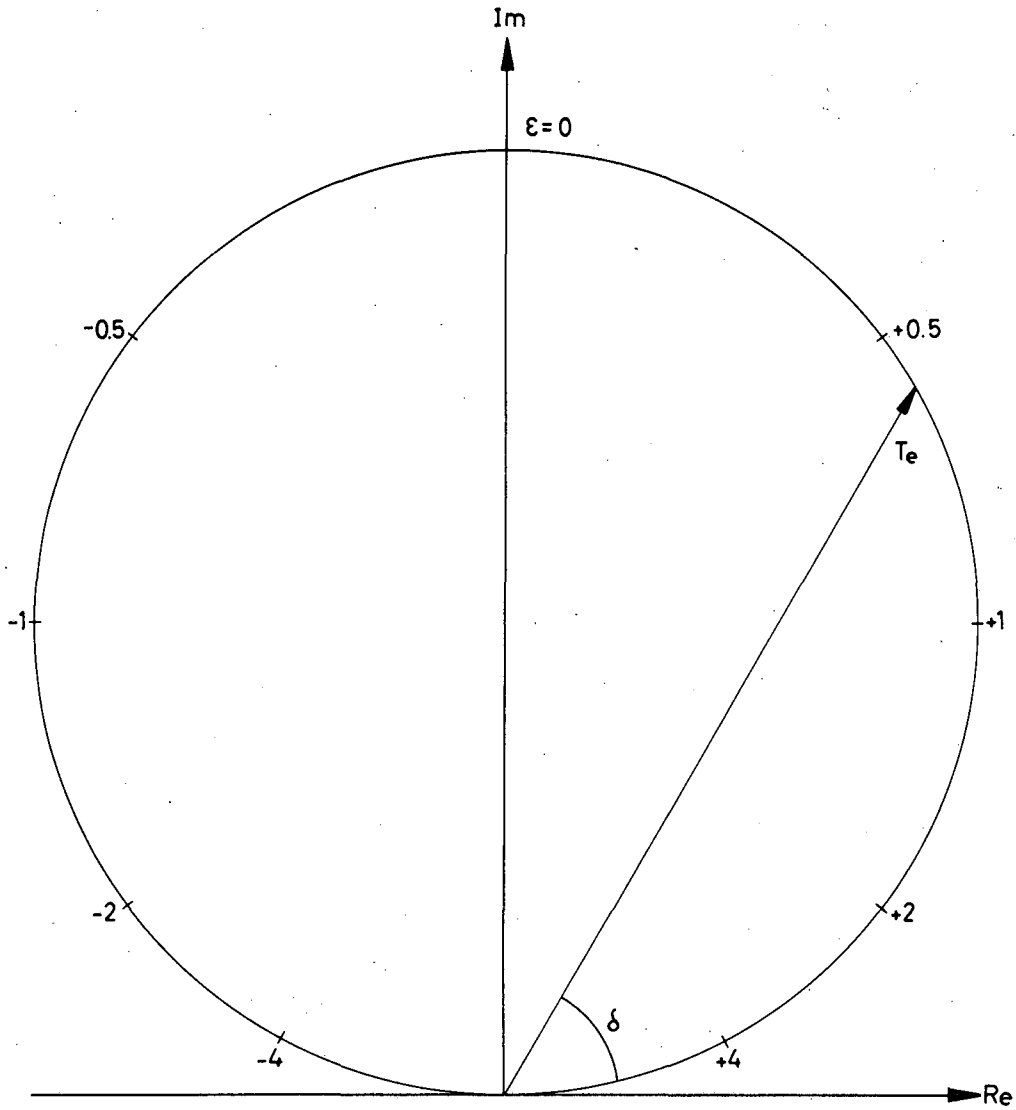
Fig. 1. The resonant elastic scattering amplitude $T_e = (\epsilon - i)^{-1}$ and $\cot \delta = \epsilon$.

we vary ϵ, the velocity of the complex point $\vec{T}$ is given by

$$\left|\frac{d\vec{T}}{d\epsilon}\right| = \frac{1}{\epsilon^2 + 1} = \text{Im } T. \tag{2a}$$

So, for example, at resonance ($\epsilon = 0$), $|d\vec{T}/d\epsilon| = 1$; a distance $\Gamma/2$ away from resonance $\epsilon = 1$, and $|d\vec{T}/d\epsilon|$ has dropped to $1/2$.

It is interesting to compare (2) with the conventional way of describing scattering in terms of a phase shift;

$$T = \frac{\eta e^{2i\delta} - 1}{2i} \tag{3}$$

[see, e.g., Tripp's Eq. (8)]. Here $\eta \leq 1$ is the magnitude of the scattered wave, 2δ is its phase shift. If we are dealing with only one-channel (i.e., purely elastic scattering), then $\eta = 1$ and we recognize that (3), like (2), describes the unitary circle of Fig. 1. (See Fig. 2). It is not hard to identify ϵ as $\cot \delta$. Hence when δ starts off clockwise along the circle it corresponds to an attractive potential, such as can produce a resonance; $\delta < 0$ corresponds to a repulsive potential.

In deriving Eq. (2) we implied a one-channel process. Now we want to generalize to several channels. This is easy for (2), hard for (3).

The total width Γ of the resonance is the sum of the partial widths for each channel,

$$\Gamma = \Gamma_\alpha + \Gamma_\beta + \dots , \tag{4}$$

and we can define probabilities for decay into each channel

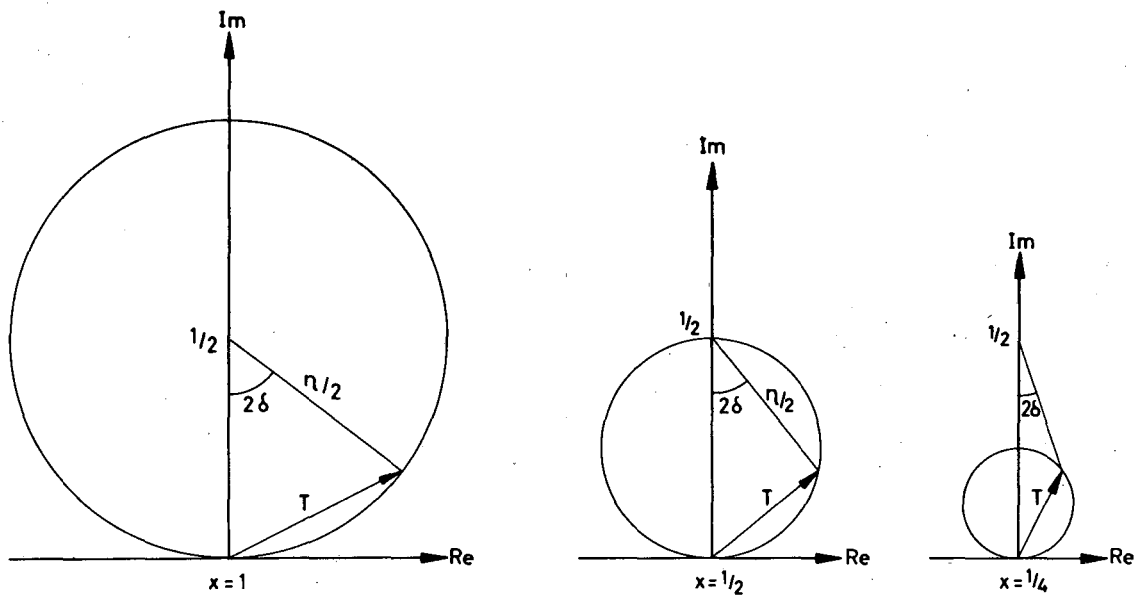$$x_\alpha = \frac{\Gamma_\alpha}{\Gamma}, \qquad \Sigma x_\alpha = 1. \tag{5}$$

Fig. 2. Resonant amplitudes for three different elasticities: x = 1, 1/2, 1/4.

