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[8]The equality of these elastic and total cross sections at "high energies" has already been pointed out (reference 3). The condition (2) specifies a precise criterion for which energies are "high enough".

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"U-SPIN EQUALITIES" AND OCTET SYMMETRY BREAKING

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An informative way to examine the role of unitary symmetry in strong interactions[1] is to consider the predictions that can be made about reaction cross sections.[2,3] The problem of comparing reactions with different incident energies and with various initial and final states has apparently been successfully overcome in an earlier analysis[4] of reactions of the type

$$\text{meson}+\text{proton}\rightarrow\text{baryon resonance}+\text{meson (vector meson)}. \quad (1)$$

The incident mesons were π^+ and K^+ mesons, and the baryon resonances belonged to the decuplet of $J^P=\frac{3}{2}^+$. Prior to this analysis, it had been proposed[3] that a test of the decuplet assignment could be made via a study of the scattering amplitudes of the "U-spin equalities" listed below,

$$(\pi^-p|N^{*-}\pi^+)/\sqrt{3}=-(\pi^-p|Y_1^{*-}K^+)=(K^-p|Y_1^{*-}\pi^+)=-(K^-p|\Xi^{*-}K^+), \quad (2)$$

$$(\pi^-p|N^{*-}\rho^+)/\sqrt{3}=-(\pi^-p|Y_1^{*-}K^{*+})=(K^-p|Y_1^{*-}\rho^+)=-(K^-p|\Xi^{*-}K^{*+}). \quad (3)$$

In the present work we analyze the data that are available on these processes to see to what extent the SU(3) predictions are obeyed. Deviations from pure SU(3) symmetry by an order of magnitude are found. The role of symmetry breaking in the interaction matrix elements is explored and correlated with the possible appearance of super resonances.

The mode of comparison, still ad hoc in nature, is described in detail in reference 4. It consists of comparing the processes at the same $Q=E^*-M_3-M_4$, and weighting each cross section σ by a phase-space factor $F=E^{*2}(p_{in}/p_{out})$, to yield the squares of the scattering amplitudes, $|M|^2=F\sigma$. In Fig. 1 we plot the results of a comparison of the data, carried out in this manner, for the processes listed in Eq. (2). Table I lists the pertinent cross sections together with associated values of E^*, Q, and F. The data are still too sparse to do this for the production of vector mesons as in the amplitudes of Eq. (3).

The salient features of Fig. 1 are the following: The equalities among the $|M|^2$ of Eq. (2) seem to divide into two subsets of equalities below a Q of approximately 600 MeV. $|M|^2$ for the $(\pi^-p|N^{*-}\pi^+)$ and $(K^-p|Y_1^{*-}\pi^+)$ processes are large and roughly equal, with matrix elements rising rapidly above threshold, reaching a maximum at $Q\cong 300$ MeV, and falling to a small value above about 600 MeV. These curves may encompass considerable structure because they cover an energy range which contains several resonances in both the π^-p and K^-p systems. The

