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$SU(6)_W$ PHOTOPRODUCTION AND MESON-BARYON SCATTERING AMPLITUDES*

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The $SU(6)_W$ description of colinear processes[1] like forward-scattering amplitudes has recently been justified by several different approaches[2] which all avoid the difficulties inherent in strict U(12) invariance.[3] These formulations imply that $SU(6)_W$ predictions should be valid even though predictions from strict U(12) are in disagreement with experiment.[3] This point of view is supported by the success of $SU(6)_W$ predictions for electromagnetic form factors,[4] vertex functions,[1] weak decays,[5] and the Johnson-Treiman relations.[6] A systematic survey of all $SU(6)_W$ predictions and comparison with experiment should furnish important tests of these formulations and may also provide indications of the underlying dynamics.[7]

In this paper we use W spin and $SU(6)_W$[1] to obtain many simple relations among photoproduction amplitudes and among scattering amplitudes which hold even when the particles involved are moving, so long as the motions are colinear. We consider amplitudes of the form $(\gamma p|MB)$ and $(MB|MB)$. The photon has the properties of the $U=0, W=1$ member of a 35-dimensional representation; M denotes the 35 pseudoscalar and vector mesons, and B represents the 56 $J^P=\frac{1}{2}^+$ baryons and $\frac{3}{2}^+$ baryon resonances. The amplitudes which are computed are labeled by the SU(6) representations which arise in the product 35×56, namely, $56+70+700+1134$. The calculation of these $SU(6)_W$ amplitudes follows straightforwardly using SU(6) Clebsch-Gordan coefficients,[8] provided that the $SU(6)_W$ classification of the particles is used.[1] The predictions so obtained are, of course, quite different from the earlier ones (except for the Johnson-Treiman[6] relations) which are strictly $SU(6)_S$ results.[8-10] They have the virtue of being relativistic, but pay the penalty of holding only in the forward or backward directions.

As mentioned in reference 1, the W-spin and S-spin classifications of the 56 baryons are the same. However, the 35-meson representation, whose $SU(3)\times SU(2)$ contents are $8^3+8^1+1^3$, and the one-dimensional representation, 1^1, differ in the two classifications as follows: The constituents of the $SU(6)_S$ 35 are the vector-meson octet, the pseudoscalar octet, and the unitary-singlet vector meson, called here ω^0. X_0 is the $SU(6)_S$ singlet. Under $SU(6)_W$ the 8^3 states (the 3 now refers to a W-spin vector) are the ±1 helicity components of the octet of vector mesons and the eight pseudoscalar mesons. A typical W-spin triplet might be $\rho_1^+, \pi_0^+, \rho_{-1}^+$. The 8^1 representation is an octet composed of all of the zero-helicity vector mesons. The 1^3 representation has as its three components $\omega_1^0, X_0, \omega_{-1}^0$. The 1^1 representation of $SU(6)_W$ has as its member ω_0^0.

With this classification scheme we first consider photoproduction processes. The $SU(6)_W$ transformation properties of the photon are, fortunately, quite simple. The photon transforms under SU(3) like the $U=0$ linear combination $(3^{1/2}\rho^0+\varphi^0)/2$, where ρ^0 and φ^0 are the $I=1$ and $I=0$ neutral members of the vector-meson octet.[11,12] (Note that there is a phase difference between the $U=0$ member described here and that of reference 11.) The photon transforms in the same way under S spin or W spin, i.e., like the ±1 helicity states of the vector mesons. Consequently, only two kinds of amplitudes are to be evaluated, $(\gamma_1 p_{1/2}|MB)$ and $(\gamma_{-1}p_{1/2}|MB)$. For each of the two kinds of initial states one may, of course, have various states for the final baryon. All possible amplitudes for photons of both helicities have been evaluated using $SU(6)_W$, and will be published elsewhere. One obtains, in addition to the U-spin relations,[12] some particularly simple results when the final state consists of a pseudoscalar meson and a spin-$\frac{1}{2}$ baryon. For this case only the $\gamma_{-1}p_{1/2}$ initial state may contribute, due to S_z and W_z conservation. The following relations among the photoproduction amplitudes hold:

$$(\gamma_{-1}p_{1/2}|\eta_0 p_{-1/2}) = 3\sqrt{3}/7(\gamma_{-1}p_{1/2}|\pi_0{}^0 p_{-1/2}) = 3\sqrt{3}/\sqrt{2}(\gamma_{-1}p_{1/2}|K_0{}^0\Sigma_{-1/2}{}^+). \quad (1)$$