Tripp points out that often Γ_α and Γ have similar energy dependence, so that the x_α tend to vary only slowly with energy. The probability amplitudes are $\pm\sqrt{x_\alpha}$.

If the incoming channel has $\alpha = 1$, the amplitude for feeding <u>in</u> to the resonance is $\sqrt{x_1}$. This factor will be common to all amplitudes $T_{1\beta}$. The probability amplitude for feeding <u>out</u> to channel β is $\sqrt{x_\beta}$, so

$$T_{1\beta} = \frac{\sqrt{x_\alpha}\,\sqrt{x_\beta}}{\epsilon - i}\,, \tag{6}$$

and for elastic scattering

$$T_{11} = \frac{x_1}{\epsilon - i}\,, \tag{7}$$

hence x_1 is usually called the elasticity.

Cross sections are related to $T_{1\beta}$ by

$$\sigma_{1\beta} = 4\pi\,\lambdabar^2\,(J + \tfrac{1}{2})\,|T_{1\beta}|^2 \tag{8}$$

$$= 4\pi\,\lambdabar^2\,(J + \tfrac{1}{2})\,\frac{x_1 x_\beta}{\epsilon^2 + 1}\,. \tag{9}$$

For elastic scattering

$$\sigma_e = 4\pi\,\lambdabar^2\,(J + \tfrac{1}{2})\,\frac{x_1^2}{\epsilon^2 + 1}\,. \tag{10}$$

The total cross section comes from $\Sigma\,x_\alpha = 1$,

$$\sigma_{total} = 4\pi\,\lambdabar^2\,(J + \tfrac{1}{2})\,\frac{x_1}{\epsilon^2 + 1}\,, \tag{11}$$

and the reaction cross section is

$$\sigma_r = 4\pi\,\lambdabar^2\,(J + \tfrac{1}{2})\,\frac{x_1(1 - x_1)}{\epsilon^2 + 1}\,. \tag{12}$$

These expressions for σ all have the same rapid energy depend-

ence in the denominator. Notice, however, that the ratio $\sigma_e/\sigma_r = x_1/(1-x_1)$

is nearly independent of energy. Thus, in a plot of σ_e vs σ_r, as in Fig. 3, a

resonance follows a nearly straight line, as shown for four cases of elasticity.

In case 4, the elastic phase shift goes to 0 deg at resonance and not to

90 deg. This can be understood by reference to Fig. 2. When the circle

is sufficiently small ($x_1 < 1/2$), the top point (the resonant energy) corre-

sponds to $\delta = 0$ deg. In this case δ never passes through 90 deg. Note,

however, that regardless of x_1 the scattering amplitude T always be-

comes purely imaginary at resonance. There is no intrinsic difference

between resonances where δ passes through 90 deg and those where it

goes through 0 deg at resonance. The point is that although η and δ

have a simple physical interpretation in terms of the scattered wave,

they are poor ways to parametrize a resonance since they change very

rapidly in the resonance region owing to the rapid variation of the denom-

inator as illustrated in Fig. 4. However, x and ϵ are appropriate vari-

ables since the elasticity is nearly independent of energy and ϵ is approx-

imately a linear function of energy for a narrow resonance.

The magnitude of a resonant cross section may range from

$4\pi\,\lambdabar^2\,(J + \frac{1}{2})$ to 0; there is no minimum size. In the case of strong ab-

sorption with $x_1 \to 0$, the cross section becomes vanishingly small. As

an example:

$$\gamma N \to N^* \to \pi N \qquad \text{small } (\sim a)$$
$$\to \gamma N \qquad \text{very small } (a^2).$$
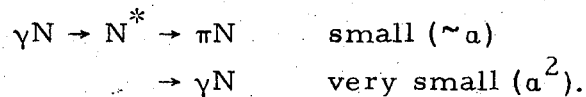
For a two-channel process, for example, Tripp writes T as a

2 by 2 matrix

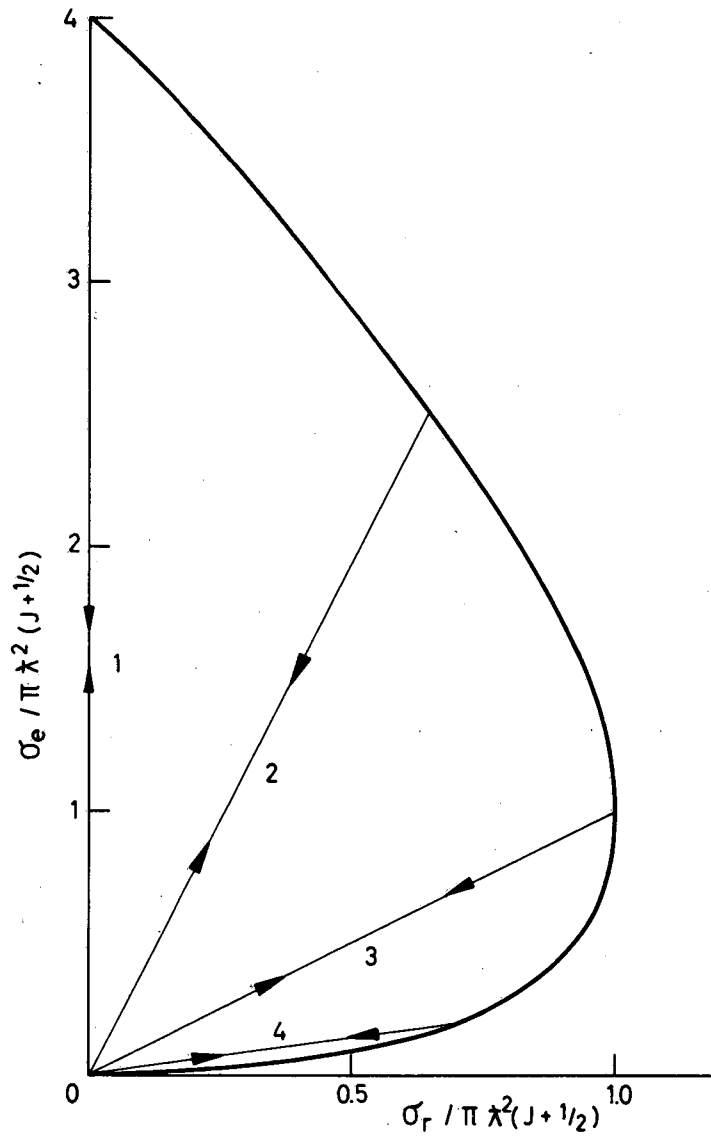Fig. 3. The ratio of elastic to reaction cross-section for four resonances of different elasticities. No. 1, x = 1; No. 2, x > 1/2; No. 3, x = 1/2; No. 4, x < 1/2.
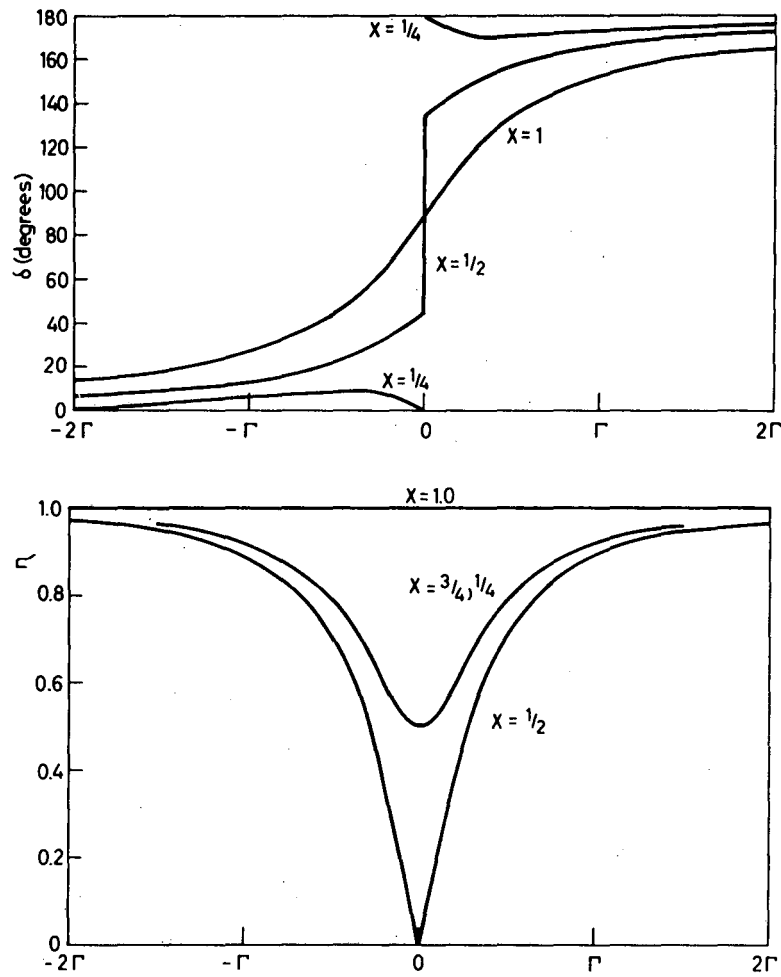
Fig. 4. The dependence of δ and η on energy for resonances of elasticities $x = 1$, 3/4, 1/2, 1/4. Although the elasticity is independent of energy, the absorption parameter η varies rapidly in the resonance region.