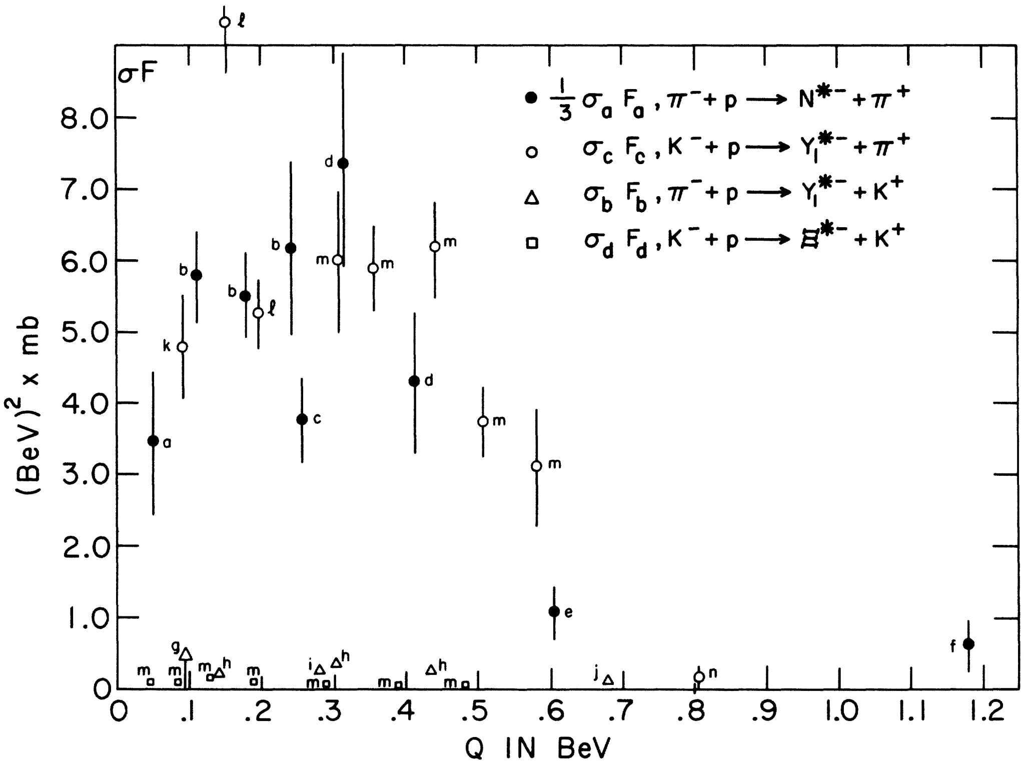

FIG. 1. Experimental values of $\frac{1}{3}\sigma_a F_a$, $\sigma_b F_b$, $\sigma_c F_c$, and $\sigma_d F_d$ vs Q for the "U-spin equalities." The letter next to each data point is the reference number of the data source (Table I).

other two processes are small and equal, showing no discernible peaking. Above 600 MeV there is no indication of any violation of the equalities. Below 600 MeV there seems to be a clear violation of the simple SU(3)-invariant relationships. Once again, one observes that reactions that involve the vertices $(N,Y) \rightarrow (Y^*, \Xi^*) + K$ are small compared to those involving $(N,Y) \rightarrow (N^*, Y^*) + \pi$. This seems to be a recurrence of earlier observations that led to the hypothesis of strong $(NN\pi)$ coupling and weaker (NYK) coupling.

Let us explore the effect of explicit symmetry breaking in the interaction matrix elements $|M|^2$. Recently, Konuma and Tomozawa[5] have examined some of the consequences of such breaking by the use of trace techniques.[6] In the present work, we make use of two alternative approaches to calculate symmetry-broken matrix elements.

Consider any process or interaction in which symmetry breaking is involved. Since the symmetry-breaking operator has the transformation properties of an $I=0$, $Y=0$ member of a unitary multiplet which is usually taken to be an octet,[7] it must then be a particular linear combination of tensor operators in U-spin space with component $U_z=0$, namely, $U^B = \frac{1}{2}(-U_0{}^0 + \sqrt{3}U_0{}^1)$. $U_0{}^0$ is a tensor operator of rank 0, i.e., a scalar, and $U_0{}^1$ is a tensor operator of rank 1, i.e., a vector operator. Using the standard methods of Racah algebra one need only compute matrix elements of the types $(\alpha UM|\frac{1}{2}(-U_0{}^0 + \sqrt{3}U_0{}^1)|\alpha' U' M')$ for the processes to be described fully.[8] This matrix element is evaluated with the following definition of the Eckart-Wigner theorem:

$$(\alpha UM|U_q{}^k|\alpha' U' M') = (kU'qM'|UM)(2U+1)^{-1/2} \times (-)^{k+U-U'} I(\alpha Uk\alpha' U'). \quad (4)$$

M and M' are the z components of the initial and final U-spin states. $U_q{}^k$ is a U-spin tensor operator of rank k and component q. α and α' represent all other quantum numbers (such as the charge) necessary to specify completely the initial and final states of the system. $I(\alpha Uk\alpha' U')$ is a reduced matrix element. The result of the explicit evaluation of the amplitudes (2) for the case of first-order octet symmetry breaking is listed below, using a phase convention consistent with the U-spin assignments shown in references 3 and 4.