This striking prediction says that for forward or backward scattering, neglecting phase-space corrections, the cross section for $\pi^0 p$ production is 24.5 times as large as that for $K^0\Sigma^+$. Similarly, the $\pi^0 p$ production is predicted to be 49/27 times as large as η production. Many exotic relations among the photoproduction amplitudes arise, but unfortunately, when the amplitudes are first squared and then summed, the resulting cross sections don't have simple ratios. However, if it is possible to measure the amplitudes for photons of particular helicity striking a polarized target and producing polarized products, then these relations may also be checked.[13] One interesting relation among amplitudes for particular polarizations is the vanishing of the amplitudes $(\gamma_{-1}p_{1/2}|\varphi_{-1}N_{1/2}{}^{*+})$, $(\gamma_{-1}p_{1/2}|\varphi_1 N_{-3/2}{}^{*+})$, and $(\gamma_1 p_{1/2}|\varphi_1 N_{1/2}{}^{*+})$, where φ is the real φ meson at 1020 MeV and may be written as the linear combination $\varphi=\omega^0+2^{1/2}\varphi^0$.[14]

We consider next the evaluation of meson-baryon scattering and reaction amplitudes. The reactions which we treat are those involving pseudoscalar mesons striking proton targets. Because all pseudoscalar mesons have $W=1$, $W_z=0$, the incident channel always involves coupling a $W=1$, $W_z=0$ meson to a $W=\frac{1}{2}$, $W_z=\frac{1}{2}$ proton to give total $W=\frac{3}{2}$ and $\frac{1}{2}$. The final state may, in general, be more complicated because of the possibility of various $W_z=S_z$ states for the final baryon. Four distinct classes of final states are possible, namely PB, VB, PB^*, and VB^*; P and V indicate pseudoscalar and vector mesons, while B and B^* correspond to the octet of $\frac{1}{2}^+$ baryons and the decuplet of spin-$\frac{3}{2}^+$ baryon resonances. As an illustration of the calculational procedure, consider the process $(\pi^- p|\rho^+ N^{*-})$. To get the cross section requires calculating the following three scattering amplitudes: The subscripts for each particle give the $S_z=W_z$ for the particular state involved. To the right of the amplitudes are given the W and W_z quantum numbers for the states involved.

$$(\pi_0{}^- p_{1/2}|\rho_1{}^+ N_{-1/2}{}^{*-}):\ \begin{pmatrix} 1 & \frac{1}{2} & \big| & 1 & \frac{3}{2} \\ 0 & \frac{1}{2} & \big| & 1 & -\frac{1}{2} \end{pmatrix}; \quad (2)$$

$$(\pi_0{}^- p_{1/2}|\rho_0{}^+ N_{1/2}{}^{*-}):\ \begin{pmatrix} 1 & \frac{1}{2} & \big| & 0 & \frac{3}{2} \\ 0 & \frac{1}{2} & \big| & 0 & \frac{1}{2} \end{pmatrix}; \quad (3)$$

$$(\pi_0{}^- p_{1/2}|\rho_{-1}{}^+ N_{3/2}{}^{*-}):\ \begin{pmatrix} 1 & \frac{1}{2} & \big| & 1 & \frac{3}{2} \\ 0 & \frac{1}{2} & \big| & -1 & \frac{3}{2} \end{pmatrix}. \quad (4)$$

These amplitudes may be evaluated using the usual SU(6) Clebsch-Gordan coefficients provided that the W-spin assignments of the various meson components are used. This means that when the $\pi_0{}^- p_{1/2}$ Clebsch-Gordan coefficients are evaluated, the $\pi_0{}^-$ is treated as the $W=1$, $W_z=0$ member of an 8^3 representation, not as the $S=0$ member of an 8^1 representation. Similarly, the $\rho_0{}^+$ is treated as the $W=0$ member of an 8^1 representation. All of the other members of the amplitudes (2), (3), and (4) have the same W and S classifications, and therefore cause no problem. Note that (2) and (4) both require W-spin-$\frac{3}{2}$ and -$\frac{1}{2}$ amplitudes, whereas amplitude (3) is pure $W=\frac{3}{2}$. The particular linear combinations of W-spin-$\frac{3}{2}$ and W-spin-$\frac{1}{2}$ contributions, denoted by G and H, respectively, which are needed for the complete evaluation of (2)-(4), are $(\sqrt{2}/3)G-(\sqrt{2}/3)H$, $(\sqrt{6}/3)G$, and $-[2/(15)^{1/2}]G-(\frac{1}{6})^{1/2}H$. To obtain the cross section σ, except for phase-space factors, the resulting amplitudes (2)-(4) must be squared and then summed. This procedure

Table I. Scattering amplitudes for meson-baryon initiated amplitudes according to $SU(6)_W$.