$$T = \begin{pmatrix} x & \pm\sqrt{x(1-x)} \\ \pm\sqrt{x(1-x)} & 1-x \end{pmatrix}.$$

It can be shown that the scattering matrix S which is related to the T matrix by

$$S = 1 + 2i\,T = \eta\,e^{2i\delta}$$

is unitary (corresponding to probability conservation) and symmetric (time-reversal invariance):

$$SS^\dagger = 1, \text{ and } S_{\alpha\beta} = S_{\beta\alpha}.$$

SU(3) or SU(6) predict the sign and magnitude of the $T_{\alpha\beta}$. The diagonal elements must be real and positive, but the off-diagonal elements carry a plus or minus sign which helps assign a resonance to the correct supermultiplet. For example, consider just the SU(2) example $N^*_{1/2} \to \pi^- p$ (channel 1) vs $\pi^0 n$ (channel 2).[†] The $T_{\alpha\beta}$ are then the products of Clebsch-Gordan coefficients

$$T = \begin{pmatrix} 2/3 & -\sqrt{\tfrac{2}{3}\cdot\tfrac{1}{3}} \\ -\sqrt{\tfrac{2}{3}\cdot\tfrac{1}{3}} & 1/3 \end{pmatrix}.$$

Of course, if we are dealing with a single resonant reaction like $K^- p \to Y^*_1(1765) \to \Lambda\pi$, all we can measure is a branching fraction which is $|T_{\alpha\beta}|^2$, i.e., the sign is unmeasurable. But if we measure interference (in angular distribution and polarization) caused by two nearby resonances, such as in the $\Sigma\pi$ decay of both $Y^*_1(1765)$ and $Y^*_1(1660)$, then even the sign becomes accessible.[7] This helps in the assignment of resonances to different supermultiplets.

[†] For this example we consider charge exchange as a reaction channel, not as part of the elastic charge as one normally does.

Finally I must mention that there is usually a background am-plitude in addition to the resonant amplitude, so that the clockwise res-onant "circle" can lie anywhere inside the unitarity circle. I will take this up in more detail in the next section when I discuss the P_{11} amplitude.

B. Argand Diagrams for πp Scattering

Figures 5 and 6 display the most interesting partial-wave scattering amplitudes, as calculated by Bareyre et al.[5] I hope that I have discussed Eq. (7) in enough detail that you can now decide for your-selves whether there are eight resonances altogether, and make your own guesses for the values of E_0 and Γ for each.

Let us compare each of the Argand plots in turn with the πp total cross-section curve, which is plotted in the upper right of the Fig. 6.

The I = 3/2 amplitudes (I call them Δ) are plotted on the top row. The I = 3/2 (π^+p) cross section is, of course, dominated by the isobar Δ(1238), whose P_{33} amplitude is plotted in the upper middle. Since 1238 MeV is only 30 MeV above threshold for Nππ we expect the amplitude to be perfectly elastic, and indeed it follows the unitarity circle very well. We expect the amplitude to move along this unitarity circle with a velocity $(1 + \epsilon^2)^{-1}$, as given in Eq. (2a). To exhibit the velocity, I have put hatch marks every 10 MeV across all the trajectories. You can see that the P_{33} amplitude performs just as expected up to ≈ 1350 MeV.

The only other features of the I = 3/2 cross section below the recurrence of Δ(1238) as Δ(1920) is a shoulder in the cross section, starting around a mass of 1600 MeV. This shoulder amounts to a rise
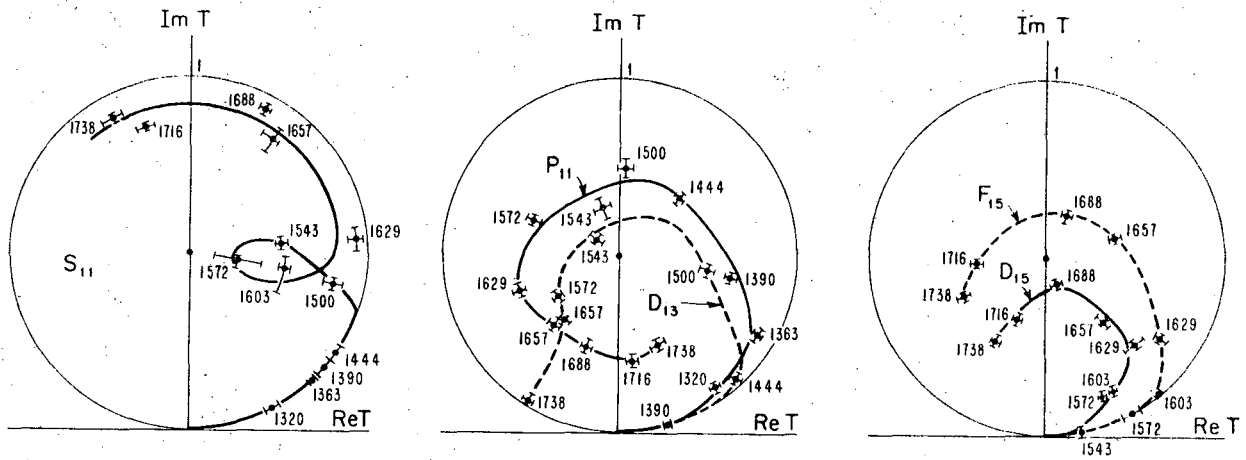
Fig. 5. Solutions of Bareyre et al.[5] to I-spin 1/2 resonant partial waves. The crosses show the amplitudes and errors computed from the data at various energies. The smooth connecting lines are guesses.
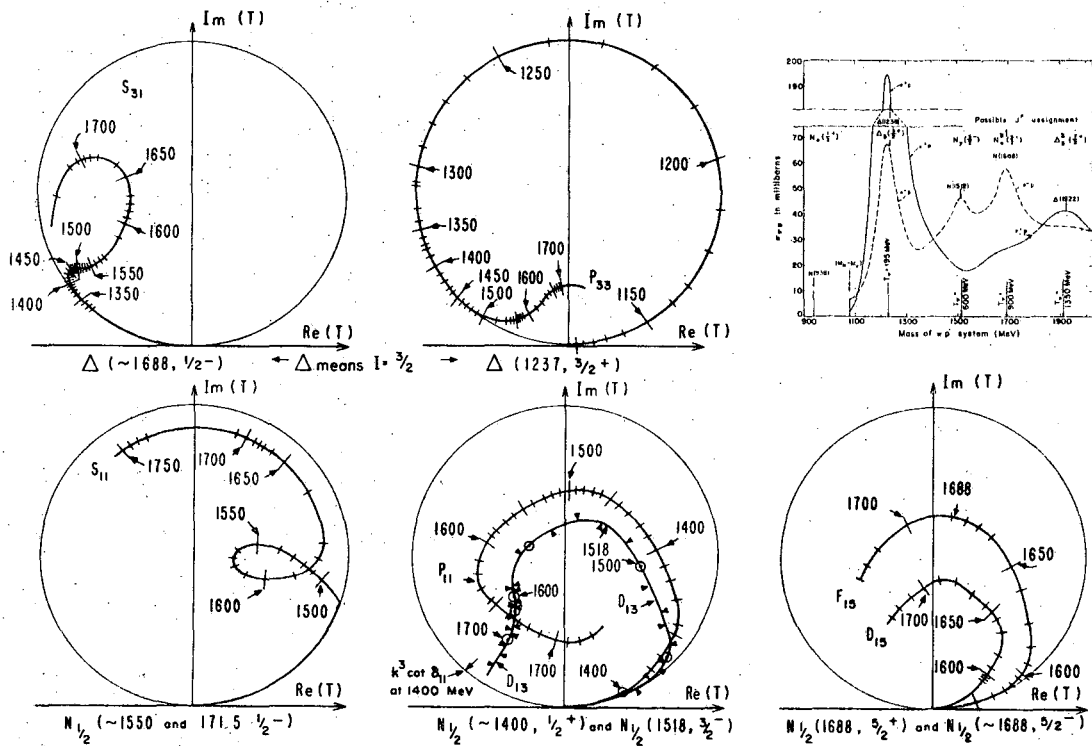
Fig. 6. The smooth guessed curves of Fig. 5 are replotted with the actual calculated amplitudes replaced by hatch marks interpolated every 10 MeV. For a resonance they should be spaced proportionally to $Im(T) = (1 + \epsilon^2)^{-1}$. The I-spin 3/2 resonant partial waves have been added at the top, along with a summary of the total cross section for $\pi^+ p$ and $\pi^- p$.

