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Meson-Baryon Scattering in the Quark Model

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We obtain many sum rules for meson-baryon scattering amplitudes considering the quark-quark and the quark-antiquark amplitudes, for the appropriate meson and baryon states. The main differences from earlier work are that mesons are consistently treated as quark-antiquark pairs and not as elementary fields, and that the usual symmetry representation of the states has been taken into account. Further, the assumption that the real part of the amplitude is dominated by quark-quark forces and the imaginary part by quark-antiquark forces yields sum rules connecting these real and imaginary parts for different processes, in consonance with duality requirements.

I. INTRODUCTION

The quark model[1] has been fairly successful in obtaining relations for meson-baryon, baryon-baryon, and baryon-antibaryon processes. The hierarchy of results obtained by Lipkin and others[2] falls mainly into three categories. These are either without any assumption of symmetry in quark space, or with $SU(2)_I$ symmetry only, or with full $SU(3)$ symmetry. However, it is observed that agreement with experimental values becomes more satisfactory as the restrictions on the quark-quark and quark-antiquark interactions are decreased. Also, it is to be noted that group-theoretical calculations of cross sections for different processes are successful only when the octet type of $SU(3)$-symmetry-breaking interactions is taken into account.[3] This was the motivation to examine a $T_3{}^3$ type of violation of $SU(3)$ symmetry in quark space itself.[4] Such an approach gave useful relations for the masses of baryons and mesons. Also, the results obtained for s-wave baryon-baryon scattering[5] with this type of symmetry breaking in quark space are different from the results obtained under a broken-$SU(3)$-symmetry scheme in the baryon space.[6]

The decay widths of baryon and meson resonances[7] and baryon-meson scattering[8] have been obtained by treating the pseudoscalar octets as fields instead of assigning them the quark-antiquark structure. Such asymmetry in the treatment of baryons (treated as $3Q$ structures) and mesons is undesirable. In this paper we obtain the relations among the scattering amplitudes or cross sections for meson-baryon processes, treating consistently baryons and mesons with usual quark structure.[4] Meson-baryon scattering processes thus include both quark-quark and quark-antiquark forces. The quark-quark amplitudes of Ref. 5 are used here. The quark-antiquark forces are taken in the crossed channel. Double-exchange processes are not taken into account, since they are known to be several orders of magnitude smaller.[9]

II. $M+B\rightarrow M+B$ PROCESSES

The main assumption involved in calculating the amplitudes for meson-baryon processes is that the quark from the meson scatters the quark from the baryon either directly or by exchange of spin or unitary spin or both. Similarly, the antiquark from the meson scatters the quark from the baryon, including also annihilation and pair creation. The noninteracting quarks or antiquarks remain passive. The quark-quark and quark-antiquark amplitudes play the basic role in generating meson-baryon scattering. In the quark-quark space, we take, e.g.,[5]

$$
\begin{aligned}
V|\mathcal{P}_+\mathcal{N}_-\rangle &= V_{dd}|\mathcal{P}_+\mathcal{N}_-\rangle + V_{de}|\mathcal{N}_+\mathcal{P}_-\rangle \\
&\quad + V_{ed}|\mathcal{P}_-\mathcal{N}_+\rangle + V_{ee}|\mathcal{N}_-\mathcal{P}_+\rangle , \\
V|\mathcal{P}_+\lambda_-\rangle &= V_{dd}{}^{(1)}|\mathcal{P}_+\lambda_-\rangle + V_{de}{}^{(1)}|\lambda_+\mathcal{P}_-\rangle \\
&\quad + V_{ed}{}^{(1)}|\mathcal{P}_-\lambda_+\rangle + V_{ee}{}^{(1)}|\lambda_-\mathcal{P}_+\rangle , \\
V|\lambda_+\lambda_-\rangle &= V_d{}^{(2)}|\lambda_+\lambda_-\rangle + V_e{}^{(2)}|\lambda_-\lambda_+\rangle ,
\end{aligned}
\tag{1a}
$$

with

$$V_i{}^{(2)} + V_{id} + V_{ie} = 2(V_{id}{}^{(1)} + V_{ie}{}^{(1)}) , \tag{1b}$$

where i stands for d or e. We note that the above

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[1] M. Gell-Mann, Phys. Letters **8**, 214 (1964); G. Zweig, CERN Report (unpublished).