Process \ Representation	56	70	700	1134
$\langle K^+p\|K^+p\rangle$	0	0	1/2	1/2
$\langle K^0p\|K^0p\rangle$	0	0	3/8	5/8
$\langle \pi^+p\|\pi^+p\rangle$	8/135	1/144	25/54	113/240
$\langle \pi^-p\|\pi^-p\rangle$	11/135	7/144	35/108	131/240
$\langle \bar{K}^0p\|\bar{K}^0p\rangle$	1/45	1/24	17/72	7/10
$\langle K^-p\|K^-p\rangle$	2/45	1/12	2/9	13/20
C	0	0	1/24	−1/24
D	1/405	−1/432	−1/648	1/720
E	1/405	2/432	−1/648	−4/720

has been carried out for all pseudoscalar mesons incident on protons to yield all possible 35×56 products. The resulting catalogue of numerical amplitudes will be published separately, but a number of interesting results which ensue are summarized as follows:

(1) The Johnson-Treiman relations[6] are satisfied; the pertinent amplitudes are listed in Table I.

(2) A very small number of the calculated W-spin amplitudes are identically zero.[15] These are

$$(K^+p\,|K^0N^{*++}),\ (K^0p\,|K^+N^{*0}),$$
$$(K^-p\,|K^-N^{*+}),\ (\bar{K}^0p\,|K^-N^{*++}). \qquad (5)$$

The first of these seems to be satisfied at 1.14 BeV/c.[16] The angular distribution for this process is strongly peaked at $\cos\theta=\hat{K}\cdot\hat{N}^*=-0.5$ with a rapid decrease towards zero at forward and backward angles for the scattered K^0. At 3 BeV/c,[17] however, this decrease at forward angles is not so marked, although the cross section at the forward angle is small.

(3) Other relations among cross sections in the $Y=2$ system are

$$\sigma(K^+p\,|K^{*+}p)=(\tfrac{2}{3})\sigma(K^+p\,|K^{*0}N^{*++})=16\sigma(K^0p\,|K^{*0}p)$$
$$=(16/3)\sigma(K^0p\,|K^+n). \qquad (6)$$

These cross sections may be obtained as multiples of $|C|^2$ where C is an $SU(6)_W$ amplitude listed in Table I.

(4) A startling number of reaction amplitudes in the $Y=1$ and $Y=0$ systems are simple multiples of one basic amplitude D listed in Table I.[18] In Table II are listed the multiples of D^2 for 36 processes, whose cross sections should stand in the indicated ratios. Since these include all of the cases for which simple SU(3) relations were obtained, we consider them further. An SU(3) sum rule was previously formulated [19] for the squares of matrix elements (called σ in this paper), which reads

$$\sigma(K^+p\,|K^0N^{*++})=\sigma(\pi^+p\,|\pi^0N^{*++})+3\sigma(\pi^+p\,|\eta N^{*++})$$
$$-3\sigma(\pi^+p\,|K^+Y^{*+}). \qquad (7)$$

From Eq. (5), the left side should be zero. $SU(6)_W$ relates the cross sections of the other three processes in terms of C^2:

$$\sigma(\pi^+p\,|\pi^0N^{*++})=(\tfrac{3}{2})\sigma(\pi^+p\,|K^+Y^{*+})$$
$$=3\sigma(\pi^+p\,|\eta N^{*++}). \qquad (8)$$

Other simple SU(3) relations were the U-spin

Table II. Cross sections for meson-baryon reactions. Coefficients listed in columns a are multiples of $|D|^2$, where D is the $SU(6)_W$ amplitude.