of a few mb, and is due to the sudden increase in the S_{31} amplitude,

plotted at the upper left, plus a change in P_{33} (upper middle). You will

notice that S_{31} starts out negative (repulsive interaction) and then de-

scribes a small resonant-like circle with a "diameter" measured ver-

tically of about 1/3, measured horizontally of about 1/4; i.e., it suggests

a resonance with an elasticity x_1 of only 1/3 to 1/4. I would guess that

this small loop is associated with a $D_{1/2}$ $\Delta\pi$ resonance, but the situation

is complicated by the fact that the $N\rho$ threshold is at 1690 MeV (in fact,

taking into account the width of the ρ we should say 1690 ± 60 MeV). For

more discussion of the $N\pi\pi$ final state, see Olsson and Yodh.[30]

Next we take up the I = 1/2 amplitudes, plotted on the bottom

row of Fig. 6. The π^-p total cross section is plotted at the upper right

as a dashed line; it shows only two I-spin 1/2 bumps that are not seen

in π^+p--there are the so-called 600-MeV bump (mass 1512 MeV) and

the 900-MeV bump (mass 1688). It has been recognized for some time

that these bumps were complicated; for instance, that there seemed to

be an S-wave $N\eta$ resonance near 1512, and a surprising amount of D-

wave present at 1688.

The S_{11} amplitude of Bareyre et al. behaves in a very animated

way. Right above $N\eta$ threshold it probably suddenly makes a tight loop

that suggests a $N\eta$ resonance with a small elasticity x_1 ($0.1 < x_1 < 0.2$).

The maximum curvature of this loop seems to be at about 1570 MeV,

but the velocity does not behave as it should, and I would say that the

parameters of this resonance are much in doubt. Indeed, the experts

tell me that it is easy to find solutions which do not even exhibit such a

resonance. After completing the $N\eta$ loop, the S-wave again becomes

almost elastic, and resonates a second time at about 1715 MeV.

The other two amplitudes that resonate near 1512 MeV are plotted in the middle diagram. They are D_{13}, $(3/2^-)$, which has been invoked ever since the 1512 bump was first discovered, and the P_{11} resonance (excited nucleon) first noted by Roper.[8] The P_{11} amplitude starts off negative, then turns around and crosses the origin at a mass 1175 MeV. It seems to reach a maximum velocity at about 1400 MeV. Let us consider the P_{11} amplitude to be the result of two opposite forces, a repulsive force responsible for a negative scattering length A, and an attractive resonant interaction. The scattering length will produce a phase shift $2i\delta$ and a contribution to the T' matrix

$$T' = \frac{e^{2i\delta'} - 1}{2i} \ .$$ (13)

You might expect the resonant interaction to contribute a term $x/(\epsilon - i)$, but this could take the total amplitude outside the unitarity circle. Landau and Lifshitz,[9] and Michael,[10] have suggested rotating the resonant circle until it is tangent with the unitarity circle, i.e.,

$$T'' = \frac{x}{\epsilon - i} e^{2i\delta'}.$$

The total amplitude, $T = T' + T''$, will now start out negative, and then superimposed on this clockwise motion will be the counterclockwise circular resonant behavior.

How far around this resonant circle is 1400 MeV? To solve this simple problem, assume that the repulsive phase shift $2\delta'$ is related to a scattering length by

$$k^3 \cot \delta' = 1/A,$$

or more precisely, using McKinley's phase shifts,[11]

$$(k/m_\pi)^3 \cot \delta' = -(.015)^{-1}.$$

Then, at 1400 MeV, δ' has reached -15 deg. So, according to (13), I have plotted a point on the unitary circle at -30 deg. It is encouraging that this point lies almost diametrically across the resonant circle from 1400 MeV. Evidence for this excited nucleon at about 1400 MeV was seen in pp diffraction scattering in 1964 by Cocconi et al. [12] and more recently by Anderson et al. [13]

I have no comment on the well-established D_{13} amplitude except to point out the striking similarity in the shapes of P_{11} and D_{13}.

Finally, the right-hand pair of amplitudes are those that resonate near 1688 MeV. The F_{15} seems to behave reassuringly like a resonance with elasticity x_1 about 0.6, and central value near 1690 MeV; D_{15} is very similar in shape, but its velocity does not seem to be well described by Eq. (2a).

My friends who are experts in these matters tell me that it is far too early to believe the exact values of the resonant energies and widths; much more data are needed before it will even be possible to rule out competing solutions that do not exhibit all these resonances. The inadequacy of the experimental data is illustrated by the fact that my cross hatching on the Argand diagrams do not vary in a smooth way.

Despite these warnings, I think that Fig. 6 suggests strongly that the number of resonances with which we have to deal is considerably higher than the number of bumps that we see in total cross section or elastic scattering experiments, and that these resonances may even tend to come in pairs of opposite parity, e.g., (P_{11} and D_{13}), (D_{15} and F_{15}), ...

C. States with Spin 7/2

I devoted a lot of time to the eight lowest πN resonances (or possible resonances), because I think that both experimentalists and theoreticians will find it convenient to be familiar with the presentation of these resonances as trajectories in the complex plane. But I do not have time to describe any other results in as much detail--luckily they are all published anyway. I shall simply introduce Table I and make brief comments about the states which are not yet listed thereon. Finally I shall introduce Fig. 7, a plot of Regge trajectories, and comment on the points that are plotted there.

1. $N^*(2190, 7/2^-)$. This state is already listed on Table I, which is taken from the October 1955 review by Rosenfeld et al.[14] However, at that time its parity was not yet established. Now two experiments have been completed, both at the Argonne National Laboratory. Yokosawa et al.[15] have used a polarized target. Their data strongly suggest a J^P assignment of $7/2^-$. Kormanyos et al.[16] have looked at π^- scattered 180 deg from an unpolarized target. The interference of N(2190) with background suggests a negative-parity resonance. So I think you can underline the J^P assignment in Table I.