[2] H. J. Lipkin and F. Scheck, Phys. Rev. Letters **16**, 71 (1966); R. H. Dalitz, in *Proceedings of the Thirteenth International Conference on High-Energy Physics, Berkeley, 1966* (University of California Press, Berkeley, 1967), p. 215; H. J. Lipkin, Phys. Rev. Letters **16**, 1015 (1966); J. J. Kokkedee and L. Van Hove, Nuovo Cimento **43**, 711 (1966); C. Becchi and G. Morpurgo, Phys. Rev. **140**, B687 (1965); R. Van Royen and V. F. Weisskopf, Nuovo Cimento **50A**, 617 (1967); P. A. Cook, *ibid.* **48A**, 570 (1967); A. N. Mitra and M. Ross, Phys. Rev. **158**, 1630 (1967); S. P. Misra and C. V. Sastry, *ibid.* **172**, 1402 (1968).

[3] H. Harari, in *High Energy Physics and Elementary Particles* (International Centre for Theoretical Physics, Trieste, 1965), p. 353.

[4] S. P. Misra and C. V. Sastry, Phys. Rev. **172**, 1402 (1968).

[5] C. V. Sastry and C. Subrahmanyam, Phys. Rev. **185**, 2027 (1969).

[6] S. D. Gupta and L. K. Pande, Phys. Rev. **143**, 1190 (1966).

[7] C. Becchi and G. Morpurgo, Phys. Rev. **140**, B687 (1965); R. Van Royan and V. F. Weisskopf, Nuovo Cimento **50A**, 617 (1967); A. N. Mitra and M. Ross, Phys. Rev. **158**, 1630 (1967).

[8] G. C. Joshi, V. S. Bhasin, and A. N. Mitra, Phys. Rev. **156**, 1572 (1967).

[9] S. D. Gupta and A. N. Mitra, Phys. Rev. **159**, 1285 (1967).

interaction is equivalent to the matrix

$$
\begin{aligned}
V=\tfrac{1}{2}\Big[\alpha_d+\beta_d\sum_{k=1}^{8}\lambda_k^{(1)}\lambda_k^{(2)}+\gamma_d\sum_{k=4}^{7}\lambda_k^{(1)}\lambda_k^{(2)}\\
+\tfrac{4}{3}\gamma_d\lambda_8^{(1)}\lambda_8^{(2)}+\sqrt{3}\delta_d(\lambda_8^{(1)}XI^{(2)}+I^{(1)}X\lambda_8^{(2)})\Big]\\
+\frac{1+\sigma^{(1)}\cdot\sigma^{(2)}}{4}\Big[\alpha_e+\beta_e\sum_{k=1}^{8}\lambda_k^{(1)}\lambda_k^{(2)}+\gamma_e\sum_{k=4}^{7}\lambda_k^{(1)}\lambda_k^{(2)}\\
+\tfrac{4}{3}\gamma_e\lambda_8^{(1)}\lambda_8^{(2)}+\sqrt{3}\delta_e(\lambda_8^{(1)}XI^{(2)}+I^{(1)}X\lambda_8^{(2)})\Big].
\end{aligned}
$$