$D=1/\sqrt{3}[(1/405)\underline{56}-(1/432)\underline{70}-(1/648)\underline{700}+(1/720)\underline{1134}]$

	Process	a		Process	a
1	$\langle K^-p\|\pi^+\Sigma^-\rangle$	3	19	$\langle \pi^-p\|\eta N^{*0}\rangle$	4
2	$\langle K^-p\|K^0\Xi^0\rangle$	3	20	$\langle \pi^-p\|\pi^0N^{*0}\rangle$	108
3	$\langle K^-p\|K^+\Xi^-\rangle$	12	21	$\langle \pi^-p\|\pi^+N^{*-}\rangle$	288
4	$\langle K^-p\|K^{*0}\Xi^0\rangle$	129	22	$\langle \pi^-p\|K^0Y^{*0}\rangle$	12
5	$\langle K^-p\|K^{*+}\Xi^-\rangle$	48	23	$\langle \pi^-p\|K^+Y^{*-}\rangle$	96
6	$\langle K^-p\|\rho^+\Sigma^-\rangle$	57	24	$\langle \pi^-p\|\rho^+N^{*-}\rangle$	504
7	$\langle K^-p\|K^0\Xi^{*0}\rangle$	24	25	$\langle \pi^-p\|K^{*+}Y^{*-}\rangle$	168
8	$\langle K^-p\|K^+\Xi^{*-}\rangle$	96	26	$\langle \pi^+p\|K^+Y^{*+}\rangle$	24
9	$\langle K^-p\|\pi^-Y^{*+}\rangle$	24	27	$\langle \pi^+p\|\pi^+N^{*+}\rangle$	24
10	$\langle K^-p\|\pi^+Y^{*-}\rangle$	96	28	$\langle \pi^+p\|\pi^0N^{*++}\rangle$	36
11	$\langle K^-p\|\pi^0Y^{*0}\rangle$	54	29	$\langle \pi^+p\|\eta N^{*++}\rangle$	12
12	$\langle K^-p\|\eta Y^{*0}\rangle$	2	30	$\langle \bar{K}^0p\|K^+\Xi^0\rangle$	3
13	$\langle K^-p\|K^{*0}\Xi^{*0}\rangle$	168	31	$\langle \bar{K}^0p\|K^{*+}\Xi^0\rangle$	57
14	$\langle K^-p\|K^{*+}\Xi^{*-}\rangle$	168	32	$\langle \bar{K}^0p\|\eta Y^{*+}\rangle$	4
15	$\langle K^-p\|\rho^+Y^{*-}\rangle$	168	33	$\langle \bar{K}^0p\|\pi^0Y^{*+}\rangle$	12
16	$\langle \pi^-p\|K^+\Sigma^-\rangle$	3	34	$\langle \bar{K}^0p\|\pi^+Y^{*0}\rangle$	12
17	$\langle \pi^-p\|K^{*+}\Sigma^-\rangle$	129	35	$\langle \bar{K}^0p\|K^+\Xi^{*0}\rangle$	24
18	$\langle \pi^-p\|\pi^-N^{*+}\rangle$	24	36	$\langle \bar{K}^0p\|K^{*+}\Xi^{*0}\rangle$	240

equalities[11]

$$\sigma(\pi^-p\,|\,\pi^+N^{*-})/3 = \sigma(\pi^-p\,|\,K^+Y_1^{*-}) = \sigma(K^-p\,|\,\pi^+Y_1^{*-}) = \sigma(K^-p\,|\,K^+\Xi^{*-}), \quad (9)$$

$$\sigma(\pi^-p\,|\,\rho^+N^{*-})/3 = \sigma(\pi^-p\,|\,K^{*+}Y_1^{*-}) = \sigma(K^-p\,|\,\rho^+Y_1^{*-}) = \sigma(K^-p\,|\,K^{*+}\Xi^{*-}), \quad (10)$$

and the simple equalities[20,21]

$$\sigma(K^-\rho\,|\,\pi^+\Sigma^-) = \sigma(K^-p\,|\,K^0\Xi^0) \quad (11)$$

and

$$\sigma(\pi^-p\,|\,K^+\Sigma^-) = \sigma(K^-n\,|\,K^0\Xi^-). \quad (12)$$

As a result of using $SU(6)_W$, the two sets of U-spin relations are simply related to each other and to the quantities in Eqs. (11) and (12). The cross sections of the members of Eq. (9) are 4/7 of the cross sections of the analogous members of Eq. (10). In addition,

$$\sigma(\pi^-p\,|\,\pi^-N^{*++}) = (\tfrac{1}{12})\sigma(\pi^-p\,|\,\pi^+N^{*-}), \quad (13)$$

unlike the SU(3) case, where no simple ratio existed. Many other relations like (13) may be extracted from Table II.

