Baryon-Antibaryon Scattering in the Quark Model

C. V. SASTRY AND S. P. MISRA
Regional Engineering College, Rourkela-8, India
(Received 15 January 1970)

Proton-antiproton and neutron-antiproton scattering are calculated in the quark model, and it is observed that $SU(3)$ violation should be taken into account in the quark-antiquark space to obtain agreement with experimental data.

INTRODUCTION

BARYON-ANTIBARYON scattering has been considered earlier in the quark model[1] by Gupta[2] in an $SU(3)$-invariant way. It was shown by Badier[3] that the agreement with experimental cross sections for baryon-antibaryon scattering is satisfactory only when $SU(3)$ violation is introduced in the quark space. However, Badier took $SU(6)$-symmetry states of the particles and assumed that the rearrangement and pair annihilation of the quark-antiquark pairs take place without any spin-spin interaction, and hence two constants only were required to describe the interaction. We feel that the description presented by Badier does not take into account all possible types of interaction, and we calculate here the proton-antiproton and neutron-antiproton scattering amplitudes. We obtain a number of well-satisfied cross-section equalities or inequalities.

We consider the $\bar{B}B$ amplitude as the sum of the amplitudes for individual $\bar{Q}Q$ scattering as well as the scattering of two quarks with two antiquarks, one quark and one antiquark being spectators. The inclusion of double scattering as a correction to the single-scattering amplitudes enables us to accommodate double-charge-exchange or double-strangeness-exchange processes in the quark model. We neglect the relatively small effect of the $\Delta S=3$ channel, as is evident from the small production cross section of Ω^- in $\bar{p}p$ collisions.[4]

We find good agreement with experiment for the sum rules obtained. For the purpose of comparison with experimental data, we use the cross sections corrected for phase space,[5] as calculated by Badier[3] (quoted in Table I) at moderately high energies (c.m. final momentum $p_f=0.8$ GeV/c). The sum rules are converted to polygonal inequalities which seem to be well satisfied.

SUM RULES

The quark-antiquark interaction can be explicitly expressed as[6,7]

$$V|\mathcal{P}_+\bar{\mathcal{N}}_-\rangle=\bar{V}_{dd}|\mathcal{P}_+\bar{\mathcal{N}}_-\rangle+\bar{V}_{ed}[|\mathcal{P}_+\bar{\mathcal{N}}_-\rangle-|\mathcal{P}_-\bar{\mathcal{N}}_+\rangle], \quad (1)$$

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

and similarly for any other quark-antiquark pair. The amplitude for the proton-antiproton pair going to any other allowed baryon-antibaryon pair is obtained by sandwiching the quark-antiquark interaction Hamiltonian between the appropriate states and assuming the additivity of the quark-antiquark amplitudes. This amounts to taking the sum of the quark-antiquark amplitudes which allow one quark from the proton to scatter one antiquark from the antiproton, the other quarks (antiquarks) remaining passive. Double scattering of quarks with antiquarks is also included as a correction to the single-scattering term.

The following sum rules for $\bar{B}B\to\bar{B}B$ (where B stands for the baryon octet), quoted by many authors, follow immediately from $SU(2)_I$ invariance of the quark-antiquark amplitudes, and they merely form a con-

TABLE I. Experimental value of the baryon-antibaryon cross sections at fixed $p_f^*=0.8$ GeV/c.[a]