Here

$$
\begin{aligned}
V_{id}&=\alpha_i-\tfrac{2}{3}\beta_i+(4/9)\gamma_i+2\delta_i\,, & V_{ie}&=2\beta_i;\\
V_{id}^{(1)}&=\alpha_i-\tfrac{2}{3}\beta_i-(8/9)\gamma_i-\delta_i\,, & V_{ie}^{(1)}&=2\beta_i+2\gamma_i\,,
\end{aligned}
$$

where i may be d or e, and $V_i^{(2)}$ is given by (1b). In the quark-antiquark space, with $\bar{V}$ describing the amplitudes as continued to the crossed channel,[4] we have

$$
\begin{aligned}
V|\mathcal{P}_+\bar{\mathcal{N}}_-\rangle&=\bar{V}_{dd}|\mathcal{P}_+\bar{\mathcal{N}}_-\rangle+\bar{V}_{ed}[|\mathcal{P}_+\bar{\mathcal{N}}_-\rangle-|\mathcal{P}_-\bar{\mathcal{N}}_+\rangle]\,,\\
V|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle&=\bar{V}_{dd}|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle+\bar{V}_{de}[|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle-|\mathcal{N}_+\bar{\mathcal{N}}_-\rangle]\\
&\quad+\bar{V}_{de}^{(1)}|\lambda_+\bar{\lambda}_-\rangle+\bar{V}_{ed}[|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle-|\mathcal{P}_-\bar{\mathcal{P}}_+\rangle]\\
&\quad+\bar{V}_{ee}[|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle-|\mathcal{P}_-\bar{\mathcal{P}}_+\rangle-|\mathcal{N}_+\bar{\mathcal{N}}_-\rangle+|\mathcal{N}_-\bar{\mathcal{N}}_+\rangle]\\
&\quad+\bar{V}_{ee}^{(1)}[|\lambda_+\bar{\lambda}_-\rangle-|\lambda_-\bar{\lambda}_+\rangle]\,, \qquad (2)
\end{aligned}
$$

and similarly for any other quark-antiquark pair.

Thus, for π^+p scattering, we find that

$$
\begin{aligned}
V|\pi^+p\rangle&=[(3V_{dd}+2V_{de}+\tfrac{3}{2}V_{ed}+V_{ee})\\
&\quad+(3\bar{V}_{dd}+\bar{V}_{de}+\tfrac{3}{2}\bar{V}_{ed}+\tfrac{1}{2}\bar{V}_{ee})]|\pi^+p\rangle\\
&\quad+[(\tfrac{1}{2}V_{ed}+\tfrac{2}{3}V_{ee})+(\tfrac{1}{2}\bar{V}_{ed}-\tfrac{1}{6}\bar{V}_{ee})]|\rho^+p\rangle\\
&\quad+\left[\frac{2}{3\sqrt{2}}V_{ee}+\left(-\frac{2}{3\sqrt{2}}\bar{V}_{ee}\right)\right]|\rho^+N^{*+}\rangle\\
&\quad+[-\bar{V}_{de}^{(1)}-\tfrac{1}{2}\bar{V}_{ee}^{(1)}]|K^+\Sigma^+\rangle+[\tfrac{1}{6}\bar{V}_{ee}^{(1)}]|K^{*+}\Sigma^+\rangle\\
&\quad+[(2/3\sqrt{2})\bar{V}_{ee}^{(1)}]|K^{*+}Y_1^{*+}\rangle\,. \qquad (3)
\end{aligned}
$$

In obtaining the above equation, we have used the $SU(6)$ structure of π^+ and p as obtained in Ref. 4. For the elastic scattering of $|\pi^+p\rangle$, this gives

$$
\begin{aligned}
\langle\pi^+p|V|\pi^+p\rangle&=(3V_{dd}+2V_{de}+\tfrac{3}{2}V_{ed}+V_{ee})\\
&\quad+(3\bar{V}_{dd}+\bar{V}_{de}+\tfrac{3}{2}\bar{V}_{ed}+\tfrac{1}{2}\bar{V}_{ee})\,. \qquad (4)
\end{aligned}
$$