2. $Y_1^*(2030), 7/2^+)$ and $Y_0^*(2120, 7/2^-)$. Table I lists a $Y_0^*(2060, 7/2^+)$. Recently, however, Wohl et al.[17] discovered that there are actually two Y^*'s near 2060; Y_1^* is actually about 30 MeV lower at 2030, and there is a $Y_0^*(7/2^-)$ at 2120. These resonances have also been seen in total-cross-section experiments by Cool et al.[18] [This situation is similar to that near 1800 MeV, where there are also two adjacent Y^*'s, again with $Y^*(1815)$ slightly heavier than $Y_1^*(1765)$]. According to Wohl

Table I. Baryons.

		Beam πp(MeV) or Kp(MeV/c)	I(J^P) ⊢⊣=estab.	Symbol	Mass (MeV)	Γ (MeV)	Mass² (BeV)²	Partial mode	Fraction (%)	Q (MeV)	p or Pmax (MeV/c)
N	p n	See Table S	1/2(1/2⁺)	N_α	+38.2 939.6		0.88 0.88	See Table S			
	$N^*_{1/2}(1480)$				Existence not yet definitely established						
	$N^*_{1/2}(1518)$	610 πp	1/2(3/2⁻)	N_γ	1518 ±10	125 ±13	2.30	πN Nππ	76±2	440 301	454 408
	$N^*_{1/2}(1688)$	900 πp	1/2(5/2⁺)	N^{II}_α	1688	100	2.85	πN Nππ ηN ΛK	≈85 <2 ≈2	610 471 201 75	572 538 389 231
	$N^*_{1/2}(2190)$	1965 πp	1/2(9/2⁺) ? ?	N^{III}_α(?)	2190	≈200	4.80	πN ΛK	≈30 seen	1112 577	888 710
	$N^*_{1/2}(2650)$	3125 πp	1/2	N	2645 ±10	≈200	7.02	πN ηN		1577 1158	1151 1090
Δ	$N^*_{3/2}(1236)$	195 πp	3/2(3/2⁺)	Δ_δ	1236	120	1.53	πN	100	160	233
	$N^*_{3/2}(1924)$	1354 πp	3/2(7/2⁺)	Δ^{II}_δ	1924	170	3.70	πN ΣK	< 67	842 237	722 430
	$N^*_{3/2}(2360)$	2452 πp	3/2(11/2⁺) ? ?	Δ^{III}_δ(?)	2360	~200	5.58	πN	≈10	1282	988
	$N^*_{3/2}(2825)$	3770 πp	3/2( )	Δ	2825 ±15	260	7.98	πN		1747	
Λ	Λ	See Table S	0(1/2⁺)	Λ_α	1115.4		1.24	See Table S			
	$Y^*_0(1405)$	<0 Kp	0(1/2⁻)	Λ_β	1405	35±5	1.97	Σπ Λππ	100 <1	76 10	151 69
	$Y^*_0(1520)$	395 Kp (MeV/c)	0(3/2⁻)	Λ_γ	1518.9 ±1.5	16 ±2	2.31	Σπ K̄N Λππ	55±7 29±4 16±2	190 87 124	266 243 251
	$Y^*_0(1815)$	1040 Kp	0(5/2⁺)	Λ^{II}_α	1815	70	3.29	K̄N Σπ Λππ Λη	≈80	383 486 420 151	541 504 515 344
Σ	Σ	See Table S	1(1/2⁺)	Σ_α	(+) 1189.5 (0) 1192.6 (-) 1197.4		1.41 1.42 1.43	See Table S			
	$Y^*_1(1385)$	<0 Kp	1(3/2⁺)	Σ_δ	1382.1 ±.9	51 ±2	1.91	Λπ Σπ	94±4 6±3	127 55	205 124
					Xscale=1.5 Xscale=2.4						
	$Y^*_1(1660)$	715 Kp	1(≥3/2)	Σ	1660 ±10	44 ±5	2.76	K̄N Σπ Λπ Σππ Λππ	≈15 ≈30 ≈ 5 ≈30 ≈20	225 328 405 188 265	406 383 439 321 389
					[mainly $Y^*_0(1405)+\pi$] ←							
	$Y^*_1(1765)$	940 Kp	1(5/2⁻)	Σ	1765 ±10	60 ±10	3.12	K̄N Λπ Σπ Λππ	≈60 Not yet resolved from $Y^*_0(1815)$	343 510	508 517
Ξ	Ξ	See Table S	1/2(1/2⁺)	Ξ_α	(-) 1321 (0) 1314		1.75 1.73	See Table S			
	$\Xi^*(1530)$		1/2(3/2⁺)	Ξ_δ	(-) 1529.7 ±0.9	7.5 ±1.7	2.34	Ξπ	≈100	73	148
			p wave								
	$\Xi^*(1818)$		1/2(3/2⁻)	Ξ	1818 ±5	≈60	3.27	Ξ*π ΛK̄ Ξπ Ξππ	≈10 ≈40 ≈40 ≈10	141 197 354 127	225 386 406 307
Ω	Ω⁻	See Table S	0(3/2⁺)	Ω_δ	1675 ±3		2.81	See Table S			

MUB-3408

Baryons, April Fool's Day, 1966

Negative Parity Baryons

5.0 — 8.0 ○ ← Δ (2825)? → ○

○ N(2190)

• Λ(2120)

$\frac{9}{2}^-$

$\frac{9}{2}^+$

4.0 — 7.0 ○ ← N (2650)? → ○

• Ξ (1815)

$\frac{7}{2}^-$

Need a × Λ to mix

• Σ (1765)

N(1688) · Δ(1688) Λ(1670)⇒Λη ○ Σ(1660)

3.0 — 6.0

• N (1688)

$\frac{7}{2}^+$

Slope = 2 GeV²/2ħ

× N(1550)⇒Nη N(1530) Λ(1520) Mixes

$\frac{5}{2}^-$

○ Δ(2360)

× Λ(1405)

2.0 — 5.0

$\frac{5}{2}^+$

Σ(2040)

1.0 — 4.0

$\frac{3}{2}^-$

○ Ξ(1933)

• Δ(1924)

$\frac{3}{2}^+$

Λ(1825)

Positive   Parity   Baryons

$\frac{1}{2}^-$

$\frac{1}{2}^+$

• Ω(1675)

N(1688)

• J^P relatively well known
○ J^P unknown
× J^P known, but masses repelled by mixing

N' (1500) •

Octet

• Ξ (1530)

Ξ (1318) •

• Σ(1385)

Σ(1193) • Λ(1115)

• Δ (1238)

N(938)

Decuplet

Octet^{II}

Decuplet^{II}

Octet^{III} ?

Decuplet^{III} ?

Mass² (GeV²)

Mass² (GeV²)

$\frac{1}{2}^+$ $\frac{3}{2}^+$ $\frac{5}{2}^+$ $\frac{7}{2}^+$ $\frac{9}{2}^+$ $\frac{11}{2}^+$ $\frac{13}{2}^+$ $\frac{15}{2}^+$

J

MUB-1632

Fig. 7. Regge plot of the baryons. This is really two independent figures, positive parity below the wiggly line, negative above. There is no theoretical reason for the fact that the ordinate is mass squared. Solid vertical lines mark J = 1/2-modulo-2; dashed lines mark 3/2-modulo-2. Possible recurrences on the solid (1/2-modulo-2) lines are joined by solid Regge trajectories. Possible recurrences on the dashed lines are joined by dashed Regge trajectories. The negative-parity Regge trajectory is simply drawn parallel to the trajectories for the 1/2$^+$ octet, which have a slope of 1 GeV per unit of J.

et al., $Y^*_1(2030)$ seems to have the Regge assignment Σ^{II}_δ; $Y^*_0(2120)$ is a candidate for Λ^{II}_γ. I think this is no problem, but let me take it up in the next section, when I discuss negative-parity Regge trajectories.