Reaction $\bar{p}p\to$	σ (μb) Experimental value	S (μb GeV^2) Experimental value (phase-space corrected)
$\bar{n}n$	5200 ± 800	3100 ± 500
$\bar{p}N^{*+}$+c.c.[b]	$\simeq1700$	$\simeq1700$
$\bar{n}N^{*0}$+c.c.	$\simeq1800$	$\simeq1800$
$\bar{N}^{*--}N^{*++}$	2400 ± 400	3000 ± 500
$\bar{N}^{*-}N^{*+}$	$\simeq1000$	$\simeq1250$
$\bar{N}^{*0}N^{*0}$	<1300	<1700
$\bar{N}^{*+}N^{*-}$	$\simeq0$	$\simeq0$
$\bar{\Lambda}\Lambda$	117 ± 18	114 ± 19
$\bar{\Sigma}^0\Lambda$+c.c.	82 ± 38	85 ± 38
$\bar{\Sigma}^-\Sigma^+$	33 ± 16	37 ± 18
$\bar{\Sigma}^0\Sigma^0$	11 ± 11	12 ± 12
$\bar{\Sigma}^+\Sigma^-$	8 ± 8	9 ± 9
$\bar{\Lambda}Y_1^{*0}$+c.c.	29 ± 21	37 ± 26
$\bar{\Sigma}^-Y_1^{*+}$+c.c.	22 ± 10	29 ± 13
$\bar{\Sigma}^0Y^{*0}$+ c.c.	3 ± 3	4 ± 4
$\bar{\Sigma}^+Y^{*+}$+c.c.	2 ± 2	3 ± 3
$\bar{Y}_1^{*+}Y^{*+}$	15 ± 10	25 ± 16
$\bar{Y}_1^{*+}Y^{*-}$	5 ± 2	8 ± 3
$\bar{\Xi}^+\Xi^-$	1 ± 1	1.5 ± 1.5
$\bar{\Xi}^{*0}\Xi^{*0}$	<5	<10
$\bar{\Xi}^{*+}\Xi^{*-}$	<4	<8

[a] See Ref. 3. S is the experimental cross section multiplied by the phase-space factor $E_0^2(p_i^*/p_f^*)$, where p_i^* and p_f^* are the initial and final momenta of the particles in the c.m. system.
[b] Here c.c. means charge conjugate.

[1] M. Gell-Mann, Phys. Letters **8**, 214 (1964); G. Zweig, CERN report (unpublished).
[2] S. D. Gupta, Phys. Rev. **159**, 1345 (1967).
[3] S. Badier, Nuovo Cimento **50A**, 313 (1967).
[4] C. Y. Chien *et al.*, Phys. Rev. **152**, 117 (1966).
[5] S. Meshkov, G. A. Snow, and G. B. Yodh, Phys. Rev. Letters **12**, 87 (1964).
[6] S. P. Misra and C. V. Sastry, Phys. Rev. **172**, 1402 (1968).
[7] C. V. Sastry and S. P. Misra, Phys. Rev. D **1**, 166 (1970).

sistency check on the model:

$$(\bar{p}p)=(\bar{p}n)+(\bar{n}n)\,, \tag{3}$$

$$2(\bar{\Sigma}^0\Sigma^0)=(\bar{\Sigma}^+\Sigma^-)+(\bar{\Sigma}^-\Sigma^+)\,, \tag{4}$$

$$(\bar{\Lambda}\Sigma^0)=(\bar{\Sigma}^0\Lambda)\,, \tag{5}$$

$$(\bar{\Sigma}^0\Lambda)=(2)^{-1/2}(\bar{\Lambda}\Sigma^-)\,, \tag{6}$$

$$(2)^{-1/2}(\bar{\Sigma}^-\Sigma^0)=(\bar{\Sigma}^-\Sigma^+)-(\bar{\Sigma}^0\Sigma^0)\,, \tag{7}$$

$$(\bar{\Xi}^0\Xi^0)=(\bar{\Xi}^+\Xi^-)-(\bar{\Xi}^0\Xi^-)\,. \tag{8}$$

In the above ,$(\bar{B}B)$ stands for $A(\bar{B}B|\bar{p}p)$ or $A(\bar{B}B|\bar{p}n)$ as may be distinguished by charge balance. The sum rules are satisfied for single- and double-scattering amplitudes separately, and they were obtained earlier from $SU(3)$ symmetry[8] and from collinear $SU(3)\times SU(3)$ symmetry,[9] as well as from the quark model.[2] If the double-scattering contribution to the scattering amplitudes is neglected, we obtain[3]

$$(\bar{\Sigma}^+\Sigma^-)=(\bar{\Xi}^0\Xi^0)=(\bar{\Xi}^0\Xi^-)=0\,. \tag{9}$$

The cross sections for the processes in the above equation, although known, are very small (Table I), indicating that the double-scattering contribution is small. Equations (4) and (5) have been checked with experimental data by Chien *et al.*[4]