The amplitudes for the other processes can also be obtained similarly. We find a number of sum rules for $M+B\to M+B$ processes, where M stands for the pseudoscalar mesons. The scattering cross sections must be corrected by the appropriate kinematic factors before confronting them with experimental data. The following sum rules follow immediately for the forward elastic scattering amplitudes *when we take $SU(3)$ symmetry in quark space*:

$$
\begin{aligned}
\tfrac{1}{2}[(K^+p)-(K^-p)]&=[(\pi^+p)-(\pi^-p)]\\
&=[(K^0p)-(\bar{K}^0p)]\,, \qquad (5)\\
2[(K^-p)+(K^+p)]&=[(K^-n)+(K^+n)]\\
&\quad+[(\pi^+p)+(\pi^-p)]\,, \qquad (6)
\end{aligned}
$$

$$(\pi^+p)+(K^-p)+(K^0p)=(\pi^-p)+(K^+p)+(\bar{K}^0p)\,, \qquad (7)$$

$$(K^-p)+2(K^+n)=(K^+p)+2(K^-n)\,, \qquad (8a)$$

$$
\begin{aligned}
(\pi^+p)+(K^-n)&=(\pi^-p)+(K^+n)\\
&=(K^-p)+(K^+p)\,. \qquad (8b)
\end{aligned}
$$

Equation (5) is the well-known Johnson-Treiman relation.[10] Equations (6) and (7) represent, respectively, the symmetric and antisymmetric sum rules obtained by Lipkin and Scheck.[11] Equation (8a) was also obtained by Lipkin and is in agreement with experiment.[12] We note that the above equations are satisfied for the quark-quark and quark-antiquark amplitudes separately. Equations (5)–(8a) were also obtained by Joshi *et al.*,[8] where they have taken the mesons as "elementary" particles rather than as quark-antiquark composites.

The sum rules derived by Barger and Cline[13] for inelastic processes such as

$$\langle K^-p|\bar{K}^0n\rangle-\langle K^+n|K^0p\rangle=-\sqrt{2}\langle\pi^-p|\pi^0n\rangle\,, \qquad (9)$$

$$
\begin{aligned}
|\langle K^-p|\bar{K}^0n\rangle|^2+|\langle K^+n|K^0p\rangle|^2&=|\langle\pi^-p|\pi^0n\rangle|^2\\
&\quad+3|\langle\pi^-p|\eta'n\rangle|^2 \qquad (10)
\end{aligned}
$$

are seen to be true here without any assumption other than the additivity of the quark-quark and quark-antiquark amplitudes. Here η' is a member of the octet without any mixing. If we take the quark-quark and quark-antiquark amplitudes to be the same, we obtain in our model one more result of Barger and Cline[13]:

$$\frac{d\sigma}{dt}(K^-p\to\bar{K}^0n)=\frac{d\sigma}{dt}(K^+n\to K^0p)\,, \qquad (11)$$

which seems to disagree with experimental data.[13] This indicates that the energy may not be high enough.

We further obtain the following sum rules connecting the inelastic scattering amplitudes in the forward direction:

$$\langle K^+p|K^+p\rangle-\langle\pi^+p|\pi^+p\rangle=\langle\pi^+p|K^+\Sigma^+\rangle\,, \qquad (12)$$

$$\langle K^-p|K^-p\rangle-\langle\pi^-p|\pi^-p\rangle=\langle K^-p|\pi^-\Sigma^+\rangle\,, \qquad (13)$$

$$\langle K^-p|\pi^0\Lambda\rangle=\sqrt{3}\langle K^-p|\pi^0\Sigma^0\rangle\,, \qquad (14)$$

$$\langle\pi^-p|K^0\Lambda\rangle=(\sqrt{\tfrac{3}{2}})\langle K^-p|\bar{K}^0n\rangle\,, \qquad (15)$$

$$\langle\pi^-p|K^0\Lambda\rangle=-\sqrt{3}\langle\pi^-p|K^0\Sigma^0\rangle\,, \qquad (16)$$

[10] K. Johnson and S. B. Treiman, Phys. Rev. Letters **14**, 189 (1965); A. Pais, Rev. Mod. Phys. **38**, 215 (1966).

[11] H. J. Lipkin and F. Scheck, Phys. Letters **16**, 73 (1966).