D. Other New States

Other new states, still too new or tentative to be included in Table I, are listed in Table Ia. For a discussion of each, I refer you to the lectures of my colleague Angela Barbaro-Galtieri, at the 1966 Erice International School of Physics.[19]

One comment about Table I. Here $\Delta(2360)$ is listed as having no information on spin and parity. A 180-deg π^+p elastic scattering experiment has been performed at Dubna by Alikhanov et al.[20] The technique is similar to that of Kormanyos et al.,[16] in which the parity of $N(2190)$ was determined to be negative. In the same way the date of Alikhanov et al. at first suggest that the parity of $\Delta(2360)$ is probably also negative. However, the Brookhaven group (Citron, Galbraith, Kycia, etc.[27]) who originally assigned the π^+p bump a mass of 2360 MeV have meanwhile raised their estimate to 2423 MeV, and Barger and Olsson[28] and Barger and Cline[29] find that they can fit the data with $J^P = 11/2^+$ and not with $P = -1$. So perhaps $\Delta(2423)$ is $\Delta\delta^{III}$.

And now one comment about some new information on the $\Sigma(2260)$ bump listed in Table Ia. This bump is seen by Cool et al.[18] only as a broad bump in their total-cross-section experiment, which yields no information on which partial waves are associated with each bump.

However, Dauber and Schlein et al.[19a] have recently performed a partial-wave analysis of $K^-p \to \Sigma^-\pi^+$ in the mass range 2100 to 2230

Table Ia. New or tentative baryons and σ(total) bumps not yet on Table I.

Condensed notation	Γ (MeV)	Beam (GeV/c)	Seen in reaction:	Mass^2 (GeV)^2	Comments and references
N(3020,)	400	4.2	$\pi^- p$, σ(total)	9.12	Citron +,[22] tentative
$N_?$(3245,)	60	5.0	$\pi^- p \to \pi^- p$ 180°	10.4	Kormanyos +,[16] $\Gamma_{\pi p}/\Gamma = x_1 < 0.05$
Δ(3220,)	440	5.0	$\pi^+ p$, σ(total)	10.4	Citron +,[22] tentative
Λ(1675, 1/2$^-$)	15	0.75	$K^- p \to \Lambda \eta$	2.81	Berley +,[23] $x_1 = 0.05$
Λ(2110, 7/2$^-$)	150	1.76	$K^- p$, σ(total), HBC	4.45	Cool +,[18] Wohl +,[17], $x_1 = 0.32$
Λ(2340,)	105	2.26	$K^- p$, σ(total)	5.48	Cool +[18]
Σ(1915, Σ^{II} ?)	65	1.26	$K^- p$, σ(total)	3.67	Cool +,[18] tentative; difficult deuterium subtraction
Σ(2260,)	180	2.06	$K^- p$, σ(total)	5.11	Cool +,[18, 19a]
Z_0(1863,)	150	1.15	$K^+ n$, σ(total)	3.47	Cool +,[24] tentative; difficult deuterium subtraction
Z_1(1910,)	180	1.25	$K^+ p$, σ(total)	3.65	Cool +,[24] analysis incomplete; near $K\Delta$ and $K^* p$ thresholds
$p\pi^+\pi^+$(1560)	200	--	$\pi^+ p$, pp, HBC	2.43	Goldhaber +,[25] Alexander +;[26] kinematic effect?

MeV and find a pronounced energy-dependence of the coefficients, part of which must arise from a $J \geqslant 9/2$ amplitude. A model fit assuming a $G_{?9}$ (or $H_{?9}$) resonance of unknown I spin as well as the F_{17} and G_{07} resonances of Wohl et al. and $S_{?1}$, $P_{?1}$, $P_{?3}$, $D_{?3}$ constant background amplitudes yields an acceptable probability. The spin-9/2 resonance parameters resulting from the fit are $M \approx 2200$ MeV and $\Gamma \approx 50$ MeV. Thus the $\Sigma(2260)$ of Cool et al. may turn out to be a complex structure consisting of several resonances, a situation which is not new to particle-physics spectroscopy.

Notice that some tentative multiplets are beginning to be seen which cannot belong to unitary 1, 8, or 10, namely Z_0, Z_1 and $p\pi^+\pi^+$; but none of them is yet established.

E. Regge Recurrences

Finally, some very brief comments on the Regge trajectories in Fig. 7.

Positive Parity. The first possible recurrences are those of the $1/2^+$ octet, which should recur at $5/2^+$. I have drawn solid lines starting at the $1/2^+$ members, and passing through $N(1688, 5/2^+)$ and $\Lambda(1815, 5/2^+)$. Before Cool et al.[18] reported the tentative $\Sigma(1915)$ I had been tempted to try to use $\Xi(1933)$ as Ξ_a^{II}, even though parallel Regge trajectories, plus the Gell-Mann Okubo formula demand, I believe, a mass 1972. If we try to guess that $\Sigma(1915)$ is Σ_a^{II}, then we will have to find a cascade of mass about 2000 MeV.

The decuplet seems to have two well-established recurrences and perhaps a third. I have joined occurrence-recurrence with dashed lines, and note that their slope is rather close to that for the octet trajectory.

I have also guessed what seemed like a reasonable positive-parity place to plot N(2190), but now that the parity of N(2190) has been determined to be negative, this guess must be withdrawn.

I have no idea how to cope with the dot labelled N'(1500) which is the excited nucleon labelled P_{11} on the Argand diagrams. As I discussed above, Eq. (13), I now realize that it is probably better to consider its mass closer to 1400.

Negative Parity. Here I have been able to plot no lines through known pairs of occurrence-recurrence. The situation is complicated by the existence of two $N_{1/2}$'s, both with $J^P = 1/2^-$, which may mix, although one seems to be mainly $N\pi$, the other mainly $N\eta$.

The $3/2^-$ octet is still incomplete. Either there must be Λ (belonging to the octet) at about 1660 MeV [hiding under $\Lambda(1675, 1/2^-)$ and $\Sigma(1660)$], or else there is octet-singlet mixing and the Λ has been repelled upwards, as indicated on Fig. 7.

There is something else about the $3/2^-$ (N_γ) situation that at first seems surprising, although I think it is all right. There are two states plotted at $7/2^-$, and, of course, they are candidates for recurrences of $3/2^-$. But at $7/2^-$ their separation is 70 MeV, at $3/2^-$ their masses overlap. However one of the states is a lambda, and so it is probably either a supermultiplet singlet, or partly singlet, mixed with octet. Hence there is little reason why the Λ trajectory should have the same slope as the rest of the octet. Barger and Cline claim quite convincingly that the new bumps on Table I and Ia, N(2640) and N(3020), are N_γ^{III} and N_γ^{IV}.

I think that you will agree with me that considerably more data are needed before the pattern becomes clear. When I talk on mesons you will see that things are tidier.

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LECTURE II: MESONS

The preceding text, Baryons, is a fairly faithful restatement
of what I actually said at Yalta. However, my two Meson lectures were
themselves a restatement of my Rapporteur's talk at the September
1965 Oxford Conference, which has already been published;[1] so it
seems inappropriate to reproduce it here. I shall therefore mention
below only those topics where there has been some considerable change
in the intervening 6 months.

Table I is a list of "well-known" mesons as presented to the
Oxford Conference. These "mesons" are "well-known" for one of three
reasons:

1. Most of them are well understood to be resonances or rather
large S-wave scattering lengths.

2. Some (notably A1 and B which I shall discuss below) are reliably
seen as bumps produced in the mass spectra of certain reactions: but
the quantum numbers and even the nature of the bump are still unclear.

3. One, the kappa, has been around so long, and has evoked so
much discussion, that I have left it on the table, even though I feel that
it is nearly dead!

Let me now go through this list, noting only the places where
there is a need for additions, or for corrections to my Oxford talk.