For $\bar{N}N\to\bar{B}B^*$ and $\bar{N}N\to\bar{B}^*B^*$, we obtain the following sum rules, once again from $SU(2)_I$ invariance of the quark-antiquark amplitudes only:

$$(\bar{n}N^{*0})=(\bar{p}N^{*+})\,, \tag{10}$$

$$2(\bar{\Sigma}^0Y_1^{*0})=(\bar{\Sigma}^-Y_1^{*+})-(\bar{\Sigma}^+Y_1^{*-})\,, \tag{11}$$

$$2(\bar{Y}_1^{*0}Y_1^{*0})=(\bar{Y}_1^{*-}Y_1^{*+})+(\bar{Y}_1^{*+}Y_1^{*-})\,, \tag{12}$$

$$(\bar{N}^{*--}N^{*++})=-(\bar{N}^{*0}N^{*0})+2(\bar{N}^{*-}N^{*+})\,, \tag{13}$$

$$(\bar{N}^{*-}N^{*+})=2(\bar{N}^{*0}N^{*0})-(\bar{N}^{*+}N^{*-})\,, \tag{14a}$$

$$(\bar{N}^{*--}N^{*++})-(\bar{N}^{*}N^{*-}) =3[(\bar{N}^{*-}N^{*+})-(\bar{N}^{*0}N^{*0})]\,. \tag{14b}$$

Equation (14b) is an $SU(3)$ prediction and was also obtained earlier in the quark model by Gupta.[2] Besides that, we obtain two more new relations (13) and (14a) connecting $(\bar{N}^*N^*)$ amplitudes. The cross-section inequalities for (13) and (14a) are

$$\surd\sigma(\bar{N}^{*--}N^{*++})\leqslant 2\surd\sigma(\bar{N}^{*-}N^{*+})+\surd\sigma(\bar{N}^{*0}N^{*0})\,, \tag{15}$$

$$\surd\sigma(\bar{N}^{*-}N^{*+})\leqslant 2\surd\sigma(\bar{N}^{*0}N^{*0})+\surd\sigma(\bar{N}^{*+}N^{*-})\,. \tag{16}$$

The triangular inequalities (15) and (16) are verified to be in good agreement with the values for the cross sections as given in Table I.

We can also obtain sum rules connecting $(\bar{B}B\to\bar{B}B)$ type of amplitudes to $(\bar{B}B\to\bar{B}B^*)$ type of amplitudes. One of them is

$$52\sqrt{2}(\bar{\Sigma}^0Y_1^{*0})=-8(\bar{\Sigma}^-\Sigma^+)+24(\bar{\Sigma}^+\Sigma^-) +(40/3)(\bar{\Lambda}\Lambda)+8\sqrt{3}(\bar{\Lambda}\Sigma^0)\,. \tag{17}$$

[8] K. Tanaka, Phys. Rev. **135**, B1186 (1964).
[9] K. C. Tripathy, Phys. Rev. **149**, 1149 (1966).

The cross-section inequalities for the above are of the type

$$52\sqrt{2}\surd\sigma(\bar{\Sigma}^0Y_1^{*0})\leqslant 8\surd\sigma(\bar{\Sigma}^-\Sigma^+)+24\surd\sigma(\bar{\Sigma}^+\Sigma^-) +(40/3)\surd\sigma(\bar{\Lambda}\Lambda)+8\sqrt{3}\surd\sigma(\bar{\Lambda}\Sigma^0)\,, \tag{18}$$

all of which can be easily verified. The other sum rules connecting different inelastic amplitudes are [from $SU(2)_I$ invariance in the quark space]