[12] H. J. Lipkin, Phys. Rev. Letters **16**, 1015 (1966).

[13] V. Barger and D. Cline, Phys. Rev. **156**, 1522 (1966).

$$\langle K^+n|K^0p\rangle=\tfrac{1}{2}\sqrt{3}\langle\pi^0\Lambda|K^-p\rangle$$
$$=\langle\pi^-\Sigma^+|K^-p\rangle, \quad (17)$$

$$\langle\bar{K}^0n|K^-p\rangle=(\sqrt{\tfrac{3}{2}})\langle K^0\Lambda|\pi^-p\rangle$$
$$=\langle K^+\Sigma^+|\pi^+p\rangle, \quad (18)$$

$$\sqrt{2}\langle\pi^0n|\pi^-p\rangle=\langle\bar{K}^0n|K^-p\rangle$$
$$+\langle\pi^-\Sigma^+|K^-p\rangle. \quad (19)$$

Equations (12)-(16) are well-known results in the quark model[14] with simple rearrangement and are obtained here also. Relations (14) and (16) are true even when $SU(3)$ violation is taken into account. Relations (17)-(19) are new.

If we define the physical η and X mesons as[4]

$$|\eta\rangle=-\sin\theta\ |q\bar{q}(ss)\rangle+\cos\theta\ |\lambda\bar{\lambda}(s)\rangle, \quad (20)$$

$$|X\rangle=\cos\theta\ |q\bar{q}(ss)\rangle+\sin\theta\ |\lambda\bar{\lambda}(s)\rangle, \quad (21)$$

we obtain the following sum rules for cross sections, most of which are independent of the mixing angle:

$$\bar{\sigma}(K^-+p\to\eta+\Lambda)+\bar{\sigma}(K^-+p\to X+\Lambda)$$
$$=\bar{\sigma}(\pi^-+p\to K^0+\Lambda)+\bar{\sigma}(K^-+p\to\pi^0+\Lambda), \quad (22)$$

$$\bar{\sigma}(\pi^-+p\to\pi^0+n)+\bar{\sigma}(\pi^-+p\to\eta+n)$$
$$+\bar{\sigma}(\pi^-+p\to X+n)$$
$$=\bar{\sigma}(K^++n\to K^0+p)+\bar{\sigma}(K^-+p\to\bar{K}^0+n), \quad (23)$$

$$\bar{\sigma}(\pi^-+p\to\pi^0+n)$$
$$=\bar{\sigma}(\pi^-+p\to\eta+n)+\bar{\sigma}(\pi^-+p\to X+n), \quad (24)$$

$$\bar{\sigma}(K^-+p\to\eta+\Lambda)+\bar{\sigma}(K^-p\to X+\Lambda)$$
$$=3[\bar{\sigma}(K^-+p\to\eta+\Sigma^0)+\bar{\sigma}(K^-+p\to X+\Sigma^0)], \quad (25)$$

$$\bar{\sigma}(\pi^-p\to\pi^0+n)=\csc^2\theta\ \bar{\sigma}(\pi^-+p\to\eta+n). \quad (26)$$

Equations (22) and (23) are obtained by Alexander *et al.*[15] in the simple rearrangement model, with $SU(3)$ symmetry. Equations (24)-(26) are new relations obtained here under $SU(2)_I$ invariance only, and Eq. (26) should be a check on the η-X mixing angle proposed earlier.[4]