(5) A different group of processes in the K^-p and $\bar{K}^0p$ (or, equivalently, K^-n) systems are related in terms of another amplitude E listed in Table I. The cross sections stand in the simple ratios given below:

$$\sigma(K^-p\,|\,\bar{K}^0n):\sigma(K^-p\,|\,K^{*-}p):\sigma(K^-p\,|\,K^{*0}n):(K^-p\,|\,K^{*-}N^{*++}):(K^-p\,|\,\bar{K}^{*0}N^{*0}):\sigma(\bar{K}^0p\,|\,K^{*0}p):\sigma(\bar{K}^0p\,|\,K^{*-}N^{*++}):\sigma(\bar{K}^0p\,|\,\bar{K}^{*0}N^{*++}) = 3:16:25:8:8:1:24:8. \quad (14)$$

(6) In addition, $\sigma(K^-p\,|\,\varphi^0\Sigma^0) = (1/27)\sigma(K^-p\,|\,\varphi^0\Lambda)$, where φ^0 is the $I=0$, $Y=0$ member of the vector-meson octet.

This plethora of cross sections which are simply related offers the possibility of comparison with a large amount of experimental data. The best way to carry out this comparison is not at all unambiguous; as a start, one way is to plot the forward and backward cross sections or perhaps their ratio, as a function of final-state kinetic energy and weight by a phase-space factor.[19,22] A considerable amount of information has been thrown away in obtaining the relations (5)-(14), because the polarized amplitudes like (1)-(4) were the quantities calculated originally. If cross sections for particular polarizations are available, then even more sensitive tests of the $SU(6)_W$ predictions may be made.

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[13]A selection of relations among amplitudes, in addition to those of Eq. (1) and in addition to those which follow from U-spin (reference 12), includes the following:

$$(\gamma_{-1}p_{1/2}|K_{-1}^{*0}\Sigma_{1/2}^{+}) = -(1/\sqrt{6})(\gamma_{-1}p_{1/2}|\rho_{-1}^{-}N_{1/2}^{*++});$$

$$(\gamma_{-1}p_{1/2}|\rho_0^{+}N_{-1/2}^{*0}) = (1/\sqrt{3})(\gamma_1 p_{1/2}|\rho_0^{+}N_{3/2}^{*0});$$

$$(\gamma_1 p_{1/2}|\rho_1^{+}N_{1/2}^{*0}) = -(\sqrt{2}/\sqrt{3})(\gamma_1 p_{1/2}|\pi_0^{+}N_{3/2}^{*0}) = -(2/\sqrt{3})(\gamma_1 p_{1/2}|K_0^{+}Y_{3/2}^{*0});$$

$$(\gamma_1 p_{1/2}|\rho_1^{0}N_{1/2}^{*+}) = -(\sqrt{2}/\sqrt{3})(\gamma_1 p_{1/2}|\eta_0 N_{3/2}^{*+}) = -(\sqrt{2}/\sqrt{3})(\gamma_1 p_{1/2}|\pi_0^{0}N_{3/2}^{*+}) = (1/\sqrt{3})(\gamma_1 p_{1/2}|K_0^{0}Y_{3/2}^{*+}).$$

[14]This result follows directly from individual quark-W-spin conservation (reference 1). The final states have strange quark spin $W_\lambda = 1$ and nonstrange quark spin $(W_p + W_n) = \frac{3}{2}$. No component of the initial state has these quantum numbers.

[15]This selection rule is also obtainable from an SU(2) subgroup of $SU(6)_W$. See H. J. Lipkin, in Proceedings of the Seminar on High-Energy Physics and Elementary Particles, International Atomic Energy Agency, Trieste, Italy, 1965 (to be published).

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[18]This result is easily seen by examining the coupling in the cross channel where the processes appear as baryon-antibaryon annihilation into two mesons. The four allowed channels in $SU(6)_W$ are 1, 35_D, 35_F, and 405. The processes listed in Table I can only go through the 405 channel since they have quantum numbers which do not appear in the 1 or 35, e.g., $Y=2$, $T=\frac{3}{2}$, $T=2$, or $W=2$. Note that all reactions $P+B \to P+B^*$ fall in this category. The W spin of two pseudoscalar mesons must be $W=0$ or 2, while the $\bar{B}B^*$ system can only have $W=1$ or 2. Only the $W=2$ channel is allowed.

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ERRATUM

NEW PHENOMENON IN SEMIMETALS AND SEMICONDUCTORS. L. Esaki and P. J. Stiles [Phys. Rev. Letters 15, 152 (1965)].

At the end of the sentence ending in line seven, p. 154, enter a superscript 7 for reference 7, which is to be added also:

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