$$(\bar{\Sigma}^-Y_1^{*+})=\tfrac{7}{2}(\bar{\Sigma}^0Y_1^{*0})-\tfrac{1}{6}\sqrt{3}(\bar{\Lambda}Y_1^{*0})\,, \tag{19}$$

$$(\bar{Y}_1^{*0}Y_1^{*0})=\sqrt{2}(\bar{\Sigma}^0Y_1^{*0})\,, \tag{20}$$

$$(\bar{N}^{*-}N^{*+})=\tfrac{1}{2}(\bar{N}^{*--}N^{*++})+\tfrac{1}{10}\sqrt{2}(\bar{p}N^{*+})\,, \tag{21}$$

$$(\bar{N}^{*0}N^{*0})=\tfrac{1}{5}\sqrt{2}(\bar{p}N^{*+})\,. \tag{22}$$

Equations (19)–(22), when expressed in terms of inequalities or equalities of the cross sections, are in agreement with Table I.

If complete $SU(3)$ symmetry is taken in the quark space, we obtain a number of sum rules which can be expressed as cross-section inequalities or equalities:

$$(\bar{\Sigma}^+\Sigma^-)=(\bar{\Xi}^0\Xi^0)\,, \tag{23}$$

$$3(\bar{\Lambda}\Lambda)+(\bar{\Sigma}^0\Sigma^0)=2(\bar{n}n)+2(\bar{\Xi}^0\Xi^0)+2\sqrt{3}(\bar{\Sigma}^0\Lambda)\,, \tag{24}$$

$$(\bar{\Sigma}^+Y_1^{*-})=(\bar{\Xi}^{*+}\Xi^{*-})\,, \tag{25}$$

$$(\bar{Y}_1^{*+}Y_1^{*-})=2(\bar{\Xi}^{*+}\Xi^{*-})\,, \tag{26}$$

$$(\bar{N}^{*+}N^{*-})=3(\bar{\Xi}^{*+}\Xi^{*-})\,, \tag{27}$$

$$(\bar{N}^{*--}N^{*++})=3[(\bar{Y}_1^{*-}-Y_1^{*+})-(\bar{\Xi}^{*0}\Xi^{*0})]\,, \tag{28}$$

$$(\bar{\Xi}^{*0}\Xi^0)=-6(\bar{\Sigma}^0Y_1^{*0})+\tfrac{2}{3}\sqrt{3}(\bar{\Lambda}Y_1^{*0})\,, \tag{29}$$

$$(\bar{\Xi}^{*0}\Xi^{*0})=3\sqrt{2}(\bar{\Sigma}^0Y_1^{*0})-\tfrac{1}{3}(\surd 6)(\bar{\Lambda}Y_1^{*0})\,, \tag{30}$$

$$(\bar{N}^{*--}N^{*++})=\tfrac{3}{2}\sqrt{2}(\bar{\Sigma}^0Y_1^{*0})-\tfrac{1}{2}(\surd 6)(\bar{\Lambda}Y_1^{*0})\,. \tag{31}$$

Some of the above sum rules can also be derived from higher-symmetry schemes.[6]

We note that Eqs. (28) and (31), which are obtained as a result of $SU(3)$ invariance in the quark space, are *not* in agreement with experimental data. As has been observed earlier,[6] we feel that $SU(3)$ is badly broken in the quark-antiquark space and for any reasonable agreement with experiment, $SU(3)$ violation should be taken into account. We note that this is very reasonable since quark-antiquark channels include strange and nonstrange mesons for which $SU(3)$ violations are known to be large. Also we note that the unitarity condition in the quark-antiquark channel will grossly violate $SU(3)$ symmetry at moderately high energies. The above results for the baryon-antibaryon scattering indicating $SU(3)$ violation may be a reflection of all this.

ACKNOWLEDGMENTS

One of us (C.V.S.) wishes to thank the Ministry of Education, Government of India, for financial help during the course of this work.