III. $M+B\to V+B$ (B^*) PROCESSES

We next consider the pseudoscalar meson and baryon producing a vector meson and a baryon. The following sum rules for cross sections are obtained with only the $SU(2)_I$ invariance of quark-quark and quark-antiquark amplitudes:

$$\bar{\sigma}(K^-+p\to\rho^-+\Sigma^+)=\tfrac{1}{8}\bar{\sigma}(K^-+p\to\rho^-+Y_1{}^{*+})$$
$$=4\bar{\sigma}(K^-+p\to\rho^0+\Sigma^0), \quad (27)$$

$$\bar{\sigma}(K^-+p\to\rho^0+\Lambda)=\bar{\sigma}(K^-+p\to\omega+\Lambda)$$
$$=27\bar{\sigma}(K^-+p\to\rho^0+\Sigma^0), \quad (28)$$

$$\bar{\sigma}(K^-+p\to\rho^0+\Lambda)=(27/8)\bar{\sigma}(K^-+p\to\rho^0+Y_1{}^{*0})$$
$$+(27/8)\bar{\sigma}(K^-+p\to\omega+Y_1{}^{*0}), \quad (29)$$

$$\bar{\sigma}(K^0+p\to K^{*+}+n)=(25/8)$$
$$\times\bar{\sigma}(K^0+p\to K^{*0}+Y_1{}^{*+}), \quad (30)$$

$$\bar{\sigma}(\pi^-+p\to\rho^0+n)=\bar{\sigma}(\pi^-+p\to\omega+n), \quad (31)$$

$$\bar{\sigma}(\pi^-+p\to\rho^0+n)=(25/16)$$
$$\times\bar{\sigma}(\pi^-+p\to\rho^-+N^{*+}), \quad (32)$$

$$\bar{\sigma}(\sigma^-+p\to K^{*0}+\Lambda)=(27/8)\bar{\sigma}(\pi^-+p\to K^{*0}+Y_1{}^{*0})$$
$$=27\bar{\sigma}(\pi^-+p\to K^{*0}+\Sigma^0), \quad (33)$$

$$\bar{\sigma}(\pi^-+p\to K^{*0}+\Sigma^0)=\tfrac{1}{2}\bar{\sigma}(\pi^++p\to K^{*+}+\Sigma^+), \quad (34)$$

$$\sigma(K^-+p\to\bar{K}^{*0}+n)=(25/8)$$
$$\times\bar{\sigma}(K^-p\to K^{*-}+N^{*+}), \quad (35)$$

$$\bar{\sigma}(K^-+p\to\phi+\Lambda)=(27/8)\bar{\sigma}(K^-+p\to\phi+Y_1{}^{*0})$$
$$=27\bar{\sigma}(K^-+p\to\phi+\Sigma^0), \quad (36)$$

$$\bar{\sigma}(\pi^-+p\to\rho^0+n)+\bar{\sigma}(\pi^-+p\to\omega+n)$$
$$=\bar{\sigma}(K^++n\to K^{*0}+p)+\bar{\sigma}(K^-+p\to\bar{K}^{*0}+n). \quad (37)$$

Many of the above relations are new to the quark model. A large number of relations can also be obtained with $SU(3)$ invariance, but most of these can be seen by inspection and are not given here.

It is interesting to note that we can also obtain some results built in from duality considerations.[16] Recently, Harari[17] and Rosner[18] have given a qualitative description of this on the basis of quark-model diagrams. There seems to be a very close analogy with the present model, mesons being treated as quark-antiquark composites. We conjecture that the imaginary part of the meson-baryon scattering amplitudes is dominated by the quark-antiquark forces and that the real part is given by quark-quark forces only. This immediately enables us to write the relations of Harari[17]:

$$\begin{aligned}\mathrm{Im}(\pi^-p\to\rho^0n)&=-\mathrm{Im}(\pi^-p\to\omega n),\\ \mathrm{Im}(\pi^+n\to\rho^0p)&=\mathrm{Im}(\pi^+n\to\omega p),\\ \mathrm{Im}(\pi^+p\to\omega\Delta^{++})&=\mathrm{Im}(\pi^+p\to\rho^0\Delta^{++}),\\ \mathrm{Im}(\rho^0p\to K^+\Lambda)&=\mathrm{Im}(\omega p\to K^+\Lambda),\end{aligned} \quad (38)$$