Table I. Data for the "U-spin equalities." Meson + proton → baryon resonance + pseudoscalar meson.

Reaction	E^* (MeV)	Q (MeV)	F (BeV^2)	σ (mb)	σF	$\frac{1}{3}\sigma F$	Reference
(a) $\pi^- + p \to N^{*-} + \pi^+$	1382	50	8.0	1.54 ±0.4		4.1 ±1.0	a
	1490	112	5.0	3.5 ±0.4		5.8 ±0.67	b
	1557	179	4.5	3.7 ±0.4		5.5 ±0.6	b
	1620	242	4.4	4.2 ±0.1		6.2 ±1.5	b
	1632	254	4.4	2.54 ±0.4		3.73 ±0.6	c
	1695	317	4.4	5.03 ±1.2		7.37 ±1.7	d
	1798	413	4.5	2.92 ±0.7		4.3 ±1.0	d
	1980	602	5.0	0.65 ±0.1		1.1 ±0.5	e
	2556	1178	6.0	0.32 ±0.16		0.64 ±0.32	f
(b) $\pi^- + p \to Y_1^{*-} + K^+$	1978	99	10.7	<0.48 ±0.015	<0.52 ±0.16		g
	2020	141	9.64	0.021 ±0.004	0.21 ±0.04		h
	2159	280	8.22	0.032 ±0.006	0.27 ±0.05		i
	2180	301	8.31	0.042 ±0.012	0.35 ±0.10		h
	2309	431	8.25	0.030 ±0.010	0.25 ±0.08		h
	2556	677	8.87	0.011 ±0.005	0.098 ±0.044		j
(c) $K^- + p \to Y_1^{*-} + \pi^+$	1616	91	5.6	0.85 ±0.15	4.8 ±0.8		k
	1722	197	5.3	1.0 ±0.07	5.3 ±0.4		l
	1831	306	5.0	1.20 ±0.2	6.0 ±1.0		m
	1892	367	5.1	1.15 ±0.12	5.9 ±0.61		m
	1963	438	5.3	1.20 ±0.12	6.3 ±0.63		m
	2031	506	5.46	0.69 ±0.09	3.8 ±0.50		m
	2104	579	5.70	0.55 ±0.14	3.14 ±0.80		m
	2330	805	6.58	0.037 ±0.008	0.24 ±0.05		n
	1680	155	5.5	1.72 ±0.2	9.4 ±1.1		l
(d) $K^- + p \to \Xi^{*-} + K^+$	2065	41	1.9	~0.006 ±0.001	0.11 ±0.02		m
	2109	85	14.6	0.009 ±0.0015	0.13 ±0.02		m
	2151	127	12.4	0.015 ±0.003	0.18 ±0.03		m
	2213	189	11.1	0.009 ±0.0015	0.10 ±0.02		m
	2314	290	10.3	0.006 ±0.0015	0.062 ±0.15		m
	2411	387	9.97	0.005 ±0.0012	0.050 ±0.012		m
	2505	481	10.0	0.003 ±0.0012	0.030 ±0.012		m

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The symmetry-broken amplitudes are

$$M_{5a}=(\pi^-p|U^B|N^{*-}\pi^+)/\sqrt{3}$$
$$=(-\tfrac{1}{4}\sqrt{3})I(101)-(\tfrac{1}{4}\sqrt{10})I(112)+(\tfrac{1}{4}\sqrt{2})I(111), \quad (5a)$$
$$M_{5b}=(\pi^-p|U^B|Y_1^{*-}K^+)$$
$$=(\tfrac{1}{4}\sqrt{3})I(101)-(\tfrac{3}{4}\sqrt{10})I(112)-(\tfrac{1}{4}\sqrt{2})I(111), \quad (5b)$$
$$M_{5c}=(K^-p|U^B|Y_1^{*-}\pi^+)$$
$$=-(\tfrac{1}{4}\sqrt{3})I(101)-(\tfrac{1}{2}\sqrt{10})I(112)+(\tfrac{1}{4})I(011), \quad (5c)$$
$$M_{5d}=(K^-p|U^B|\Xi^{*-}K^+)$$
$$=(\tfrac{1}{4}\sqrt{3})I(101)-(\tfrac{1}{2}\sqrt{10})I(112)-(\tfrac{1}{4})I(011). \quad (5d)$$