A. I-Spin = 0 Mesons

There is no significant news about the mesons on Table I. At
Oxford I discussed the question of the $S^0(720, 0^{++})$, also called the ϵ^0.
At that time the evidence for S^0 was inadequate to satisfy our criteria

Table I. Mesons.

	Mass (MeV)	$I(J^{PG})C$ ⊢—⊣=estab.	Symbol	Γ (MeV)	M^2 (BeV)²	Important decays — Partial modes	Fraction (%)	Q (MeV)	p or Pmax (MeV/c)
η	548.8 ±0.5	$0(0^{-+})C^+$	η_β	<10	0.301	See Table S			
ω	782.7 ±0.5 Xscale=1.6	$0(1^{--})C^-$	η_γ	9.3 ±1.7	0.613	$\pi^+\pi^-\pi^0$	89	369	327
						$\pi^+\pi^-$	≈1†	504	366
						neutral($\pi^0\gamma$)	10±1	648	380
						$\pi^+\pi^-\gamma$	<3.2	504	366
						e^+e^-	<0.14	782	391
						$\mu^+\mu^-$	<0.12	572	377
X^0	959 ±2	$0(0^{-+})C^+$	η_β	<4	0.920	$\eta 2\pi$	78±4	131	232
						$\pi\pi\gamma$	22±4	680	459
K_1K_1	≈1000	May be just large $\bar{K}K$ scattering length, see listings of data cards.							
φ	1019.5 ±0.3 Xscale=1.7	$0(1^{--})C^-$	η_γ	3.1 ±0.6	1.039	K_1K_2	35±6	23	109
						K^+K^-	50±6	32	126
						$\pi\rho+3\pi$	15±7	117	188
						$\pi^0\gamma$		885	501
						$\mu^+\mu^-$	<0.5	808	499
						e^+e^-	<0.4	1018	510
f	1253 ±20	$0(2^{++})C^+$	η_α^{II}	100 ±25	1.571	$\pi\pi$	large	974	611
						4π	8±6	695	547
						$\bar{K}K$	<16	265	386
E	1420	$0(\ )C$??	η	70	2.02	$K^*\bar{K}$	large	25	126
						$K\bar{K}\pi$	small	283	421
						2π	?	1131	691
						$\bar{K}K$	?	422	503
						3π	?	991	670
$\pi^\pm$	139.6	$1(0^{--})C^+_n$	π_β		0.019	See Table S			
π^0	135.0				0.018				
ρ	769 ±3 Xscale=1.1	$1(1^{-+})C^-_n$	π_γ	112 ±4 Xscale=2.6	0.582	2π	100	483	355
						4π	<5	204	241
						$\pi\gamma$	<2	623	369
A1	1072 ±8 Xscale=1.6	$1(1^{+-})C^+_n$	π	125	1.145	$\rho\pi$	≈100	188	251
						$\bar{K}K$	<5	C forbidden for odd J	
B	1220	$1(\geq 1^{+})C^-_n$	π_δ	125 ±17 Xscale=2.2	1.488	$\omega\pi$	≈100	293	335
						$\pi\pi$	<30	Permitted only for 1⁻	
						$\bar{K}K$	<10	assignment, if J<3	
						4π	<50	657	525
A2	1324 ±9 Xscale=2.5	$1(2^{+-})C^+_n$	π_α^{II}	90 ±10	1.753	$\rho\pi$	≈70	408	418
						$\bar{K}K$	≈10	159	430
						$\eta\pi$	≈20	622	529
$K^\pm$	493.8	$1/2(0^-)$	K_β		0.244	See Table S			
K^0	497.8				0.248				
κ	725 ±2	$1/2(0^+)$	K	<12	0.526	$K\pi$	≈100	90	
K^*	891 ±1	$1/2(1^-)$	K_γ	50 ±2 Xscale=1.2	0.794	$K\pi$	≈100	258	288
						$K\pi\pi$	<0.2	118	215
						$\kappa\pi$	<0.2	27	82
C	1215 ±15	$\leq 3/2(\ )$??	K	60 ±10	1.476	$K\rho$	?	-30	<0
						$K^*\pi$	?	184	253
K^*	1410 ±10	$1/2(2^+)$	K	100 ±20	1.988	$K\pi$	?	775	

†Assuming no ωρ interference.

for Table I. Since then I have heard no news from the Princeton spark-

chamber experiment which is underway to confirm it, nor has there

been any very convincing new buble-chamber data. So I would continue

to consider S^0 very tentative.

B. I-Spin = 1 and the Deck Effect

At Oxford I discussed the A1 in terms of Deck effect. I said

that the B needed more study, since it is supposed to be $\pi\omega$ resonance,

but there was 2σ evidence that the Dalitz plot for ω from B-mesons was

different from the normal ω Dalitz plot. Finally I dismissed the $K^*(1320)$

as a low-energy $K^*\pi$ peak which tended to move around in mass as the

beam momentum varied.

Let me now commend to your attention two new papers:

1. On the B front, in a counterattack on the problem of the strange

ω-Dalitz plot, Chung et al.[2] have analyzed 508 B events, as compared

with the 214 of Goldhaber et al. which looked strange. The 508 new

ones look all right. Clearly we have to keep track of the world's supply

of ω's from B decay, but perhaps the Goldhabers were just the victims

of a statistical fluctuation.

2. On the $K^*(1320)$ front, the Goldhaber group[3] have analyzed 421

reactions:

$$4.6 \text{ GeV/c } K^+p \to K^*\pi p$$

and looked at the $K^*\pi$ peak at 1320 MeV. In Fig. 1 I show some of these

events (the topology $K^+p \to K^{*0}\pi^+p$) together with the latest CERN-

Brussels spectra (private communication from B. Jongejans). In the

CERN data the $K^*\pi(1320)$ and the $K^*\pi$ decay of the $K^*(1405)$ are not

resolved, but in the Goldhaber data a valley seems to be appearing

Fig. 1. Collected K*π spectra.
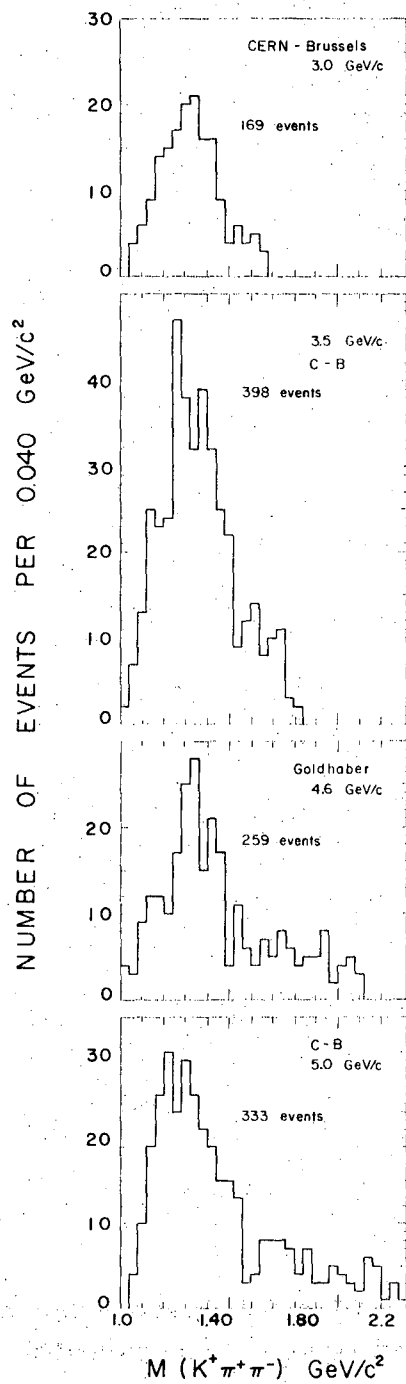
MUB-11604

between peaks at 1320 and about 1430 MeV. Again more data are needed, but Goldhaber suggests that $K^*(1320)$ should be considered as a meson whose production is enhanced by Deck effect; and I agree.

Note Added in Proof, July 1966: A 1^+? Nonet?