Also, the scattering amplitudes for the processes $K^+n\to K^0p$, K^*N, K^*N^*, and $K^-p\to\pi^-\Sigma^+$, $\pi^0\Sigma^0$, $\pi^0\Lambda$, $\rho^0\Lambda$, $\omega\Lambda$ become real. Further, we note that

$$\mathrm{Im}(K^-p\to\rho^0\Lambda)=0, \quad (39a)$$

$$\mathrm{Im}(K^-p\to\omega\Lambda)=0, \quad (39b)$$

and

$$\mathrm{Re}(K^-p\to\rho^0\Lambda)=\mathrm{Re}(K^-p\to\omega\Lambda), \quad (39c)$$

which gives

$$\sigma(K^-p\to\rho^0\Lambda)=\sigma(K^-p\to\omega\Lambda).$$

[14] H. J. Lipkin, F. Scheck, and H. Stern, Phys. Rev. **152**, 1375 (1965).

[15] G. Alexander, H. J. Lipkin, and F. Scheck, Phys. Rev. Letters **17**, 412 (1966).

[16] R. Dolen, D. Horn, and C. Schmid, Phys. Rev. **166**, 1768 (1968); D. P. Roy and M. Suzuki, Phys. Letters **28B**, 558 (1969).

[17] H. Harari, Phys. Rev. Letters **22**, 562 (1969).

[18] J. L. Rosner, Phys. Rev. Letters **22**, 689 (1969).

Equation (39c) was obtained by Harari[17] from (39a) and (39b) through dispersion relations, which has not been necessary here.

For the sake of interest, we write down here a few more relations which follow from the above conjecture:

$$\mathrm{Im}(K^-p\to \bar{K}^{*0}n)=(5/2\sqrt{2})\,\mathrm{Im}(K^-p\to \bar{K}^{*0}N^{*0})$$
$$=(5\sqrt{2}/3\sqrt{3})\,\mathrm{Im}(K^-p\to \phi\Lambda)\,, \qquad (40)$$

$$\mathrm{Im}(\pi^-p\to \pi^0n)=\tfrac{1}{2}\sqrt{2}\,\mathrm{Im}(K^-p\to \bar{K}^0n) \quad \text{(Ref. 19)}, \qquad (41)$$

$$\mathrm{Im}(\bar{K}^0p\to \phi\Sigma^+)=(1/2\sqrt{2})\,\mathrm{Im}(\bar{K}^0p\to \phi Y_1^{*+})\,, \qquad (42)$$

$$\mathrm{Im}(K^-p\to \bar{K}^0\Lambda)=-3\,\mathrm{Im}(K^-p\to \bar{K}^0\Sigma^0)\,, \qquad (43)$$

$$\mathrm{Im}(\pi^-p\to K^{*0}\Lambda)=3\,\mathrm{Im}(K^-p\to \bar{K}^{*0}\Sigma^0)\,. \qquad (44)$$

We note that since spin is included, the present conjecture has more dynamical content and seems to give all the results of Harari and Rosner.

Again, for high-energy processes, when we assume that quark-quark and quark-antiquark forces are equal in magnitude, we get

$$\mathrm{Re}(K^-p\to \bar{K}^0n)/\mathrm{Im}(K^0p\to K^+n)=1\,, \qquad (45)$$

$$\mathrm{Re}(\pi^-p\to \pi^0n)/\mathrm{Im}(\pi^-p\to \pi^0n)=1\,, \qquad (46)$$

and

$$\mathrm{Re}(K^-p\to \bar{K}^0n)/\mathrm{Im}(K^-p\to \bar{K}^0n)=0\,. \qquad (47)$$

We may compare these results with the results of the Regge-pole model[19,20]:

$$\mathrm{Re}(K^-p\to \bar{K}^0n)/\mathrm{Im}(K^0p\to K^+n)=1\,,$$
$$\mathrm{Re}(\pi^-p\to \pi^0n)/\mathrm{Im}(\pi^-p\to \pi^0n)=\tan\tfrac{1}{2}\pi\alpha_\rho\,, \qquad (48)$$
$$\mathrm{Re}(K^-p\to \bar{K}^0n)/\mathrm{Im}(K^-p\to \bar{K}^0n)=\cot\pi\alpha_\rho\,,$$

where $\alpha_\rho=0.5$. This result, of course, could be accidental, although amusing.