The result follows immediately that

$$M_{5a}+M_{5b}=M_{5c}+M_{5d}. \quad (6)$$

This agrees, apart from signs due to a different phase convention, with the result of Konuma and Tomozawa.[9] Note that only one reduced matrix element, $I(112)$, remains when the indicated sum is taken on both the left and right sides of Eq. (6). $I(112)$ is due to a $U=2$ final state which may arise from either a (41) amplitude or from a (22) amplitude, as is discussed later. If $I(112)$ vanishes, then $M_{5a}=-M_{5b}$ and $M_{5c}=-M_{5d}$, contrary to the experimental situation.

Equation (6) does not provide very stringent conditions on the cross sections $\sigma_{5a},\cdots,\sigma_{5d}$ which are proportional to $|M_{5a}|^2,\cdots,|M_{5d}|^2$. These conditions on the squares of the amplitudes $|M_{5a}|^2$ through $|M_{5d}|^2$ are certainly consistent with the experimental data. In the region where $|M_{5a}|\gg|M_{5b}|$ and $|M_{5c}|\gg|M_{5d}|$, i.e., $Q<600$ MeV, Eq. (6) predicts $|M_{5a}|\approx|M_{5c}|$, which agrees with the observations. Hence we conclude that first-order octet symmetry breaking is sufficient to "explain" the large discrepancy.

An alternative more detailed view of the symmetry-breaking process may help us to see why processes 5(a) and 5(c) have large experimental $|M|^2$ while 5(b) and 5(d) are small. As described previously,[3,4] the SU(3)-invariant amplitudes $A^{(\lambda\mu)}$, in terms of which one writes the amplitudes (2), contain only those symmetries common to both the initial and final states, namely (22), (30), and two (11)'s. Note that the (41) part of the baryon-resonance meson wave function remains unprobed. If we introduce octet symmetry breaking into the interaction, the scattering amplitudes contain terms of the type

$$((11)\otimes(11)|(11)|(30)\otimes(11)). \quad (7)$$

A (41) contribution may arise from two separate sources, namely $[(11)\otimes(11)]_{22}\otimes(11)$ and $[(11)\otimes(11)]_{30}\otimes(11)$. These contributions produce an overlap with the (41) contribution from the final state. Only contributions from the (41) symmetry and some of the (22) symmetries allow the amplitudes M_{5a} to be different from M_{5b} and M_{5c} to be different from M_{5d}. In fact, a detailed examination of the amplitudes of Eq. (7) indicates that in order to make M_{5a} and M_{5c} large, and M_{5b} and M_{5d} small, one must invoke an interference between the (41) and/or (22) amplitudes with the $A^{(\lambda\mu)}$'s.

Let us try to correlate these results with our previous analysis of π^+p and K^+p reactions, because both studies involve different states of the same SU(3) multiplets. The processes analyzed previously were

$$K^++p\to N^{*++}+K^0,\quad \pi^++p\to N^{*++}+\pi^0, \quad (8a, 8b)$$
$$\pi^++p\to N^{*++}+\eta,\quad \pi^++p\to Y_1^{*+}+K^+. \quad (8c, 8d)$$

An up-to-date plot of the available data is displayed in Fig. 2; the data are taken from reference 4 and from Daudin et al.,[10] Foelsche and Kraybill,[11] Yamamoto et al.,[12] Abolins et al.,[13] and the Aachen group collaboration.[14] Note that the curves for $|M|^2$ for the $N^{*++}K^0$ and $N^{*++}\pi^0$ processes are qualitatively similar to those for $N^{*-}\pi^+$ (Fig. 1), i.e., they peak at $Q\cong 300$ MeV. The other two π^+p-initiated processes are smaller and there is also a rise in the $N^{*++}\eta$ curve. Recall that a good fit with the SU(3) prediction[4]

$$|M_{8a}|^2=|M_{8b}|^2+3|M_{8c}|^2-3|M_{8d}|^2 \quad (9)$$

was obtained without the introduction of symmetry breaking in the interaction. Why it was not necessary there and yet is required for the equalities (2) is not at all clear. It is also worth noting that the system of experimental curves for the production of vector mesons[4] in K^+p- and π^+p-initiated processes displays a qualitatively different appearance from those in which pseudoscalar mesons are produced.