In UCRL-16930 (submitted to Phys. Rev. Letters), Shen, Butterworth, Fu, Goldhaber and Goldhaber present further evidence that $K^*(1320)$ is more than just Deck effect:

a. The 1320 peak is quite narrow: $\Gamma = 80 \pm 20$ MeV.

b. The $K\pi\pi$ Dalitz plot is concentrated where the K^* and ρ bands overlap.

c. Deck effect (π exchange) would give a K^* angular distribution proportional to $\cos^2\theta$. But right at 1320 MeV there is mild evidence (limited statistics) that a flatter contribution appears.

Shen et al. suggest that if $K^*(1320)$ is more than Deck effect, why not A1? Certainly there is a suggestive analogy in the spectra: $K^*\pi$ has bumps at $K^*(1320)$, $K^*(1405)$ (which they find at 1430); $\rho\pi$ has bumps at A1(1070), A2(1325). They point out that one can then form a (1^+?) nonet: A1, $K^*(1320)$, E(1420), D(1290). From A1 and $K^*(1320)$ one calculates $m_8 = 1390 \pm 20$ MeV, so that the octet is mainly E, with a mixing angle given by $\sin^2\theta = 0.2 \pm 0.12$. The partial widths predicted by SU3 then agree with experiment to within the now-familiar factor of about 2.

My guess of $J^P = 1^+$ for $K^*(1320)$ has to ignore a recent paper by the Wisconsin group [Phys. Rev. 16, 1069 (1966)] which reports a $K\pi$ decay mode. I find this paper difficult to reconcile with the Goldhaber group data.

Fig. 2 is taken from my Oxford talk, [1] where I tried to group leftover mesons (K_C, A1, D, E) into a 1^+ nonet. I have modified it, abandoning K_C in favor of $K^*(1320)$ as suggested by Shen et al. Please remember that this nonet is still speculation, but there are now so many bumps to keep track of that I personally find it helpful to classify them mentally according to the simplest scheme consistent with the data. In that spirit the nonet is useful.

None of these bumps has been reliably seen in any reactions other than highly peripheral ones, where the Deck effect can be significant. (end of note in proof).

For further discussion of the A1 and the B, see the recent Letter by Ferbel. [4]

My last comment under I = 1 news is that the Maglic group seems now to confirm that there are one or more $X^-(1670)$ mesons which decay into 1 charged, and 3 charged particles. [5] At Oxford I presented figures of various slightly contradictory neutral and charged bumps at about 1670 MeV in 2π mass spectra. These data have not changed much. In addition Vetlitsky et al. [6] now give some very tentative evidence for a $3\pi(1630)$ bump!

C. I-Spin = 1/2 K Mesons

1. The kappa. At Oxford I said that the kappa was at best shy and at worst deceitful. By now I say that it is critically ill. I have heard of several experiments that were supposed to confirm it, and each one has either failed completely or failed to find it in the sought-for channel and found instead a small $K\pi$ peak near 725 MeV in some other channel.
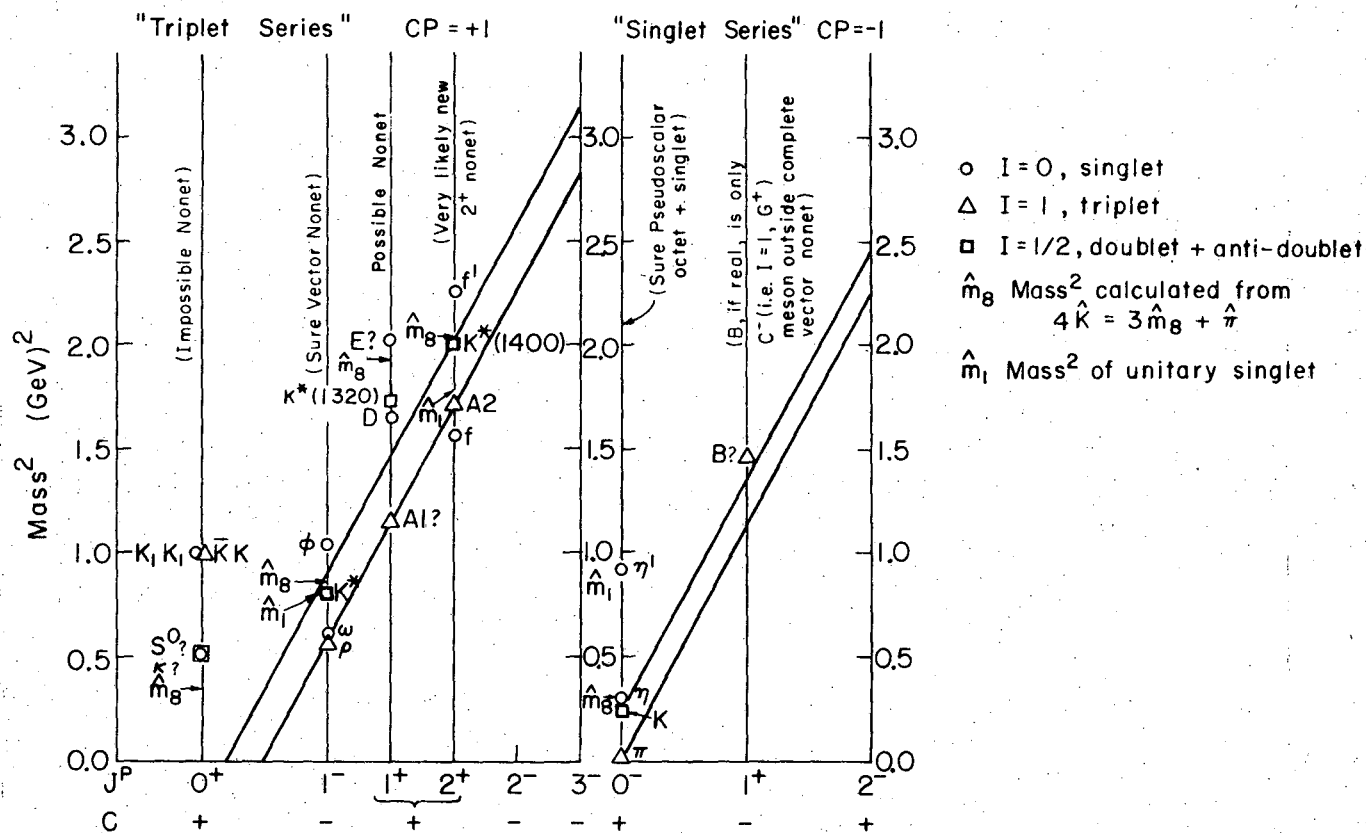
Fig. 2. Four nonets and some leftover mesons. This is taken from Fig. 61 of the Oxford Meson review,[1] except that in the possible 1$^+$ nonet, K_C has been replaced by K*(1320).

MUB-8630

This seems reminiscent of the situation with flying saucers, the Loch Ness Monster, and the Abominable Snow Man. If these are not familiar to you, I am sure that you can invent Russian counterpart legends. I think, like them, the kappa will be hard to bury, and yet I do not think that we can continue to take it seriously unless it is bolstered by one high-statistics experiment.

2. $K^*(1320)$. I have already discussed this out of order and along with the A1 and the B.

3. $K^*(1790)$. D. R. O. Morrison, of the Aachen-Berlin-CERN-London (IC)-Warsaw collaboration, has told me privately of a clear $K\pi\pi$ peak at 1790 MeV, $\Gamma = 70$. He announced it at the 1966 Washington APS meeting, but as yet there are no preprints.

4. $K^+K^+(1280)$? The Wisconsin group (Erwin et al.[7]) have recently published a K^+K^+ spectrum of 105 events, that casts doubt on the original CERN peak at 1280 MeV. However, if you look at my Oxford compilation, you will see that 102 of these events had already been kindly supplied me by Professor Walker. The peak is surely in doubt.

This concludes my brief news bulletin.

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