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[19] A. Ahmadzadeh and C. H. Chan, Phys. Letters **22**, 692 (1966).

[20] V. Barger and L. Durand III, Phys. Rev. **156**, 1525 (1967)

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Test of Duality in π^+p Backward Angular Distributions*

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A model in which the backward π^+p angular distribution is assumed to arise from a sum of direct-channel resonances is compared with the data at intermediate energies. Many as yet undiscovered resonances are assumed to exist as Regge recurrences of experimentally known resonances. The agreement between the results of the model and experiment is qualitatively quite good at angles near the backward direction for incident pion momenta between 2.2 and 5.0 GeV/c. In particular, the position and the shape of the minimum around $u\simeq -0.2$ (GeV/c)^2 in the differential cross section is correctly obtained. Since a similar minimum has previously been obtained in a model with Regge-pole exchange in the crossed channel, the result of the calculation gives support to the concept of duality at intermediate energies.

1. INTRODUCTION

One of the most striking features of π^+p elastic scattering at intermediate[1–4] and high[5] energies near the backward direction[6] is a minimum in the differential cross section near $u=-0.2$ (GeV/c)^2, where u is the square of the four-momentum transfer from the

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[1] J. P. Chandler, R. R. Crittenden, K. F. Galloway, R. M. Heinz, H. A. Neal, K. A. Potocki, W. F. Prickett, and R. A. Sidwell, Phys. Rev. Letters **23**, 186 (1969).

[2] A. S. Carroll, J. Fischer, A. Lundby, R. H. Phillips, C. L. Wang, F. Lobkowicz, A. C. Melissinos, Y. Nagashima, and S. Tewksbury, Phys. Rev. Letters **20**, 607 (1968).

[3] J. Banaigs, J. Berger, C. Bonnel, J. Duflo, L. Goldzahl, F. Plouin, W. F. Baker, P. J. Carlson, V. Chabaud, and A. Lundby, Nucl. Phys. **B8**, 31 (1968); W. F. Baker, K. Berkelman, P. J. Carlson, G. P. Fisher, P. Fleury, D. Hartill, R. Kalbach, A. Lundby, S. Mukhin, R. Nierhaus, K. P. Pretzl, and J. Woulds, Phys. Letters **28B**, 291 (1968); W. F. Baker, P. J. Carlson, V. Chabaud, A. Lundby, J. Banaigs, J. Berger, C. Bonnel, J. Duflo, L. Goldzahl, and F. Plouin, *ibid.* **25B**, 361 (1967); W. F. Baker, P. J. Carlson, V. Chabaud, A. Lundby, E. G. Michaelis, J. Banaigs, J. Berger, C. Bonnel, J. Duflo, L. Goldzahl, and F. Plouin, *ibid.* **23**, 605 (1966).

[4] J. Orear, R. Rubinstein, D. B. Scarl, D. H. White, A. D. Krisch, W. R. Frisken, A. L. Read, and H. Ruderman, Phys. Rev. **152**, 1162 (1966).

[5] A. Ashmore, C. J. S. Damerell, W. R. Frisken, R. Rubinstein, J. Orear, D. P. Owen, F. C. Peterson, A. L. Read, D. G. Ryan, and D. H. White, Phys. Rev. Letters **19**, 460 (1967); J. Orear, D. P. Owen, F. C. Peterson, A. L. Read, D. G. Ryan, D. H. White, A. Ashmore, C. J. S. Damerell, W. R. Frisken, and R. Rubinstein, *ibid.* **21**, 389 (1968).

[6] For a summary of the experimental information, see M. Derrick, in *Proceedings of the Topical Conference on High Energy Collisions on Hadrons, CERN, 1968* (Scientific Information Service, Geneva, 1968), p. 111.