One interpretation of the processes which peak at a $Q\cong 300$ MeV is that there are "super resonances" being formed which correspond to composites of the $N^{*++}K^0$, $N^{*++}\pi^0$, $N^{*-}\pi^+$, and $Y^{*-}\pi^+$ systems. The energies of these super resonances, which equal the masses of the constituents plus the Q of 300 MeV, are then about 2030, 1670,

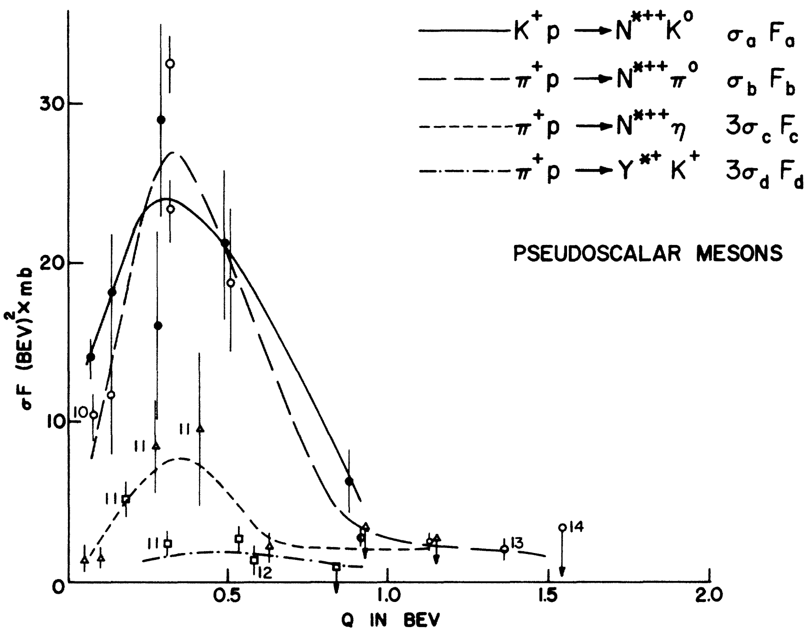

FIG. 2. Experimental values of $\sigma_{8a}F_{8a}$, $\sigma_{8b}F_{8b}$, $\sigma_{8c}F_{8c}$, and $\sigma_{8d}F_{8d}$ vs Q. The lines are drawn roughly through the data points simply as a guide. The numbers next to some of the data points give the reference number for those data points. The data unaccompanied by numbers were copied from our earlier paper on these reactions[4] and the references are given there.

1680, and 1820 MeV, respectively. The masses of the $N^*\pi$ systems are very close to the known $N^*(1688)$ and to the "shoulder" in the π^+p total cross section at about 1650-1680 MeV. The $Y_1^*\pi$ mass lies very close to the 1815-MeV $Y=0$ resonance. An N^*K resonance is more of an enigma, inasmuch as there has been no convincing evidence of any $Y=2$ meson-baryon resonance. Any attempt to ascribe the peaks in the four processes to one amplitude would require that amplitude to be of a (22) type. [A (41) channel is not allowed since it does not couple to the $I=1, Y=2$ K^+p system.]

Clearly, we have not found a unique and compelling interpretation of the data when we try to correlate the K^+p and π^+p reactions with the K^-p and π^-p reactions. For example, one may adopt the point of view that the peak exhibited in the K^+p reaction (8a) is not of the same character as that of the peaks in the other three channels [(5a), (5c), (8b)] with large cross sections. The K^+p peaking may be simply a manifestation of the competition between available phase space and unitarity, whereas the peaking in the other three channels could be predominantly related to the resonances which are known to exist in the mass region corresponding to $Q \cong 300$ MeV. Such a line of argument (which essentially denies SU(3) invariance) makes it hard to understand the success of the SU(3) relation (9) for both pseudoscalar and vector meson production.

In conclusion, we find that the predictions of pure SU(3) invariance are badly violated for the "U-spin equalities." The inclusion of octet symmetry breaking in the scattering amplitudes is sufficient to explain this violation, provided that additional amplitudes from the (41) and/or (22) representations are large. In addition, the Q plots of Figs. 1 and 2 suggest the possibility of super resonances.

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LEPTONIC DECAY OF THE Ω^- PARTICLE*

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Recently a particle of strangeness -3 and of mass about 1680 MeV has been found[1] which fits the prediction[2-5] for the tenth member (the isosinglet) of the spin-parity $\frac{3}{2}^+$ baryon decuplet. Because such a particle can decay only via the weak interactions, it is interesting to study its leptonic decays, since they may appear with a rate large enough to be observed in the near future.

Assuming V-A leptonic interaction, the most general interaction for the process

$$\Omega^- \to \Xi^0 + l + \bar{\nu}, \quad l=\mu, e, \tag{1}$$

can be written in the form

$$H' = [\bar{\Xi}(G_A{}'O^{\nu\rho}/\sqrt{2} + i\gamma_5 G_V{}' Q^{\nu\rho}/\sqrt{2})\Omega_\nu] \times [\bar{l}\gamma_\rho(1-i\gamma_5)\nu], \tag{2}$$

where

$$O^{\nu\rho} = (f_1 + f_2 P^\lambda p_\lambda/Mm)g^{\nu\rho} + (f_3 P^\rho/M + f_4 p^\rho/m + f_5\gamma^\rho)p^\nu/m,$$

$$Q^{\nu\rho} = (f_1{}' + f_2{}' P^\lambda p_\lambda/Mm)g^{\nu\rho} + (f_3{}' P^\rho/M + f' p^\rho/m + f_5{}'\gamma^\rho)p^\nu/m, \tag{3}$$

P, M and p, m being the four-momentum and the mass, respectively, of the Ω^- and of the Ξ^0 particle; f_1, f_2, f_3, f_4, and f_5 are form factors (f_1 which is equal to unity has been put in for convenience only). Ξ, l, and ν are the usual spinors, whereas Ω_ν is a $\frac{3}{2}$ spin operator. We adopt for it the Rarita-Schwinger representation[6] and, following Kusaka[7] and Brown and Telegdi[8] we will use the set of orthonormal positive-energy spin states defined as

$$\Omega_\nu{}^\xi = H_\nu{}^\xi\Omega^+ + F_\nu{}^\xi\Omega^-, \tag{4}$$

where ν and ξ are vector and polarization indices, respectively, $\Omega^\pm$ are spin-up and -down positive-energy $\frac{1}{2}$-spinors, and $H_\nu{}^\xi, F_\nu{}^\xi$ are the following four-vectors:

$$\begin{aligned}
&H_\nu{}^{(1)} \equiv 2^{-1/2}(1, i, 0, 0), && F_\nu{}^{(1)} \equiv 0,\\
&H_\nu{}^{(2)} \equiv 0, && F_\nu{}^{(2)} \equiv 2^{-1/2}(1, -i, 0, 0),\\
&H_\nu{}^{(3)} \equiv (1/\sqrt{6})(1, -i, 0, 0), && F_\nu{}^{(3)} \equiv (\sqrt{\tfrac{2}{3}})(0, 0, 1, 0),\\
&H_\nu{}^{(4)} \equiv (\sqrt{\tfrac{2}{3}})(0, 0, 1, 0), && F_\nu{}^{(4)} \equiv -(1/\sqrt{6})(1, i, 0, 0).
\end{aligned} \tag{5}$$

In the square matrix element we need, the leptonic term is straightforward. In the baryonic term, instead, we have the products $\Omega_\nu{}^\xi\bar{\Omega}_\mu{}^\xi$ which are linear combinations of spin-up and -down Dirac spinors. Thus we need two step operators such that (lower indices refer to energy and upper indices refer to spin)

$$O_-\Omega_+{}^+ = \Omega_+{}^-,$$

$$O_+\Omega_+{}^- = \Omega_+{}^+, \tag{6}$$